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Kapil Gupta *Editor*

Innovations in Manufacturing for Sustainability

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Innovations in Manufacturing for Sustainability

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Preface

Sustainability is a global concern these days. The United Nation's intervention has accelerated sustainability drive worldwide and encouraged involvement at all levels. Manufacturing sector, where fabrication, machining, and materials processing are the major activities, is also busy inventing, developing, and implementing sustainable techniques.

This book provides a comprehensive collection of information and research work conducted on innovative sustainable techniques developed in various segments of manufacturing for improved quality, productivity, and sustainability. It consists of eight chapters on sustainable manufacturing. Chapter "Dry and Near-Dry Machining Techniques for Green Manufacturing" describes dry and near-dry machining techniques for green manufacturing, where innovative minimum quantity lubrication-assisted machining and dry cutting techniques with some case studies are discussed. Chapter "Cryogenic machining" provides a comprehensive information on cryogenic coolant-based sustainable machining. It reports a detail on the influence of cryogenic environment on machinability. Chapter "Sustainability Issues in Electric Discharge Machining" is dedicated to sustainability in electric discharge machining where the performance analysis of green electric discharge machining with the help of an experimental study is done. Chapter "Energy-Efficient Casting Processes" sheds light on sustainability interventions in casting. It is mainly focused on energy-efficient casting processes. Sustainability in additive manufacturing is focused in Chapter "Research Framework of Sustainability in Additive Manufacturing: A Case of Fused Deposition Modeling." A life cycle energy analysis of fused deposition modeling techniques is discussed. Sustainability concerns in various welding techniques are highlighted in Chapter "Sustainability in Welding and Processing." Chapter "Green Machining of Thin-Wall Titanium Alloy" presents green machining of thin-wall titanium and latest technology on the treatment of exhausted cutting fluid. At last, sustainability assessment-based comparative evaluation of gear manufacturing techniques is provided in Chapter "Sustainability Assessment-Based Comparative Evaluation of Precision Miniature Gear Manufacturing Processes."

The present book is intended to facilitate the researchers, engineers, technologists, and specialists who are working in the field of advanced and sustainable manufacturing. It intends to encourage researchers to go for research, development, and innovations with an objective to find the sustainable solutions to the problems encountered in the manufacturing sector by keeping the environment clean and green.

I sincerely acknowledge Springer for this opportunity and their professional support. Finally, I would like to thank all the chapter contributors for their availability and valuable contributions.

Johannesburg, South Africa Kapil Gupta
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Contents

Dry and Near-Dry Machining Techniques for Green Manufacturing

Sujan Debnath, Moola Mohan Reddy and Alokesh Pramanik

Abstract Dry and near-dry techniques have been developed for sustainability interventions in machining. These techniques not only take care of sustainability and make the machining green, but also improve productivity and surface quality. This chapter comprehensively discusses various important aspects of these green manufacturing techniques. It discusses the conventional cutting fluids, their ecological problems, recently developed green lubricants, and lubrication techniques and their applications. It also overt the latest development in oil-, aqueous-, and gas-based synthetic and semi-synthetic cutting fluids and their relative advantages and disadvantages toward green manufacturing. The environmental and health issues related to cutting fluids and the latest technologies to minimize the detrimental effects of cutting fluids on human and the environment have been discussed. Finally, the latest trends toward green manufacturing including dry machining, near-dry (i.e., minimum quantity lubrication (MQL)) machining, and nano-enhanced MQL machining are discussed. At the end, two MQL-based machining case studies utilizing vegetable-based cutting fluids have been presented to highlight the importance of advanced green manufacturing.

Keywords Dry machining · Green manufacturing · Machinability
MQL · Nanofluid · Near-dry machining

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1 Introduction

Owing to environmental concerns and growing regulations over contamination and pollution, the demand for renewable and biodegradable cutting fluids is rising. This chapter discusses the conventional cutting fluids, their ecological problems, recently developed green lubrication techniques, and their applications. The chapter then covers the latest development on oil-, aqueous-, and gas-based synthetic and semi-synthetic cutting fluids and their relative advantages and disadvantages toward green manufacturing. The environmental and health issues related to cutting fluids and the latest technologies to minimize the detrimental effects of cutting fluids on human and the environment have been discussed. Subsequently, the chapter introduces the newly developed environmental friendly vegetable-based cutting fluids and their methods of application. Finally, the latest trends toward green manufacturing including dry machining, near-dry (i.e., minimum quantity lubrication (MQL)) machining, and nano-enhanced MQL machining are discussed.

1.1 Introduction to Cutting Fluids

The basic functions of a metal cutting fluid are to provide cooling and lubrication effect between tool and the workpiece. A metalworking fluid may significantly reduce the tool wear, improve machine surface integrity as well as assist in removing the chips from the cutting zone which greatly contributes in sustainable metalworking. Cutting fluids have been utilized in metal cutting operations for the last 200 years. In 1907, Taylor reported by applying large amount of water as a coolant; the cutting speed could be increased up to 40% in machining steel with high-speed steel tool. Despite of its excellent cooling ability, water is considered as a poor lubricant and initiates serious corrosion problems. Therefore, new coolants with good lubricating properties have been commercially developed to improve the surface integrity of the part as well as reduce the cutting force and power required in the machining process [31]. The properties of cutting fluid may require more cooling, lubricating, or both depending on the desired surface finish. The effectiveness of cutting fluid depends on a number of factors such as type of machining operations, cutting parameters, and methods of cutting fluid application.

1.2 Characteristics of Cutting Fluids

Cutting fluid primarily acts as a lubricant and cools the workpiece as well as the cutting tool's edge in a machining process. To fulfill these functions, the chemical composition of cutting fluids should be stable with the changes of pressure, temperature, and time. Using effective coolant, the temperature can be maintained below the thermal softening temperature of the tool material which can significantly prolong the tool life. Moreover, the coolant application can significantly reduce the workpiece distortion that may occur due to high cutting speed and temperature. Besides, cutting fluid can also decrease the diffusion and adhesion types of tool wear.

The capability of cooling strongly depends on the thermal properties of cutting fluids. For instance, fluid with a high-specific heat absorbs a large amount of heat. Besides, a high degree of fluid contact with the tool, chip, and workpiece can be ensured by selecting fluids with low film coefficient with low surface tension [14].

The lubricants in cutting fluids separate the direct contact between rake face and chips, flank face, and machined surface as well as reducing adhesion and abrasion [53]. As a consequence, lubricants reduce friction and heat generation. However, lubricant-type cutting fluids are not suitable in high cutting speed operations. This is because high cutting speed produces high temperatures which cause the lubricant oil to evaporate before lubricating [17]. Hence, they are suitable in low cutting speed machining and difficult-to-machine materials.

Cutting fluids also flush away the chips and metal particles at the workpiece interface to prevent clogging of tool and built-up edge (BUE) occurrence. Flow rate and viscosity of the cutting fluids influence the effectiveness of chip removal. Oil with low viscosity is exceedingly thin at high temperatures and extremely thick at low temperatures (Kuram et al. [27, 28]. Furthermore, cutting fluids in a machining reduce cutting power significantly. Thus, cutting fluid can offer a number of advantages in order to satisfy a wide variety of requirements [53].

1.3 Types and Application of Cutting Fluid

Cutting fluids can be classified into three main categories, namely oil-based, aqueous-based, and gas-based, as shown in Fig. 1. Oil-based cutting fluids are preferable when a good lubricating property is required, whereas aqueous-based cutting fluids are desirable where cooling and lubricating properties are essential. Aqueous-based cutting fluids are further classified into emulsions and solutions form.

1.3.1 Oil-Based Cutting Fluids

Mineral, animal, vegetable, and synthetic oils are used to derive oil-based lubricants. These are also called as neat oils. Petroleum-based mineral oils possess superior lubricating characteristics and therefore more frequently used. The oil-based cutting fluids usually contain additives such as fatty lubricants, extreme pressure additive, odorants, thickness modifiers, and polar additives to enhance their applications.

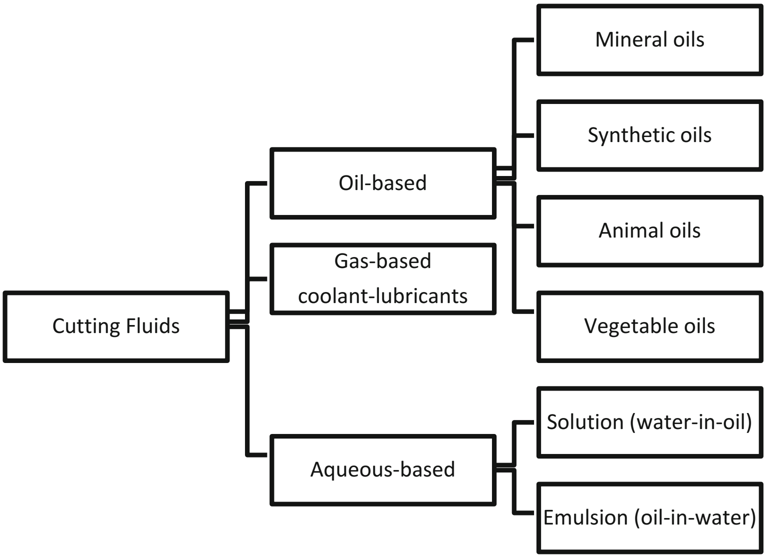

Fig. 1 Classification of cutting fluids

Oil-based lubricants are excellent in lubrication, anti-seizure, and corrosion resistance and have comparatively less tendencies to become rancid. However, due to their poor cooling ability, oil-based lubricants have high flammability. As a result, it produces mist and smoke at higher load and temperature during machining [51]. Hence, oil-based lubricants are used principally for low-speed operations where temperature rise is not significant [27, 28].

Neat oil lubricant with the chemical additives such as sulfur, chlorine, and phosphorous forms a thin solid salt layer on the hot and clean metal surfaces. This extreme pressure film reduces the friction between chip and tool in metal cutting effectively [17]. Chlorinated paraffin is sometimes added in cutting fluids due to their chemical stability, viscosity, flame resistance, low acute toxicity, and the capability to release small amounts of hydrochloric acid at high temperatures [41].

1.3.2 Aqueous-Based Cutting Fluids

The aqueous-based products are mixed with water to the desired concentration prior to use. After mixing water with aqueous-based product, blending oil or mineral oil is blended in water with the addition of an emulsifying agent to form emulsion at a typical ratio of water to oil 30:1. However, the stability of emulsion is the most vital property of soluble oils [27, 28]. In emulsion, the presence of water makes it superior in cooling, while the presence of oil reduces the tendency of water to cause oxidation. The emulsion is desirable in high-speed and low-pressure operations where the temperature rise is significant [43].

1.3.3 Synthetic and Semi-Synthetic Cutting Fluids

Synthetic cutting fluids are good coolants which are made of chemical with additives and diluted in water and free from mineral oil. They have a clear and watery appearance which provides good visibility of the cutting operation. Adding organic and inorganic chemical solutions ensures water softening, corrosion resistance, lubrication, surface tension reduction, and blending in synthetic fluids. However, lack in oiliness of synthetic lubricants limits the lubrication performance compared to other cutting fluids [17]. As a result, synthetic cutting fluids are particularly used for low-force operations where cooling is a primary concern.

Semi-synthetic fluids are chemical emulsion, which contain diluted mineral oil in water with some additives. The additives are used to reduce the size of oil particles which makes it more effective lubricants [24]. Semi-synthetic fluids contain mineral oils of concentration varying from 10 to 50%, which provides better lubrication compared to synthetic oils [15]. Both the synthetic and semi-synthetic fluids are good in cooling property and corrosion resistance. Moreover, they prevent bacteria growth which reduces irritation to the skin and odor [58].

1.4 Ecological Problems of Conventional Cutting Fluids

This section highlights the environmental and health problem like lung cancer, respiratory diseases, dermatological and genetic diseases due to the additives in the cutting fluid. Moreover, waste disposal of mineral oil is costly and affects the environment harmfully. Thus, this section will also discuss on the latest technologies to dispose or minimize the detrimental effects of cutting fluids on human and the environment.

The toxic effects of cutting fluids are major concern for green manufacturing. Report shows that around 80% of all occupational infections of the operators are due to skin contact with cutting fluids [49]. This is because the substances present in the composition of conventional cutting fluids cause serious health effects on the workers and the surrounding environment [9]. The frequent use of cutting fluids over time induces chemical changes of cutting fluids due to the environmental exposures, contamination from metal chips and tramp oil. As a consequence, the effectiveness of the cutting fluids is harmfully affected by the growth of bacteria and yeast. Therefore, the disposal of low-quality degraded cutting fluids become mandatory. However, disposal of waste cutting fluids is expensive and affects the environment adversely [8].

The International Agency for Research on Cancer (IARC) reported that petroleum-based cutting fluids which contain heterocyclic and polyaromatic rings are carcinogenic, and exposure to it may result in occupational skin cancer [1]. Toxic and less biodegradability cutting fluids are responsible for environmental problems and serious health concerns such as cancer, skin, respiratory, and genetic diseases [29]. Moreover, the bacterial growth in the cutting fluids initiates the presence of microbial masses.

Thus, the addition of biocides assists in order to control the bacterial growth in the cutting fluids. However, the cutting fluids containing biocides affect the natural decomposition process during discharge to the environment. Therefore, many countries restrict the disposal of biocides into the sewage systems [51]. Moreover, cutting fluids are vaporized and atomized due to high pressure and temperature in machining operations. It results in the formation of mist, fumes, smoke, and odors in cutting fluid. When chemical additives, namely sulfur, chlorine, phosphorus, hydrocarbons, and biocides, are added with these contaminated cutting fluids can cause skin reactions and respiratory problems [24].

Petroleum-based cutting fluids are widely utilized in metal cutting. However, they cause significant environmental pollutions throughout their life cycle. Nearly 38 million metric tons of lubricants were used in 2005 with an estimated increase of 1.2% over the next 10 years was reported by Shokrani et al. [51]. According to the report, the estimated cutting fluid cost is 16% which includes the purchasing, preparation, maintenance, and the disposal costs. In contrast, cost related to cutting tools is only 2–4% of the total manufacturing cost. The report also mentioned that the cost related to disposal of cutting fluids could be two to four times compared to the purchasing cost. This higher cost is unavoidable due to the fact that the cutting fluids are not biodegradable and require expensive treatment prior to disposal. Mineral-based cutting fluids are hazardous for storage and even for disposal. Therefore, special physical or chemical treatment is required in order to remove the toxic components inside the cutting fluid before disposal as recommended by an Environmental Protection Agency (EPA) [23].

Disposal of cutting fluids containing chlorinate is only allowed to be burned in special incineration sites since the toxic dioxins can lead to uncontrolled burning. Therefore, it is classified as hazardous waste to human life as well as to the environment [25]. Cutting fluids containing chlorinate is classified as hazardous waste to human life as well as to the environment and require special incineration sites in order to avoid uncontrolled burning [25]. Chlorine additives in cutting fluid can cause corrosion on the machined surface, for instance, when machining titanium alloys [51].

Aqueous-based emulsions have no fire hazard and lower rate of oil misting which is an advantage to use it as a coolant. This coolant offers reduced cost since it can be diluted with water. However, the presence of bacteria, yeasts, and fungi in high amount of water causes separation in the emulsions which is a disadvantage. Corrosion, poor lubricating properties, and aesthetically unpleasant results are resulted due to the uncontrolled growth of such microbial in the aqueous emulsion [53].

1.5 Newly Developed Environmental Friendly Cutting Fluids

The public awareness on “go green, think green, and act green” toward green manufacturing issues has been gradually becoming a philosophy. Numerous literature show that vegetable-based cutting fluids perform better and they are biodegradable. In this topic, vegetable-based, gas-based, chemical additives to the lubricant and their method of applications including internal tool cooling, manual, high-pressure cooling, mist cooling, and wet cooling techniques are discussed.

Good-quality cutting fluids should have excellent lubricating and cooling properties and safely disposable after treatment [43]. Bio-based cutting fluids are generally renewable and highly biodegradable and possess less adverse effect on health. Therefore, they are extremely attractive to replace petroleum-based cutting fluids.

In the early 90s, biodegradable lubrication became one of the hot research topics due to its environmental impact. According to the New York Transparency Market Research report, the demand for bio-based lubricants was 505.6 kilotons in 2011, which is expected to increase to 785.0 kilotons in 2018 whereas the demand of synthetic lubricants was 35.10 million tons in 2011 and is predicted to reach 41.52 million tons in 2018. This clearly indicates that the synthetic lubricants are gradually replaced by biodegradable lubricants. Biodegradable cutting fluids with less environmental contamination provide satisfactory economic conditions with high reliability. The disposal of bio-based cutting fluid contributes less mist in the air and minimizes occupational health risks [27].

The current research addresses several aspects of an environmentally adapted cutting fluid in terms of biodegradability, toxicity, and renewability. The research also focuses on the composition, selection, application techniques, quantity optimization, and recycling of the vegetable-based cutting fluids for green machining. A recent development of biodegradable cutting fluids including vegetable-based cutting fluids, gas-based coolant lubricants, and chemical additive-enhanced cutting fluids and their application techniques are briefly introduced in the subsequent topics [9].

1.5.1 Vegetable-Based Cutting Fluids

Growing demand for biodegradable cutting fluids has motivated toward the development of vegetable oils as an alternative to mineral-based cutting fluids [22]. Numerous literature show that vegetable-based cutting fluids offer better performances and they are more readily biodegradable. Vegetable oils provide high-strength lubricant film by strong interaction with the metallic surfaces as well as reduce friction and wear. This is because molecular films are oriented due to the polarities of fatty acid which produces oiliness and thus imparts anti-wear properties. Moreover, fatty acid in vegetable oils provides stable viscosity coefficient due to the strong intermolecular interaction [31, 49]. Besides, vegetable oils reduce smoke formation and fire hazard since it has higher flash point than mineral-based cutting fluids [27, 28]. The flash point is the lowest temperature of the cutting fluid to form an ignitable mixture in air near the surface of the cutting fluid. The lower the flash point, the easier the material to catch fire [23]. Therefore, cutting fluids with higher flash point can withstand high temperature during machining. However, oxidative stability, high freezing points, low thermal stability, and poor corrosion protection are the drawbacks of vegetable oil-based cutting fluids [49].

Kuram et al. [27, 28] studied the influence of various vegetable-based cutting fluids on specific energy, tool life, and surface roughness for end milling. The authors reported that the overall machining performance is improved using vegetable-based cutting fluids. The experimental data analyzed by Julie et al. [23] revealed that soybean-based cutting fluid achieved better tool wear performance compared to petroleum-based cutting fluids. The study conducted by Kuram et al. [27] showed that vegetable-based cutting fluids (sunflower) required the least thrust force compared with the commercial cutting fluids during drilling of AISI 304 austenitic stainless steel with high-speed steel tool. Belluco and Chiffre [6] experimented on five vegetable-based cutting fluids at different levels of additives in comparison with commercial mineral-based oil. The outcome revealed that all vegetable-based oils produced better results than mineral oil in terms of tool life and thrust force.

Xavior and Adithan [59] reported that coconut oil had improved the surface finish as well as reduced the tool wear compared to mineral oils on machining of AISI 304 material with a carbide tool. Vamsi Krishna et al. [57] applied nanoboric acid particle suspensions in SAE-40 oil and coconut oil during turning of AISI 1040 steel using cemented carbide tool inserts. The result indicated better performance for coconut oil-based nanoparticle suspensions compared to synthetic-based (SAE-40) lubricant due to the better lubricating properties of the base oil. Thus, vegetable-based cutting fluids have potential to replace mineral-based cutting fluids due to better machining performance and less environmental impact.

1.5.2 Gas-Based Coolant Lubricants

Gas-based coolant lubricants are air, nitrogen, argon, helium, or carbon dioxide which are generally in gaseous form at room temperature. However, they also can be cooled–pressured fluids in certain machining applications. Since the gas-based coolant lubricants are inert in nature, they are highly corrosion resistant especially at high cutting temperatures. Their hybridization with conventional cutting fluids in the form of mist or droplets ensures better lubrication. Different approaches have been used to enhance the cooling capacity of these gas-based coolant lubricants such as compressing, cooling, and liquefying. For high cutting parameters, compressed gas-based coolant lubricants are preferable since conventional cooling techniques are unable to penetrate the chip–tool interface. Moreover, the tool life is enhanced by applying chilled air as a coolant in machining. This is because chilled air can absorb large heat at the cutting zone and prevents chemical reaction between the tool and the workpiece materials [51].

1.5.3 Chemical Additive-Enhanced Cutting Fluids

Sometimes, cutting fluids are formulated with different additive agents to obtain better properties. Agents are added into the base fluid in order to alter both physical and chemical properties so that the cutting fluids can be adapted to a large variety of applications. The elements added to cutting fluids are anti-wear additives, anti-corrosion agents, foam-retarding substances, mist impede materials, dispersing materials, high-pressure additives, surface-active materials, emulsifying agents, biocides, fragrant additives, and coloring agents [53]. The purpose of chemical additive in composition of cutting fluids is to improve the functions, for instance regulating the pH value, improving flash point, functioning as an emulsifier, binding, anti-foaming, extreme pressure, corrosion resistance, odorless, spreading, and wetting [7].

Chemical additives such as sulfur, chlorine, and phosphorous reduce the friction between chip and tool in metal cutting effectively due to the formation of thin solid salt layers on the hot and clean metal surfaces [17]. Nevertheless, the usage of cutting fluids containing chloroparaffins as extreme pressure additives is no longer legal. This is because in extreme pressure cutting fluids, chlorinated paraffin changes to dioxin which can cause chlorine acne.

Cetin et al. [7] evaluated vegetable-based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L. The results revealed that vegetable-based cutting fluids with extreme pressure additive have effectively improved the performances in reducing the surface roughness, and cutting forces with respect to commercial mineral and semi-synthetic cutting fluids. Kuram et al. [29] carried out experiments on vegetable-based cutting fluids with extreme pressure during turning of AISI 304L. 8 and 12% concentration of sulfur-based extreme pressure additives were added to both sunflower-based and canola-based cutting fluids for performance comparison in terms of surface roughness, tool wear, and feed forces. Besides, John et al. [22] explored that ethoxylates of fatty acid esters is a good surface-active agent for oil in water emulsions. Surface-active additives in the form of phosphorous or sulfur compounds are normally added into synthetic ester oil to further improve their lubrication properties [25].

1.5.4 Nanoparticle-Enhanced Cutting Fluids

Nanofluids are the fluid where nanometer-sized particles, fibers, wires, rods, and sheets are dispersed in the base fluid. Nanolubricant is a novel engineering material dispersed in base oil which could be an effective method to reduce friction and enhance cooling capabilities significantly during machining. Nanoparticles have significantly large surface area compared to its density. Thus, when nanoparticles are well dispersed in cutting fluid, it will allow the particles to interact with the contact surface of cutting zone more effectively to provide better lubricating effect as well as a good media for improved thermal conductivity. Nanofluids are generally prepared using a two-step method in industry. First, nanoparticles are procured as dry powder. Then the nanosized powders are dispersed into the base fluid by using ultrasonic agitator or magnetic force or high shear mixing.

2 Cooling and Lubricating Techniques

A good cooling technique can effectively control the heat generation in machining which may lead to an efficient and economic machining. Several techniques have been proposed in recent time to control the temperature in the cutting zone in order to improve machinability including coolant with high pressure (HPC), internal tool cooling, minimum quantity lubrication (MQL), and cryogenic cooling shown in Fig. 2 [47].

2.1 Conventional Methods

The most popular conventional method of applying cutting fluids in machining operation is flood cooling. The other cooling techniques include internal tool

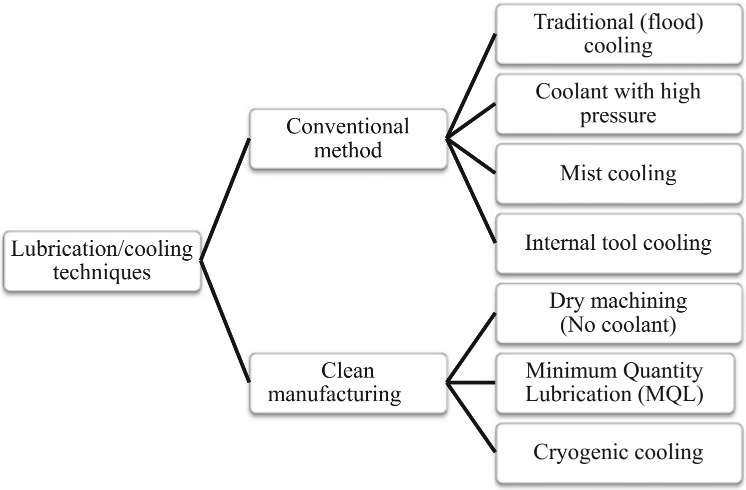

Fig. 2 Methods to apply cutting fluids in machining operations

cooling, coolant with high pressure, mist cooling, and internal tool cooling. All the conventional cooling techniques are briefly introduced in this section.

2.1.1 Traditional (Flood/Wet) Cooling Technique

Flooding or wet cooling is the most common technique in machining process that is generally used with coolant-type cutting fluids. In this process, a steady stream of fluid is supplied at the cutting zone for machining operation. Flow rate can be in the range of 10–225 L/min depending upon the number of cutting point tools [24]. For better cooling performance, flood cutting fluid with high pressure can be directly applied into the cutting zone. However, flood coolant technique may have adverse effect on the human health and the environment.

2.1.2 High-Pressure Cooling Technique

The high-pressure system is applied where heat generation is significant due to the increase of speed and power. In this process, the high-pressure coolant can remove large amount of heat quickly from the cutting zone. Specially designed nozzles are utilized to deliver cutting fluids on the clearance or relief face of the tool with a pressure in the range of 5.5–35 MPa and speed in the range of 350–500 km/h. This high fluid pressure allows better penetration of the coolant into the cutting zone that will increase production efficiency. This application improves the tool wear and provides better cooling effect. Moreover, the coolant pressure forces the chip away from the tool rake face [47]. Research shows high-pressure cooling performs better in terms of tool wear compared to dry cutting and wet cutting for machining austenitic stainless steel [37].

2.1.3 Mist Cooling Technique

Mist cooling technique is mostly applied for water-based cutting fluids. In this process, the cutting fluids are applied by the pressurized air stream at a high-speed mist. Effective cooling is achieved due to the evaporation of the fluid droplets suspended in the air [46]. In this process, fluids are able to enter in the unreachable areas of the cutting zone and also provide better visibility compared to flooding [17, 24]. The pressure level can be within the range of 70–600 kPa to apply water-based fluid. However, venting is required for the operator from directly inhaling of air-borne fluid particles since toxic mist or vapor may cause irritation and serious respiratory problems [55]. Research shows cold water mist jet cooling technique performs better in terms of cooling effect and the tool life compared to cool air jet and flood cooling methods for machining hard materials [4].

2.1.4 Internal Tool Cooling

Internal tool cooling or coolant-fed tooling is one of the methods of cutting fluid application. In some of the drills and tools itself, there are holes provided so that pressurized fluid can be pumped through the body of the tools and access to the cutting edge. Moreover, some of the inserts also have holes through or built directly into the tool holders to distribute the coolant to the underside of the chip [46]. Another method is manual application by using a squirt can or paint brush. This method is used in operations where the cutting speeds are low and vulnerable to friction such as tapping [17].

2.2 Advanced Green Manufacturing

The widespread use of oil-based cutting fluids causes significant environmental pollution throughout their life cycle. Statistics show that the purchasing, preparation, maintenance, and the disposal costs related to the cutting fluids contribute significantly in the total manufacturing cost. Moreover, the new legislation on environmental and health protection, which is expected to become even more stringent in the future, has led to intensive scientific research toward a green manufacturing [56]. Therefore, the focus on cutting fluids has shifted toward green manufacturing, namely dry machining, minimum quantity lubrication (MQL), nanofluid in MQL, and cryogenic machining.

2.2.1 Dry Machining

Dry machining, meaning no cutting fluids applied in the machining process. This method is applied to avoid the problems of cutting fluid such as contamination, disposal, and hazardous components in cutting fluid. Dry machining does not provoke the pollution of air or water resources. As a result, disposal cost of cutting fluids will be reduced. Dry machining is applicable for most of the cutting operations including turning, milling, and gear cutting on steels, steel alloys, and cast irons.

Sreejith [54] investigated the cutting parameters for machining relatively soft aluminum alloy 6061 at various cutting environments, namely dry machining, machining with minimal cutting fluid, and machining immersed in cutting fluid. The research work concluded that at high cutting speed, it is possible to achieve good machinability even operating in dry machining conditions. Diniz and Micaroni [12] carried out several finish turning experiments with variable cutting speed, feed and tool nose radius, with and without the use of cutting fluid. The objective of the research was to figure out the best condition for the use of dry cutting. They concluded that feed and tool nose radius have to be increased and the cutting speed to be decreased to achieve dry cutting method without damaging the tool life while improving the surface roughness and power consumption. Although the use of cutting fluids in wet cooling may improve the tool life, dry cutting showed less power consumption and better surface finish.

A study was conducted by [61], on the tool life and cutting force parameters on Inconel 718 with the effort to reduce or completely remove cutting fluids for environmental friendly cutting. The results indicated that due to the cooling air supply to the cutting zone, it is not always possible to utilize dry cutting. Therefore, it suggested using at some minimum quantity lubricants or cutting fluids during machining difficult-to-machine materials. In other words, dry machining leads to problems such as overheating the tool. The presence of high friction between the tool and workpiece in dry cutting condition significantly increases the temperature resulting in higher level of abrasion, diffusion, and oxidation. The workpiece also experiences a large amount of heat and consequently hinders the achievement of tight tolerances and metallurgical damage to its superficial layer [12].

Techniques employed by researchers to compensate the effects of the elimination or minimizing of cutting fluids in machining could be achieved by improving cutting tool properties with coating and developing new tool features and geometries. The advanced tool materials with lower friction coefficient, high hardness, good oxidation resistance, and high heat resistance can greatly help to make the application of dry machining more practicable. This has led to the introduction of advanced tool materials such as cubic boron nitride (CBN), polycrystalline cubic boron nitride (PCBN), polycrystalline diamond (PCD), cermets, and ceramic tools.

In this regard, tool coating is considered as a technique to apply the characteristics of several materials on the surfaces of the cutting tools. These nanostructured materials may enhance the characteristics of the cutting tool by providing different properties such as higher hardness, higher strength, higher Young's modulus, higher wear resistance, higher fracture toughness, higher chemical stability, and reduced frictional behavior [30]. Generally, coated tools perform better than uncoated tools in dry machining through the three mechanisms of (i) increasing the tool hardness; (ii) preventing the tool material to be exposed; and (iii) reducing the friction coefficient. For instance, aluminum oxide coating provides stability at high temperature and it works as a thermal insulator. Titanic carbide provides abrasive resistance, and titanium Nitride prevents built-up edge. A list of common coating materials with general purpose in machining is provided in Table 1.

However, choosing the right coating for the intended application is a challenging task. Each selection of coating has relative impact on machining and tool life. There is a wide selection of coatings that are available from manufacturers, namely Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and alternate surface treatments. One of the best ways to determine effective coating is through trial and error. It is always good to check with the coating manufacturers for newly developed coatings which can perform better against heat, friction, and abrasion.

Kustas et al. [30] compared the effect of multi-layer solid lubricant (MoS_2/Mo)-coated high-speed steel (HSS) drill tools with an uncoated drill in machining Ti64 workpiece material. It was found that the uncoated drill was tangled into the

Table 1 Coating materials and their general purpose in machining process

Coating materials	General purpose
Titanium nitride (TiN)	Prevents built-up edge
Aluminum oxide	Provides stability at high temperature; works as an thermal insulator
Titanic carbide	Abrasive resistance
Titanium carbo-nitride (TiCN)	Adds more hardness and better surface lubricity
Titanium aluminum nitride (TiAlN or AlTiN)	Better tool and better life in high-heat applications
Chromium nitride (CrN)	Provides the anti-seizure (prevent BUE)
Diamond	Ideal for cutting graphite, metal matrix composites (MMC), high silicon aluminum, and many other abrasive materials

workpiece due to the increase in torque during machining operation. Meanwhile, cutting torque reduced by 33% using coated drill without any evidence of fracture. Nabhani [35] studied CVD TiN/TiCN/TiC triple-coated carbide tools in dry turning of Ti48 titanium alloy. In this coating combination, chemical reaction occurs between carbon substrates of the tool material and titanium and forms a TiC layer. This TiC layer protects the cutting tool from abrasion and reduces the diffusion rate which increases the tool life. Thus, the formation of a protective layer due to the chemical reactions between tool and workpiece materials may increase the tool life.

2.2.2 Near-Dry Machining

From the previous discussion, it is established that dry machining can be a sustainable option since it offers least concerns regarding environmentally impact and machining cost. Nevertheless, dry machining is not a great option when machining difficult-to-machining materials due to significant increase of temperature at the cutting zone deteriorating the machining performance.

A viable alternative proposed by the researchers to overcome the shortcomings of dry machining is near-dry machining or micro-lubricant machining. Minimum quantity lubricant (MQL) is more popularly used among the researchers to represent near-dry machining. In near-dry machining, a very small amount of cutting fluid (in terms of mm/h) is mixed with dry compressed air to form an aerosol and transmitted to the cutting zone through nozzle. Researchers suggest that near-dry machining can be a viable compromise between dry cutting and flood cooling in terms of good machinability ensuring good surface finish, tool life, and environmental friendliness [16, 32].

Minimum Quantity Lubrication (MQL)

Minimum quantity lubricant (MQL) is considered as an environmentally friendly and economically beneficial method for machining operations where dry machining is not possible especially when machining high-strength materials with good surface quality are of interest. MQL technique is more preferable over dry machining for processing high-speed machining alloys, namely nickel- and titanium-based alloys. MQL machining has been recognized as one of the cleaner manufacturing methods that comply with the ISO 14000 standard [61].

MQL fluids are classified into two major categories, namely synthetic esters and fatty alcohol. Synthetic ester which is usually vegetable oil is more popular due to their good lubrication properties in terms of corrosion prevention, high flash and boiling points. However, fatty alcohol due to their high-specific heat consumption offers better heat removal compared to synthetic esters. Therefore, fatty alcohol is utilized as MQL when heat removal is the main purpose, and synthetic esters are applied when lubrication is the key requirement [33].

The principal of MQL is that it applies a fine mist of air–fluid mixture containing only a few amount of cutting fluid to the cutting zone through the spindle of the machine tool. The diameter of nozzle used in MQL application is around 1 mm, and the pressure applied is around 500 kPa with flow rate in the range from 0.25 l/h to 2 l/h, which is substantially low compared to the flood cooling [56].

Generally, in all MQL systems, the coolant and pressured air are mixed together and a controlled flow of the mixture is delivered through the tubes and nozzles into the cutting point. It is known as cooling through-the-tool where the nozzle could be external or internal. MQL machinery available in the market consists of mainly five parts, namely air compressor, CL container, tubings, flow control system, and spray nozzles. Figure 3 shows the schematic view of MQL delivery system [18, 33]. Generally, biodegradable cutting fluids are used in MQL that can remain stable to be used for longer period [13]. Vegetable oils, synthetic esters, and fatty acids which possess excellent lubrication at high pressure are preferably used in MQL at small quantities [47].

Banerjee and Sharma [5] concluded that MQL technique is a better option than wet machining at higher speeds and feed rates. Moreover, the friction at the tool–workpiece interface will be reduced significantly in MQL. MQL plays an important role in improving the dimensional accuracy of a finished job in straight turning due to the removal of large heat [26]. Using MQL, Hassanpour et al. [21] found that increasing cutting speed has a significant influence in the reduction of surface defects while studying hard milling of AISI 4340. Shokoohi et al. [50] developed a combined cooling method (CCM) where pre-cooling workpiece is integrated with MQL method which resulted in substantial improvement in terms of machining parameters as well as health and environmental problems. Rabiei et al. [40] concluded that MQL technique produced better surface quality as compared to wet grinding when machining hard steels. In conclusion, MQL technique reduces the consumption of cutting fluid and improves overall performances in terms of surface quality and tool life as well as cost saving and contribute toward cleaner production.

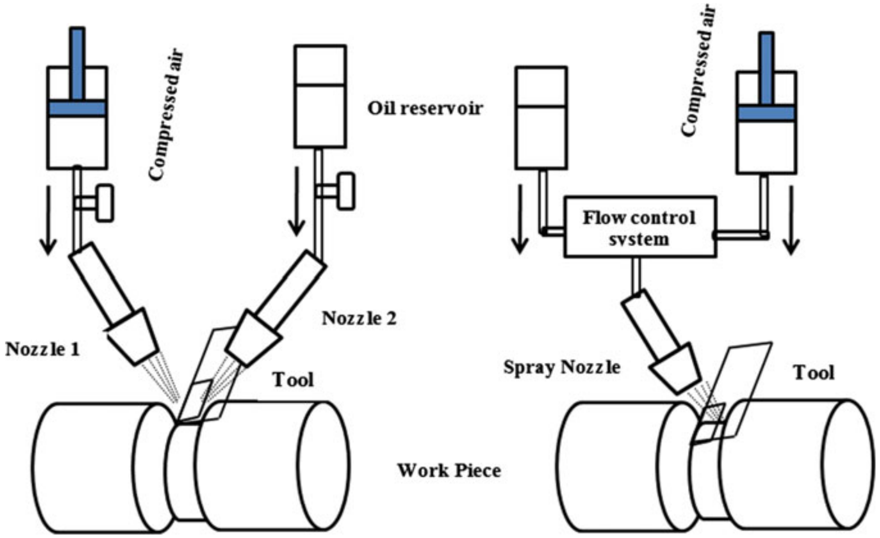

Fig. 3 Schematic of MQL delivery system

Nanofluid Additives in Green Manufacturing

MQL system uses very little quantity of fluid or lubricant. Therefore, the fluid should have much better properties compared to the fluids in flood cooling. Application of nanoparticle in MQL technique can significantly enhance the properties of the fluid for effective cooling and lubrication. Solid particles can improve the thermal conductivity and lubricating characteristics of the MQL and the nanoparticle due to the higher surface area can significantly enhance thermal conductivity of the MQL. However, the nanoparticles should be well dispersed in the base fluid in order to provide efficient lubrication. Both metallic and non-metallic nanoparticles can be used to formulate nanofluids. In practice, lubricants, namely graphite, boric acid, and MoS_2, are applied in machining. Applications of silver, SiO_2, and Al_2O_3 are also reported in literature [2, 3, 42].

Researchers have reported a noticeable reduction in friction and an increment in load bearing capacity of friction parts by adding nanoparticles into conventional fluid. Sharma et al. [48] found that nanofluid exhibited better tribological and thermophysical properties relative to its base fluid and reduced the cutting forces, surface roughness, cutting zone temperature and tool wear. Nanofluid enhances anti-wear and friction reduction including ball bearing effect, formation of tribo-film, mending effect, and polishing effect. According to Peng et al. [39], different mechanisms were explored as follows:

- The nanosized spherical particles are more likely to roll between two surfaces and flip the sliding friction into a combination of rolling and sliding frictions;

- The nanosized particles have a tendency to interact with friction pairs to develop a surface protective film;
- The nanosized particles are deposited on the contact surface to form a physical tribo-film that compensates for the loss of mass, which is known as “mending effect”;
- Compressive stress concentrations due to high contact pressure can be decreased by a number of nanoparticles which uniformly bear the compressive force.

Recent research works related to the application of various nanoparticles in machining operation are briefly discussed in this paragraph. Nanographite was utilized in MQL for turning by Amrita et al. [2, 3], and the result shows that machinability improved significantly in terms of the cutting forces, tool wear, cutting temperature, and surface roughness. Saravanakumar et al. [44] used silver nanoparticles dispersed in MQL and reported significant improvement in terms of cutting forces and surface roughness. Sayuti et al. [45] achieved best surface quality with proper nanofluid concentration and air pressure with SiO_2 nanofluid in MQL while turning of hardened steel AISI 4140. Water-based TiO_2 nanofluid were investigated by Najiha et al. [36] in end milling of aluminum alloy and recorded a major improvement in terms of edge integrity, namely edge chipping and edge fracture. Hadi and Atefi [20] studied the effect of MQL with gamma-Al_2O_3 nanoparticles in end milling processes by dispersing gamma-Al_2O_3 nanoparticle to vegetable oil with small volume fraction and reported significant improvement of surface roughness for AISI D3 steel work material compared to pure MQL. Ooi et al. [38] investigated the nanosuspended lubrication using SiO_2 nanoparticles in cutting oil facilitated by high-pressure stream air in machining of tempered aluminum. The authors reported significant improvement in surface roughness and reduction in cutting force and cutting temperature. Zhang et al. [60] concluded that palm oil-based nanofluids with the addition of molybdenum disulfide (MoS_2) nanoparticles in the form of nanoparticle jet in MQL yield the best lubricating property because of the high-saturated fatty acid and high film-forming property of carboxyl groups in palm oil.

In conclusion, utilization of nanoparticles as coolant and lubricant leads to lower tool temperature, tool wear, higher surface quality, and less environmental dangers. However, nanoparticles are very expensive and its application requires special devices which is the main barrier for wide range of applications of nanofluids in machining. Agglomeration and sedimentation are kind of other drawbacks in nanoparticle application. Moreover, the nanoparticle is not suitable to use in wet machining due to its expansive nature. Therefore, its application with MQL technique makes it as a sustainable alternative to the wet machining.

2.2.3 Comparative Study Between Dry Machining and MQL

Based on the previous study, it was established that both the dry machining and MQL can greatly contribute toward cleaner production. However, it is important to know which method to be applied for effective machining. Thus, a comparative study between dry machining and MQL may help in selecting the suitable method based on the cutting environments, namely cutting tool material, workpiece, and cutting conditions. Generally, MQL can offer a considerable reduction of cutting forces and improved surface roughness compared to dry cutting.

The following remarks can be useful in comparison with dry machining with MQL:

- When minimum quantity of lubricant approaches to zero, it is called dry machining.
- Dry machining is a better option compared to MQL when environmental and economic factors are considered.
- In dry machining, temperature of the cutting tool is very high which induces excessive tool wear resulting in shorter tool life and poor machinability.
- The chips generated in dry machining are tangled around the cutting zones which adversely affect the machined surface.
- In MQL machining, the cutting fluid is eventually disposed to the environment which contaminates water, soil, and environment.
- Cutting fluid in MQL has adverse effect on human health.
- Optimization between dry machining and MQL in order to remove cutting fluid is a pressing research topic to tap the maximum benefits of the both sustainable techniques.

The results show that it is possible to use very small amount of cutting fluid or even dry machining condition with high cutting speed for aluminum alloy 6061 [54]. Dhar et al. [11] carried out experiments to compare the effectiveness of MQL in plain turning of AISI 1040 steel with uncoated carbide insert compared to dry and wet machining. The experiments were carried out at different speed–feed combinations with respect to cutting temperature, chip reduction coefficient, and dimensional deviation. The authors observed that the performance of MQL machining is better than that of wet machining. MQL enabled a substantial reduction in cutting temperature improving the dimensional accuracy. MQL enhanced the chip–tool interaction while maintaining the sharpness of the cutting edges because MQL tends to reduce wear and damage on the tool tip. Thepsonthi et al. [55] explored the application of MQL in pulsed-jet form in the high-speed milling of hardened steel using coated carbide ball end mill. Performances of pulsed-jet application were found superior in terms of cutting forces, surface finish, tool life, and tool wear compared to dry cutting when machining in high cutting speed. Silva et al. [52] scrutinized the behavior of the MQL application in grinding of hardened AISI 4340 steel and concluded that MQL can be applied efficiently with better cutting performance compared with conventional cooling method.

Zhang et al. [61] examined the tool life and cutting force in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions. The experimental result revealed that MQL with biodegradable vegetable oil substantially improves the machinability of Inconel 718 in terms of the tool life and cutting forces. Hadad and Sadeghi [19] studied machining of AISI 4140 alloy steel and found that MQL produced the best surface quality for a selected range of depth of cut compared to dry and wet turning. They also concluded that MQL technique develops minimum cutting force to perform turning operation compared to dry turning and wet turning. Lohar and Nanavaty [34] concluded a 40% reduction of cutting force, 36% reduction of cutting temperature and 30% improvement of surface finish when applying MQL compared to dry turning for machining alloy steel AISI 4340.

3 Case Studies on Machinability Using Different Coolant Conditions

Two case studies have been conducted to highlight the importance of advanced green manufacturing. In case 1, different flow rates of vegetable-based cutting fluid were studied on machinability of turning process. In case 2, dry cutting condition was compared with two different vegetable-based cutting fluid conditions.

Case Study 1

In this research work, the effect of flow rate and speed of cutting fluid applied on the surface roughness of workpiece and tool wear in turning was studied. For the experiments, mild steel bars are considered as the workpiece and chemical vapor deposition (CVD)-coated carbide insert used as the tool. A vegetable-based water-miscible metalworking cutting fluid, namely Yushiroken MIC 2500, was applied in this case study. Four cutting parameters, including cutting velocity, feed rate, depth of cut and flow rate of cutting fluids, were considered. Taguchi method has been applied in order to find the optimal cutting conditions for surface finish and tool life. Three types of cutting fluid conditions were considered, namely low flow rate low velocity (LFLV), low flow rate high velocity (LFHV), and high flow rate low velocity (HFLV).

The ranges of cutting velocity, feed, and depth of cut are considered (Table 2) based on tool manufacturer's recommendation.

Taguchi experimental design was used to run the nine combinations of experiments. Since the smaller the surface roughness and tool wear values are desired in this experiment, thus the signal-to-noise ratio chosen is smaller is the better

Table 2 Selection of levels for each parameter [10]

Parameter	Level for each parameter		
	Level 1	Level 2	Level 3
Cutting speed, V_c (m/min)	100	140	180
Feed rate, F_r (mm/rev)	0.05	0.06	0.07
Depth of cut, Doc (mm)	0.5	1.0	1.5
Cutting fluid condition, Q	LFLV	HFLV	LFHV

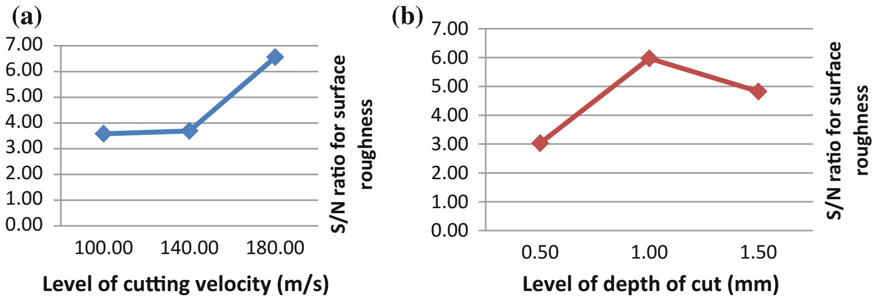

Fig. 4 Influence of **a** cutting velocity and **b** depth of cut on surface roughness [10]

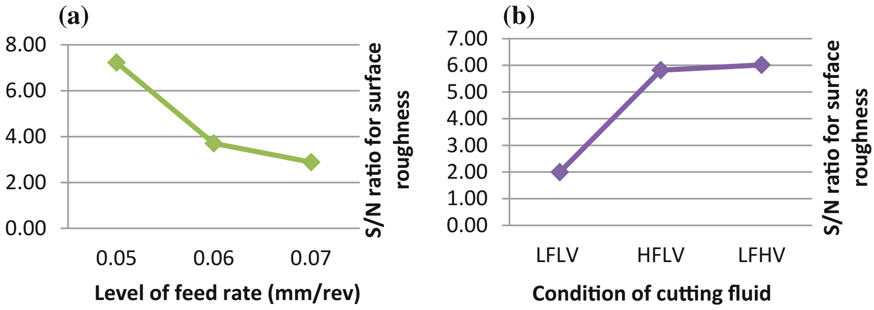

Fig. 5 Influence of **a** feed rate and **b** cutting fluid conditions on surface roughness [10]

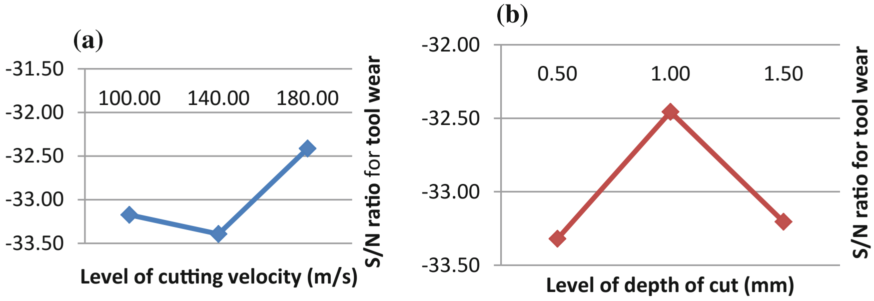

Fig. 6 Influence of **a** cutting velocity and **b** depth of cut on tool wear [10]

(minimize): $S/N = -10\log(1/n\sum_{i=1}^{n} y_i^2)$, where n is the number of experiment and y_i is the measured value. The average S/N ratio is plotted against test level for each control parameter (Figs. 4, 5, 6, and 7).

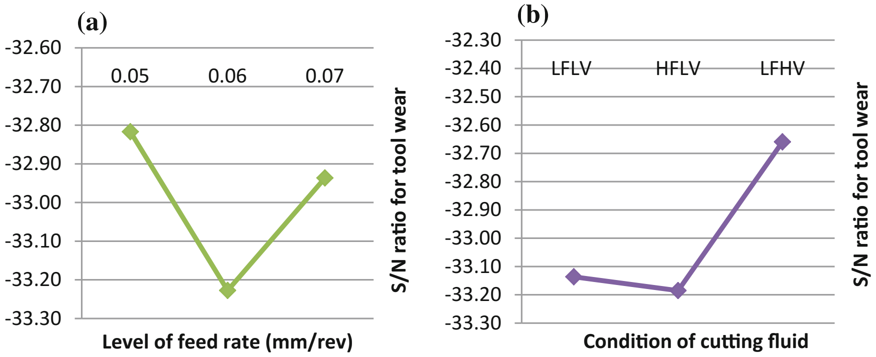

Fig. 7 Influence of **a** feed rate and **b** cutting fluid on tool wear [10]

The following conclusions have been drawn from this case study:

- Feed rate is the most significant factor (34.33%) in determining the surface roughness while cutting speed is the main contribution (43.12%) in determining the tool wear. Cutting fluid's condition contribution is 33.12% for surface roughness and 13.77% for tool wear.
- The optimal parameters for both surface roughness and tool wear obtained were at high cutting speed, medium depth of cut, low feed rate, and LFHV cutting fluid applied. High cutting speed was selected to avoid the formation of BUE. Low feed rate was desired to minimize the temperature rise at the tool–chip interface.
- Among the three conditions (LFLV, HFLV, and LFHV) of cutting fluid applied, LFHV was the most effective in reducing the surface roughness as well as tool wear. This was because LFHV can provide better penetration to the interface and hence minimizing the friction as well as reducing the temperature generated at cutting zone.

Case Study 2

The objective of this experiment was to evaluate the resulting surface roughness and cutting forces using palm oil-based cutting fluids. The influence of crude palm oil and refined palm oil (Super Olein cutting fluid) was compared with dry machining. Taguchi L4 array consists of nine experiments conducted for each cutting type of fluid.

Analysis of variance (ANOVA) was utilized, and the contour plots of surface roughness were developed against the depth of cut and cutting speed for dry machining (Fig. 8) and coolant machining (Fig. 9). The contour plots of surface roughness and cutting force against depth of cut and feed rate for Super Olein machining are given in Figs. 10 and 11, respectively. From Figs. 8 and 9, it can be concluded that lower surface roughness (<1.5 µm) can be obtained at the lower depth of cut using coolant machining.

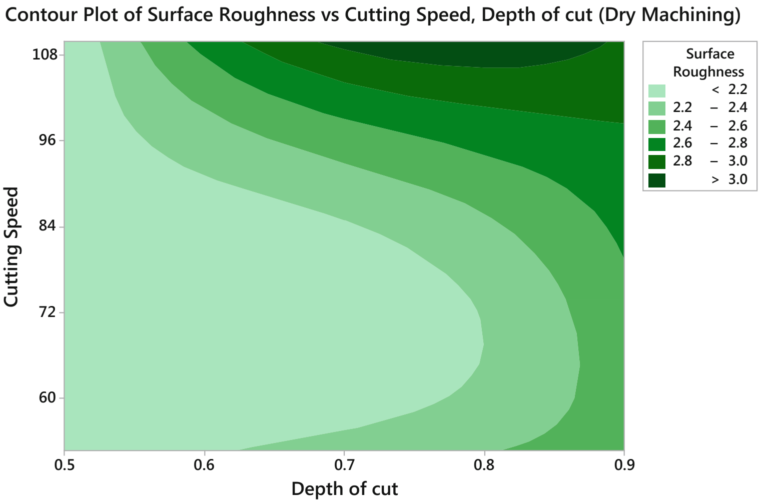

Fig. 8 Contour plot of surface roughness for dry machining

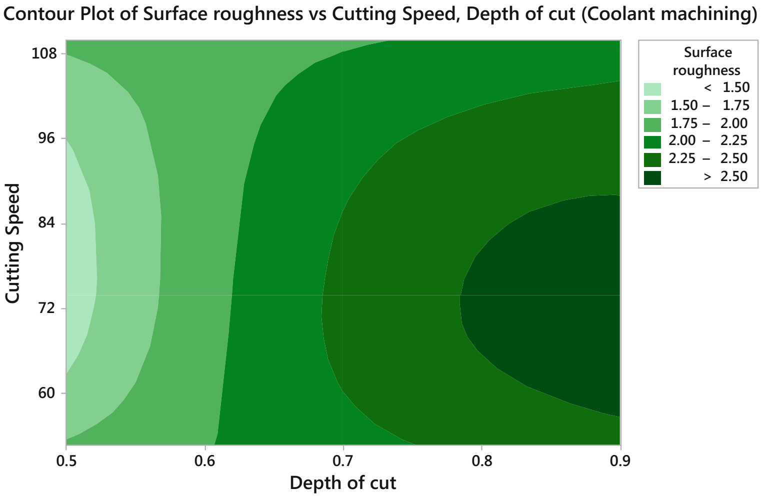

Fig. 9 Contour plot of surface roughness for coolant machining

In the case of Super Olein machining, it is possible to achieve lower surface roughness even at high depth of cut by choosing appropriate feed rate values. The cutting force can be reduced even at higher feed rate by considering low depth of cut.

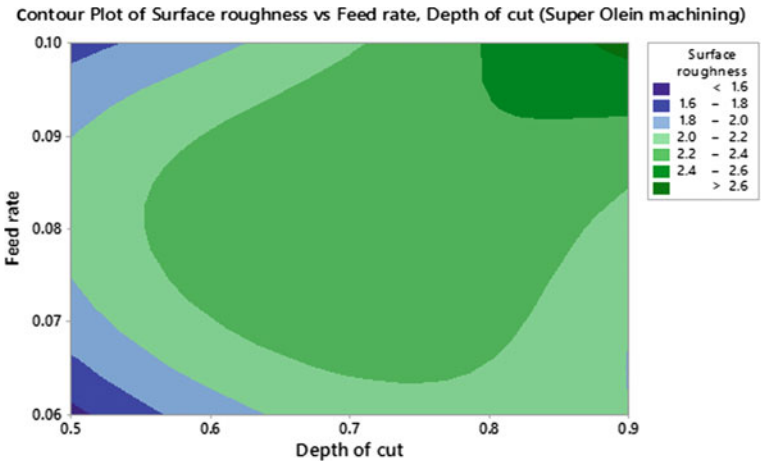

Fig. 10 Contour plot of surface roughness for Super Olein machining

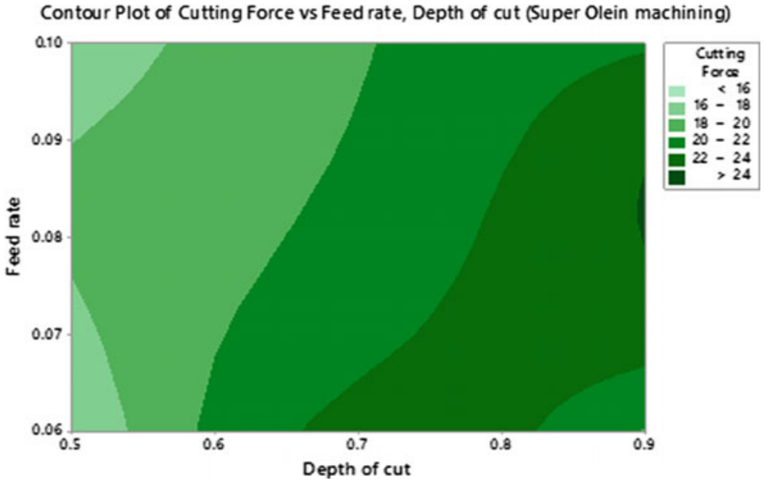

Fig. 11 Contour plot of cutting force for Super Olein machining

4 Summary

A detailed discussion on conventional and green lubricants and lubrication techniques has been done in this chapter. Literature review and case study reveal the superiority of green lubricants and lubrication techniques over conventional fluid and cooling method. It is seen that latest development in green/sustainable lubrications such as nanoparticle-enriched MQL is playing vital role in cost saving, productivity improvement, and sustainability. However, the shortcomings as regard to these have been considered and are being researched to improve the performance and minimize environmental footprints. The current trend of research is likely to focus on optimization of the green lubrication processes to enhance machinability. It is hoped that the chapter would facilitate the readers and further encourage the research and development attempts in order to establish the field further.

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Cryogenic Machining

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Abstract In the present industrial scenario, manufacturing has become the backbone for the growth of any country. The advancement in manufacturing technology and methodology adopted has led to industrial growth, but it has some adverse effects on environment as well on human being such as environmental pollution and production of poisonous gases. Therefore, it is essential to find a sustainable manufacturing solution which is eco-friendly, highly productive, and economical from all aspects for human being's comfort and environment. Cryogenic machining is one of the best sustainable substitutes for conventional machining. Major defects due to high temperatures can be reduced because of excellent coolant properties of cryogenic materials which slowed down the heat generation at the interface of tool and workpiece. This chapter introduces cryogenic machining and sheds light on its various important aspects along with presenting its comparison with the other machining methods based on different material properties, viz. surface finish, cutting temperature, and tool life.

Keywords Cryogenic machining · Sustainable manufacturing · Liquid CO_2
Tool life · Surface roughness

1 Introduction

Due to global warming and rapid expenditure of natural assets, most of the countries have applied strict regulation on manufacturers to control the environmental pollution. Consequently, people have developed various sustainable processes for making eco-friendly products with economical processes. Sustainability is adapted to different areas of production, viz. engineering, manufacturing, and design. In these areas, some factors turn out to be of extreme importance for

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sustainability such as efficient utilization of energy and inventories, efficient waste reduction processes for clean and "green" environment, and profitable manufacturing processes [1]. For sustainable manufacturing, it is important to minimize tool failure which causes uneconomical production.

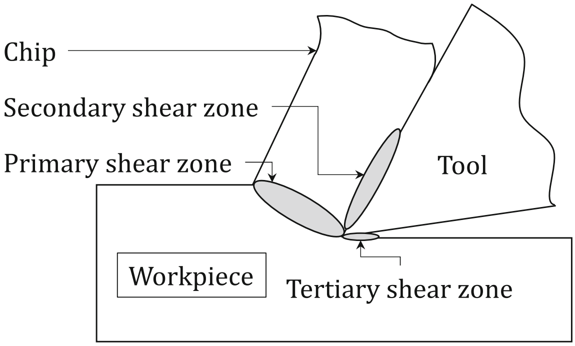
The cutting zone temperature is the major cause of poor machinability, especially in case of tool wear. Generally, during the machining process, all works which are performed to remove chips are transformed into heat because of high friction. This work is divided into three different zones, viz. primary shear zone (work for generation of chip and new surface by shearing the material), secondary shear zone (work for removal of chip from rake surface), and tertiary shear zone (work for shifting freshly machined surface from flank face of the tool). Figure 1 shows the plastic deformation zones for orthogonal cutting process [2].

The temperature generated at primary and secondary shear zones transferred to the tool and chip. In this region, heat transfer through conduction is slower than the heat produced on the tool; thus, temperature increases on plastically unstable zone ("growth of a locally thinned region or neck in a material upon the application of stresses") [3]. It results in local melting on tool, and this phenomenon of metal softening due to rise of temperature is known as adiabatic softening [4]. The thermal softening on the tool makes it easier for high wear rate. Therefore, lubricoolants are extensively used to decrease the cutting temperature, to diminish the wear rate and improve the workpiece quality [2].

Here, problem of tool failure and work surface deterioration can also be resolved exceptionally by coolant and lubricants. Therefore, various processes can be used such as plasma hot cutting [5], high-pressure liquid supply [6], minimal quantities lubricant [7], cutting fluids [8], gaseous machining, and cryogenic machining [9].

In recent past, soluble oils were applied as a conventional cutting fluid for cutting to enhance tool life by decreasing friction and temperature among tool, chip, and workpiece during machining. By lubricating surfaces of tool and workpiece, the cutting forces are decreased. Moreover, they prohibited the adhesion and welding-type seizure at an interval of chip and tool. Chip removal from the cutting zone reduces damage to the tool and machined surface [10].

Fig. 1 Plastic deformation regions for orthogonal cutting [2]



In conventional metal machining, bacteria, microbial organisms, anti-corrosive, emulsifiers, machine lubricant, and other contaminants are mixed with coolant oil. Due to bacteria, coolant becomes less efficient by dividing the emulsion. Consequently, coolant lubricant property weakened, and hence, cutting tool life decreases. Additionally, due to microbial inadequate effect, pH of coolant is reduced; workpiece and tool become more corrosion supportive. Therefore, biocides are needed to manage coolant bacteria and microbial action for increment of valuable coolant life. These biocides are highly uneconomical and dangerous additives for environment. Biocides are complex to manage, and dumping of it can make coolant more expensive. These are chemically less reactive; hence, they cannot be disposed-off easily from the surrounding. Therefore, many municipalities have prohibited the use of biocides. Moreover, conventional cutting fluids affect badly the worker health. They come in contact by skin or by lungs through inhalation of aerosols. Due to these biocides, many types of skin and lung diseases arise to workers [10]. Therefore, it is necessary to introduce an environment friendly, workers' health-favorable and economical cooling sustainable manufacturing method for machining such as gaseous and cryogenic cooling.

Stanford et al. [11] have used nitrogen gas as cooling substance with cutting fluid in order to reduce the use of flooded cutting fluid. In this work, time taken for cutting was 100 s. and impacts on temperature of different cooling approaches, viz. compressed air, no coolant, nitrogen gas at three different temperatures (room temperature, −40 and −150 °C), and flood cooling as shown in Fig. 2. Gaseous machining produces less temperature than dry cutting because of reduction in sticky behavior between workpiece and tool surface. Because of high pressure of compressed air or nitrogen, chips are removed easily. Gaseous machining is easily available and economical; however, it gives less cooling effect than other cooling approaches. Therefore, furthermore research in this field is required to fulfill the demand of high cooling effect.

Cryogenic machining has dominance over other conventional machining processes and used as a sustainable manufacturing process, due to its characteristics such as minimum heat generation, eco-friendly, no chemical dissociation,

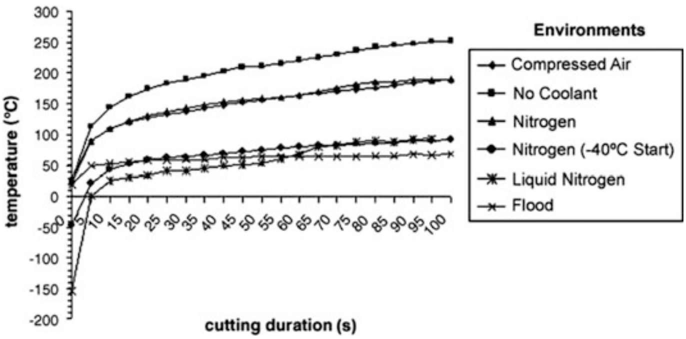


Fig. 2 Difference in temperature between gaseous cooling and other cooling method [11]

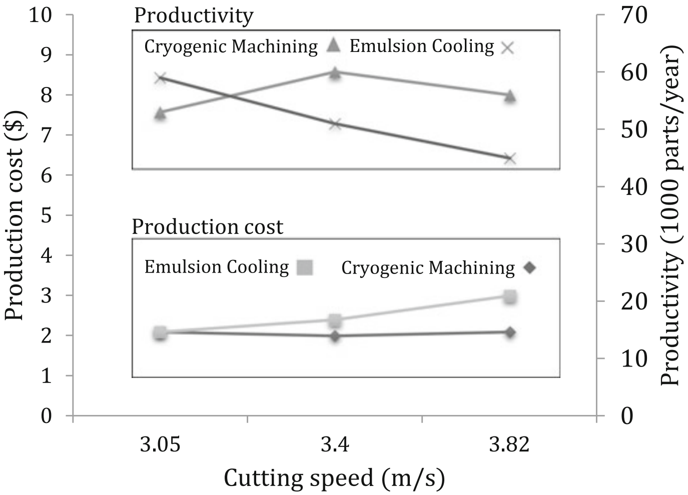


Fig. 3 Economical comparison between cryogenic and emulsion cooling [10]

low production cost, and highly productive. In Fig. 3, relationship between conventional emulsions' cooling with cryogenic machining has shown in terms of production cost and productivity for AISI304 material. As compared to conventional machining, cryogenic machining yields the dual benefit of low production cost and high productivity. Therefore, cryogenic condition plays an important role for sustainable machining purposes. Consequently, cryogenic machining has been more focused on research and industrial application in the recent past [10].

In the 1950s, cryogenic machining was performed first time and found to be eco-friendly and health-favorable sustainable manufacturing process with excellent cooling and lubrication properties. National Research Foundation (NSF) from the Columbia University (NY) has developed a research program comprising of 12 companies from machine tool builder, automotive and aerospace industry to found an economical cryogenic machining approach [12]. According to Zhao and Hong, cryogenic machining is a potentially effective approach for heat removal [13]. Cryogenic machining is done with the help of cryogenic materials as coolant/lubricant. Cryogenic materials are those substances whose boiling point temperature lies below 93 K such as nitrogen, hydrogen, helium, neon, oxygen, CO_2, normal air. Liquid nitrogen, liquid helium, and liquid CO_2 are widely used in cryogenic applications in industrial, clinical, and research applications.

On primary and secondary regions, heat and temperature generation rely on cryogenic fluid flow velocity. In an experiment, it is seen that cryogenic material flow rate has a very partial effect on machine tool power expenditure, by attaining advanced cutting speeds; cryogenic coolant can appreciably decrease the power expenditure for eliminating a fraction amount of workpiece material [14].

2 Experimental Procedure for Cryogenic Machining

For analyzing the effect of cryogenic coolant on the material removal ability of heat resistant or wear-prone materials, an arrangement of cryogenic machining setup has been designed and developed. Meanwhile, for providing a controlled stream of liquid nitrogen (LIN) at −197 °C, arrangements have been done such as Dewar flask for storage, cryogenic pump for taking it from storage, and nozzle for delivery at tool surface. Figure 4 shows cryogenic milling operation with heat plate. In this experiment, workpiece was capable to shift in Y-direction, while tool could shift in X- and Z-directions. The design fulfills two main purposes, viz. 3D free-form machining and direct cryogenic cooling of tool surface.

In this cryogenic milling setup, the thermocouple is used for temperature measurement which is attached near the tool tip and shielding is provided to reduce the radiation effect. Shielding is used to prevent the high temperature difference of heated surrounding and lower temperature coolant. Nozzle was used to supply cryogenic coolant, and copper plate with two electric heaters was used to preheat the workpiece [15].

Figure 5 illustrates the experimental setup to support CO_2 nozzle for milling process, in which shielding, dynamometer for force measurement, CO_2 spray unit, and gas nozzle for spraying CO_2 directly on tool tip have been used.

During turning operation, tool and workpiece are in continuous touch, while in milling operation it is discontinuous. Therefore, it allows a distinctive technique of applying LIN without cooling the workpiece direct to the tool which is useful at

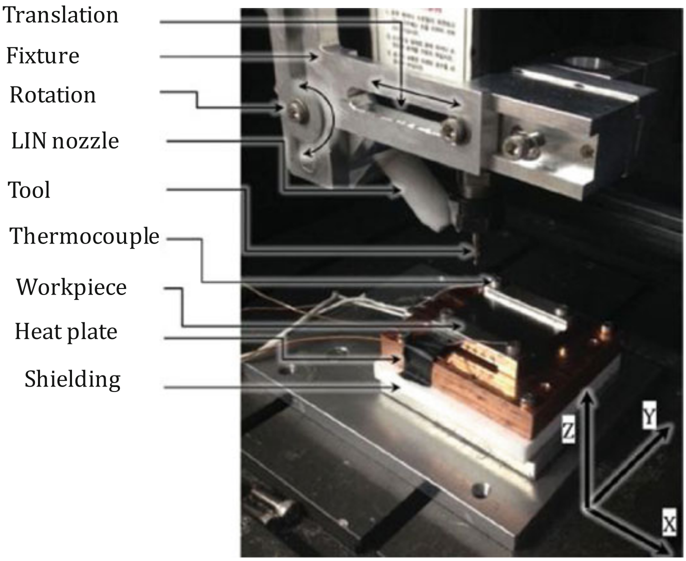


Fig. 4 Experimental setup of LIN cryogenic machining with heat plate [15]

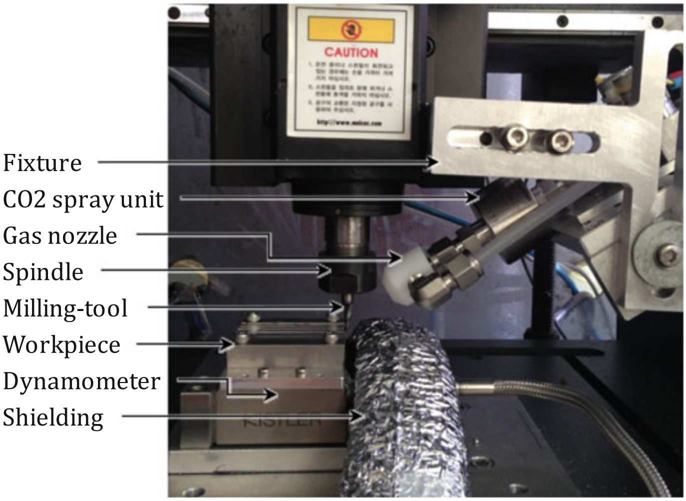


Fig. 5 Experimental setup to support CO_2 nozzle for milling process

higher cutting speed. Figure 6 shows the experimental setup with LIN cooling used by Hong et al. for turning operation of Ti–6Al–4V. [16].

In this setup, by placing supply head over chipbreaker, primary nozzle or both primary and secondary nozzles were triggered to spread LIN directly on tool rake or together on both tool rake and flank. For providing LIN from delivery tank into supply head, a tube of low thermal conductivity stainless steel covered in high vacuum was adopted [16].

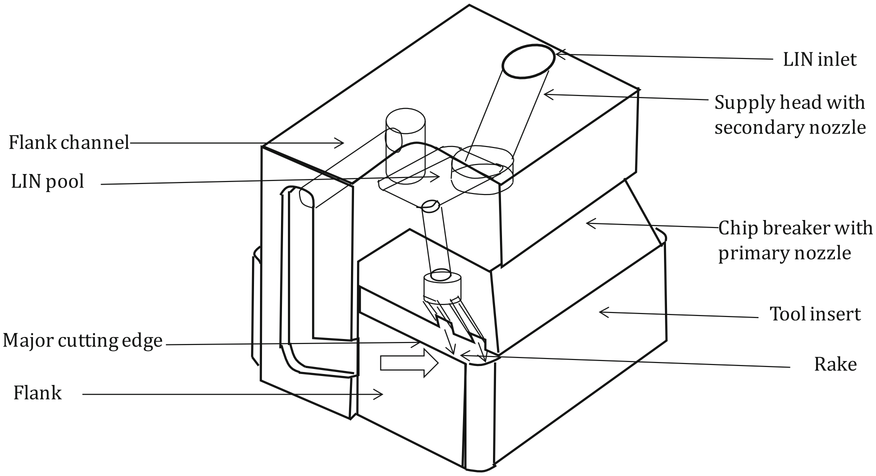


Fig. 6 Setup of a two-nozzle cryogenic turning [16]

3 Methods of Cryogenic Cooling

Cryogenic cooling could be done in different ways such as: pre-cooling of workpiece, indirect cooling or cryogenic tool back cooling, general flooding, enclosed bath and jet cooling by micro-nozzles. Cryogenic cooling enhances material properties; thus, different types of beneficial outcomes such as sustainability, low production cost, high productivity can be obtained by its use.

3.1 Pre-cooling of Workpiece

This type of cryogenic machining is done by cooling workpiece and chip initially to modify their properties and results in high productivity and sustainability.

Figure 7 illustrates the experimental system used to support pre-cooling of workpiece. Hong and Ding [17] have used two thermocouples for monitoring purpose of workpiece temperature about −196 °C earlier than the machining process gets started. With the help of this machining process, temperature of tool is decreased effectively; hence, life of tool is enhanced for cutting titanium alloy. Hong et al. [18] have enhanced low carbon steel chip breakability for smaller feed with minimal possible damage to machined surface. Cryogenic pre-cooling is not suitable for high-volume production.

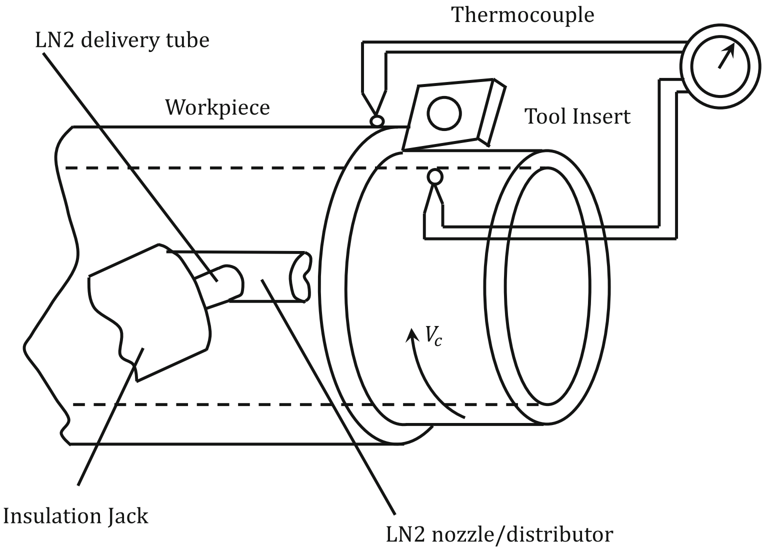


Fig. 7 Schematic of the experimental system for cryogenic pre-cooling of workpiece [17]

3.2 Indirect Cooling

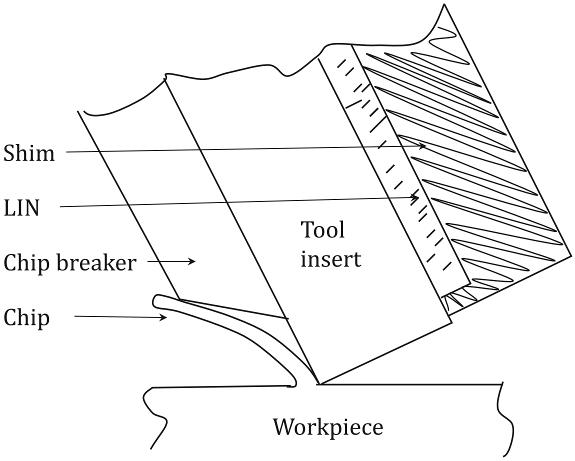
This cooling process is known as conductive remote cooling and cryogenic tool back cooling. In this method, cutting point cooled by heat conduction of cryogenic material is situated at tool holder or tool face. This approach of cryogenic cooling is impressive if contact area of cryogenic coolant with tool surface is more. Figure 8 illustrates the schematic of the experimental system for indirect cryogenic cooling. Here, LIN is provided on an enclosure bounded by tool and shim to cool the tool rear part. Since, LIN is not in contact with the workpiece, hence it does not change mechanical properties of the workpiece [17]. However, this method of cooling has some limitations such as poor thermal conductivity of tool material and large tool thickness for heat conduction.

3.3 Jet Machining

This machining is known as jet machining because cryogenic coolant is supplied to the tool tip through micro-nozzles. In this method, cryogenic coolant is provided on tool cutting tip with the help of two nozzles. Hong et al. have used two nozzles, primary and secondary, as shown in Fig. 9. Primary nozzle is inserted between tool surface and chip breaker, while secondary nozzle is placed to the flank surface close to cutting tip to reduce flank wear. They have used LIN delivery nozzle system, with a chipbreaker, and LIN is inserted into chipbreaker and rake surface of tool. Chips are uplifted with the help of chipbreaker; therefore, LIN extended up to chip–tool boundary [9].

Hong and Broomer [10] used three nozzles in a design for spraying LIN into chip–tool boundary. LIN is focused on three directions through flank nozzle on

Fig. 8 Schematic of the experimental system for indirect cryogenic cooling [17]



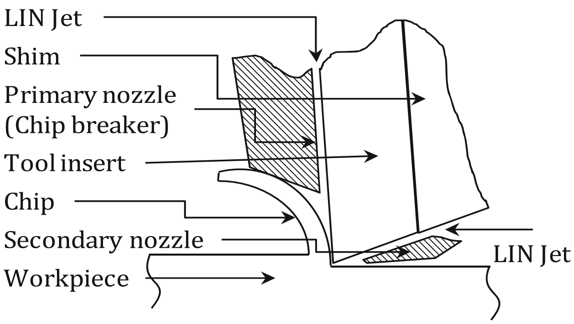


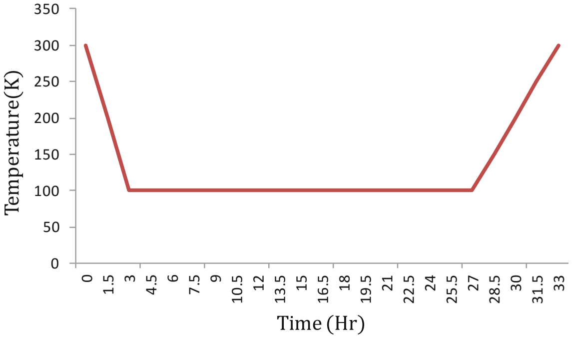
Fig. 9 Cryogenic jet cooling with two nozzles [9]

cutting edge, through Z-direction nozzle on parallel to the spindle axis and through X-direction nozzle on perpendicular to the spindle axis. In design of Venugopal et al. [19], nozzle is placed on tool post for injecting LIN jet on flank and rake face of tool. In another design, Dhar et al. [20] focused LIN jet on flank and rake face, alongside principal and secondary cutting ends. Cryogenic jet cooling has distinct advantage such as minimal waste due to coolant applied directly to tool location, where the object is parted off and high temperature produced. The quantity of the cryogenic material supplied to the cutting zone depends upon the heat generated at the cutting zone, surplus supply of cryogenic may cool the workpiece, which may result in the failure of the workpiece material [9].

3.4 Cooling Treatment by Cryogenic Material

Treatment process by cryogenic material is better alternative for material property enhancement since its mechanism brings superior wear resistance and surface finish quality to tool. The samples are cryogenically treated at machinery that could supervise temperature and time as needed during thermal phase. Then, sample is heated up to the room temperature to enhance desired properties [21, 22]. The steps used by Yong et al. [23] for cryogenic treatments were: (i) Sample positioned in the treatment chamber. (ii) Temperature slowly decreased from room temperature to −184 °C in 6 h. (iii) Constant temperature maintained for 18 h. (iv) Temperature slowly increased up to room temperature in 6 h. Result of the treatment: samples are tempered. Figure 10 shows the temperature variation used by Lal et al. [22] for wear test of steel tools with TiN-coated and TiN-uncoated conditions. They have calibrated at eleven different treatment conditions for wear resistance analysis and found that isothermal process is main cause to wear resistance increment of tools during cryogenic treatment process. Cryogenic treatment significantly enhances resistance to chip formation of tool as well resistance to flank wear [23].

Fig. 10 Cryogenic treatment sequence used by Lal et al. [22]



3.5 Cryogenic Minimum Quantity Lubrication

Recently, Zou et al. [24] have approached to new method, namely cryogenic minimum quantity lubrication (CMQL) for study on ease of machining of diamond tool which is the combination of cryogenic machining and MQL.

Figure 11 shows the basic concept used by Zou et al. [24] for cutting 3Cr2NiMo steel through diamond tool. In this experimental work, they combined compressed gas, micro-lubrication oil, and vaporized to create a cryogenic gas–liquid mixture and this mixture is supplied to cutting region with some velocity and pressure by a nozzle. These minute oil droplets are penetrated inside the cutting region effectively for better cooling and lubrication. Using this experimental setup, they induced cooling temperature −30 °C, flow rate 40 ml/h, and air pressure 60 bar. Maximum temperature of diamond tool is measured by infrared thermal imager and compared for the effect of cooling and lubrication. CMQL has given enhanced output for machinability through diamond tool than flood oil cooling, cryogenic machining,

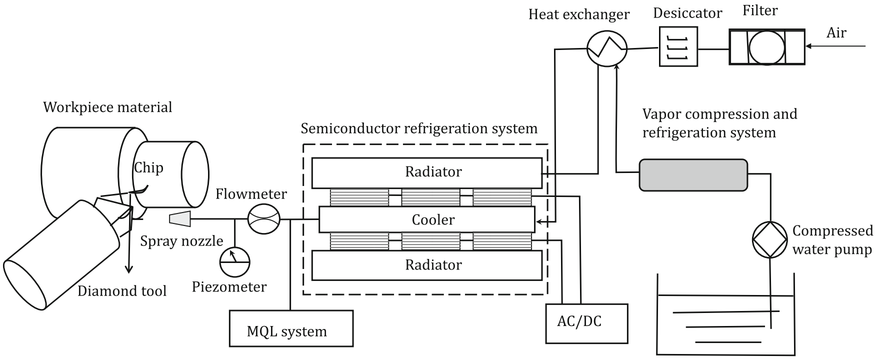


Fig. 11 Schematic of CMQL setup [24]

and MQL. In other words, CMQL can be defined as direct cooling produced through cryogenic gas and minute lubrication oil, indirect cooling activity and direct lubrication activity of minute lubrication oil. For cutting oil, carbon nano-fluid showed enhanced tool life and better surface finish than polyethylene glycol (PEG), synthetic ester oil, and emulsion cooling.

4 Effect of Cryogenic Machining

4.1 Influence of Cryogenic Cooling on Tool Life and Wear

Measurement of flank wear has considerable importance in wear and life analysis of HSS cutting tools [25]. During cutting of titanium alloy, wear induces "edge depression" on cutting edge, which results in degradation of tool geometry [19, 26]. Venugopal et al. [19] have found that the main tool wear method is adhesion dissolution diffusion of crater while scratchy and chemical erosion wear occur at the flank in machining titanium alloy with uncoated carbide. Figure 12 shows the variation in tool wear for different cooling processes, viz. wet, dry, and cryogenic machining. In this figure, different types of wear developed on uncoated carbide tool flank surface during turning of titanium alloy at 100 m/min cutting speed and 0.20 mm/rev feed are shown. Cryogenic cooling obstructs the development of wear impressively at medium cutting speed. Enhancement in wear resistance attributes to the refinement of the grain size as well as the reduction of β phases. Additionally, the development of large dislocation density and both together can release a high amount of energy generated by sliding friction which blocks the development of cracks on the affected zone and consequently enhancement in the wear resistance of titanium alloy [27].

Untempered cryogenically treated sample provides superior outcome than tempered with TiN cryogenically treated sample; therefore, it is highly recommended to use the untempered cryogenic-treated sample [22]. At the time of deep cryogenic treatment (DCT), enhancement in wear resistance property of workpiece magnesium aluminide ($Mg_{17}Al_{12}$) occurs because of development of structure tightening. Aluminum atoms jump to close defects because of tightened structure and results nucleation of β phase precipitates [28]. Paul et al. [29] have found that cryogenic machining with LIN jet decreases tool failure caused due to wear and enhances the tool life compared to dry and wet cutting of AISI 1060 steel. Wang and Rajurkar [30] have found that the CBN tool wear is extensively exaggerated by the cutting temperature in finishing silicon nitride. In the study of cryo-treated M35 HSS, it is found that modification of austenite phase into martensite phase contributed to abrasive wear resistance because of a significant enhancement in hardness [31].

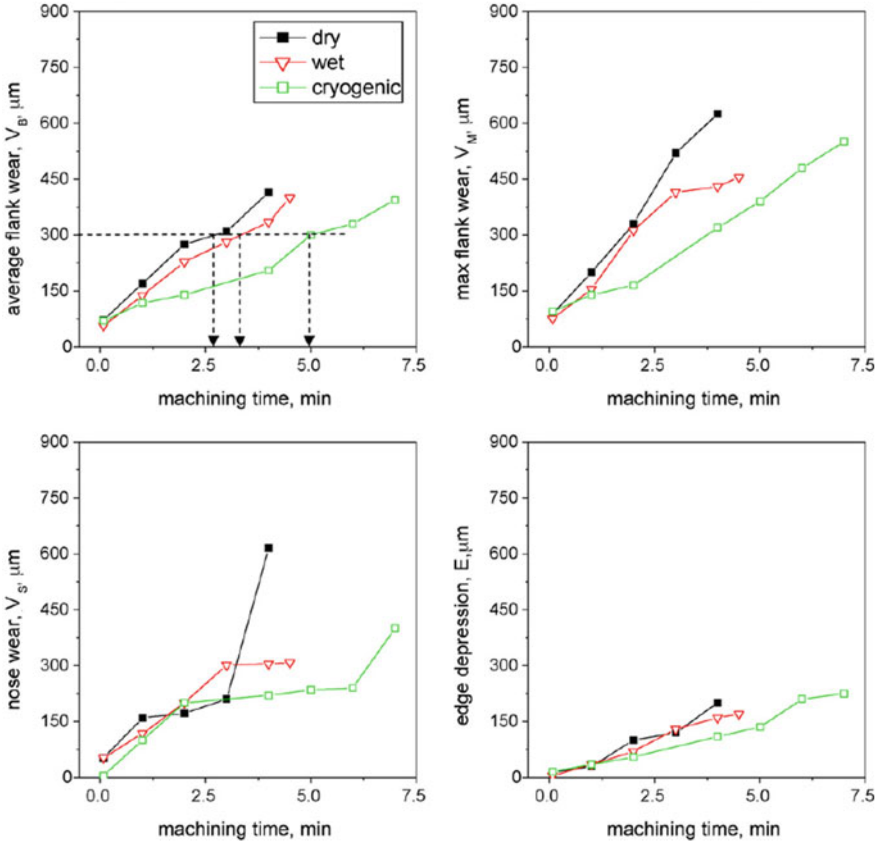


Fig. 12 Variation in tool wear under cryogenic condition [19]

4.2 Influence of Cryogenic Cooling on Tool and Workpiece Temperature

While studying behavior of titanium alloy as a sample and WC (tungsten carbide) as a cutter, it is concluded that cryogenic material diminishes the cutting zone temperature by removing heat. Microstructure and chip morphology indicate that the cryogenic material possibly enhances the tool life by blocking quantity of heat produced as well as conduction of heat toward cutting end. Moreover, due to cryogenic material, reduction in tool–chip contact length occurs, which consequently decreases in frictional heat on rake face [32].

Hong et al. have found 26% fall in peak temperature through jet cryogenic machining of AISI 1008, and they proposed that chip breakability or embrittlement of AISI 1008 can be increased by cryogenic machining [18]. In machining of various types of steel [20, 29, 33], use of LIN jet diminishes normal machining

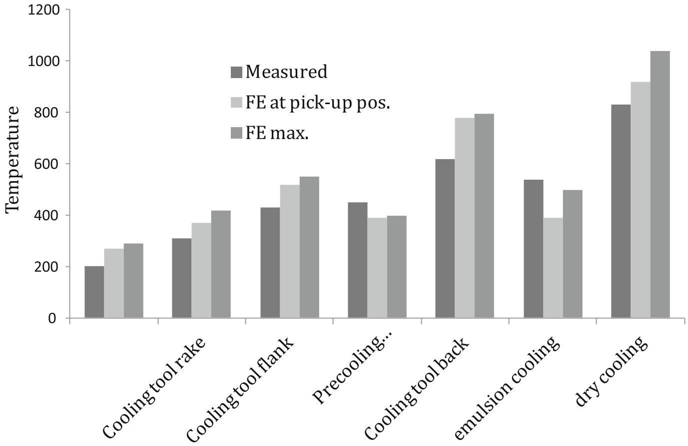


Fig. 13 Resultant of cooling approach on temperature (°C) [17]

temperature approximately 10–35% based on tool geometry, workpiece, and machining parameters. Moreover, it is observed that cryogenic machining productivity reduced with raise in cutting velocity and supply rate. Chip is brittle in nature on tool rake surface; therefore, increase in cutting speed occurred, blocking of cryogen at hot tool–chip interface. Hong and Ding [17] have obtained impact of different cooling methods on cutting temperature and compared them with predicted temperature of finite element pickup position and maximum finite element temperature as shown in Fig. 13. In their study, various cryogenic machining processes are compared in turning of titanium alloy. It is seen that instantaneous cryogenic jet machining at rake and flank surface is four times superior compared to dry machining in terms of reduction in cutting zone temperature [17]. Wang and Rajurkar [30] have seen in their study that the CBN tool wear is appreciably exaggerated by the cutting temperature in machining silicon nitride. CBN tool is less worthy to keep high strength at high temperature and LIN cooling limits the machining temperature to 829 °C; therefore, CBN material is able to retain its high strength. It is concluded that by cryogenic process, cutting zone temperature does not exceed too much that makes positive impacts.

4.3 Influence of Cryogenic Machining on Material Properties

Liquid gases are employed to preserve the cutting temperature down in cryogenic cooling, manipulate the material characteristics, and increase the usefulness of cutting tool. During temperature reduction, increment in hardness, and physical and chemical steadiness affinity occurred, which supports cryogenic cutting.

Experiments for carbide–cobalt alloys on cryogenic low temperature provide advantageous properties, such as high fracture strength and excellent crushing strength. Due to diverse characteristics of carbide tools, production industries could select different types of cryogenic cooling method for machining [34]. Silva et al. [25] have found that hardness and micro-hardness of M2 HSS cryogenic-treated and cryogenic-untreated workpiece were equal. However, in another study, improvement in hardness and homogeneity in hardness with deep cryogenic treatment of quenched and tempered HSS are found [35]. The contradictions in results are found due to difference in method used for cryogenic treatment.

Li et al. [36] have studied that if nitrogen induced in AISI H13 steel, its hardness is improved by 3–5 HRC while preserving its impact toughness. Due to nitrogen atoms relocates away from residual carbonitrides in the procedure of tempering, hazy steel lattice is found which enhances the tempered hardness of steel. Simultaneously, because slow dislocation along the expansion of carbides provides better resultant carbide atoms, it supports to enhance the crushing toughness while steel opposes to fatigue failure. During cutting of AISI 1008, cutting temperature can be modified in micron level by cryogenic machining. Consequently, modification in properties of AISI 1008 for each localized zone is occured like enhancement in material rigidity, physical and chemical steadiness affinity [34, 37] etc. To enhance the chip brittleness during machining of AISI 1008, a usual ductile substance, a cryogenic jet machining setup was developed. Using this cooling method, heat reduction is possible in chip because it maintains temperature near to brittle temperature of the sample which results in improvement in machinability of highly ductile material like AISI 1008 [32]. Yan and Xie [38] have concluded that with reduction in steel temperature from 20 to −165 °C, no change in elasticity, enhancement in yield and ultimate strength and decrement in ductility, fracture strain, percentage of cross-sectional area of reinforced steel occurred. The crucial temperature at which the failure transforms from ductile to brittle was −80 °C for the hardened HRB335-, HRB400-, and SLTS-reinforced steels. Figure 14 shows the result found by Yan and Xie [38] in which they plotted relationship between different material properties with cryogenic temperature. In this figure, they have shown the impact of cryogenic machining on various material properties for different categories of steel such as HRB335, HRB400, and SLTS, viz. elastic modulus of steel, yield strength of the reinforced steels, ultimate strength of the reinforced steels, fracture strain of the steel, percentage of reduction in cross-sectional area of reinforced steel, significance of temperature on yield strength and ultimate strength of the reinforced steels.

4.4 Influence of Cryogenic Machining on Friction

The cryogenic materials have been used as a coolant and lubricant in machining during recent years. LIN is a valuable lubricant for cryogenic cutting if it is utilized properly. During dry cutting operation, strong adhesive bond between cutting tool

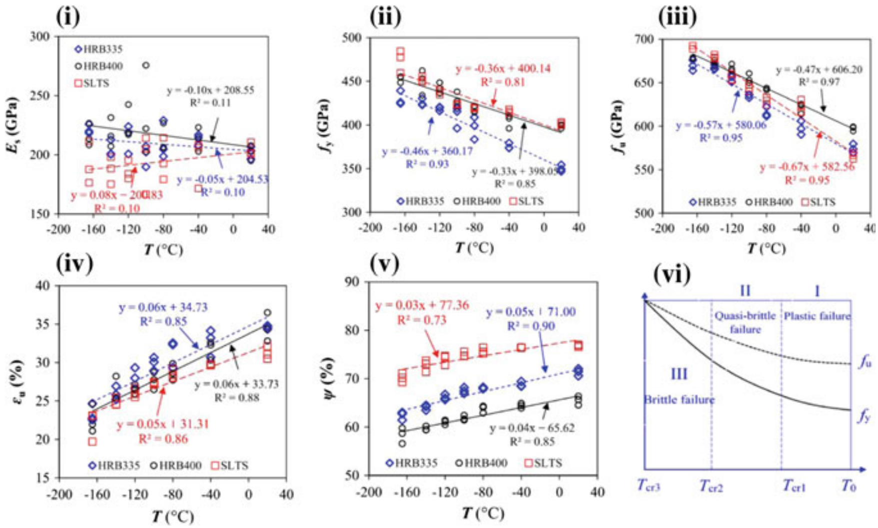


Fig. 14 Variation in mechanical characteristics of steel due to cryogenic cooling [38]

rake surface and chip surface was found, which significantly decreased by cryogenic lubrication, and helps to attain low friction [8, 16]. In an experiment, Hong et al. [6] have used carbide tool, Ti–6Al–4V alloy, and low carbon steel disks and found that LIN-filled surface forms low coefficient of friction as compared to dry surfaces and emulsion oil-filled surfaces for common disk substance at various sliding velocities. In this experiment, it is found that cryogenic treatment decreases coefficient of friction for titanium alloy under enforced load of 50 N, and during the process of cryogenic treatment at low temperature and at high soaking time, results decrease in coefficient of friction [27]. Bordin et al. [39] have analyzed that chip–tool contact length is a significant consideration because it causes variation in friction variation. Therefore, a smaller significance of tool–chip surface contacts length preferred; consequently, higher coolant diffusion, low friction, and a superior cooling effectiveness caused higher tool life. During a study of machining titanium alloy in two conditions, it is seen that coefficient of friction at the tool–chip boundary offered through cryogenic liquid was less than MQL liquid [40].

Hong [41] has done some experiments to examine the lubrication method of LIN material in aspect of five tribological plate disks as illustrated in Fig. 15. In the experimental setup, two probable LIN lubrication mechanisms have been taken, on first condition LIN added on to the disk or flat specimen which creates a physical obstacle for temperature increment and on second condition hydrodynamic effect creates obstacle due to the addition of LIN between two contact samples. He used five pairs of material as a disk for studying LIN lubrication effect for friction test. Those five pairs are as follows: disk versus specimen of AISI 1018, uncoated carbide insert versus AISI 1018 disk, AISI 1018 disk versus coated carbide insert, Ti–6Al–4V disk versus uncoated carbide insert, and Ti–6Al–4V versus coated

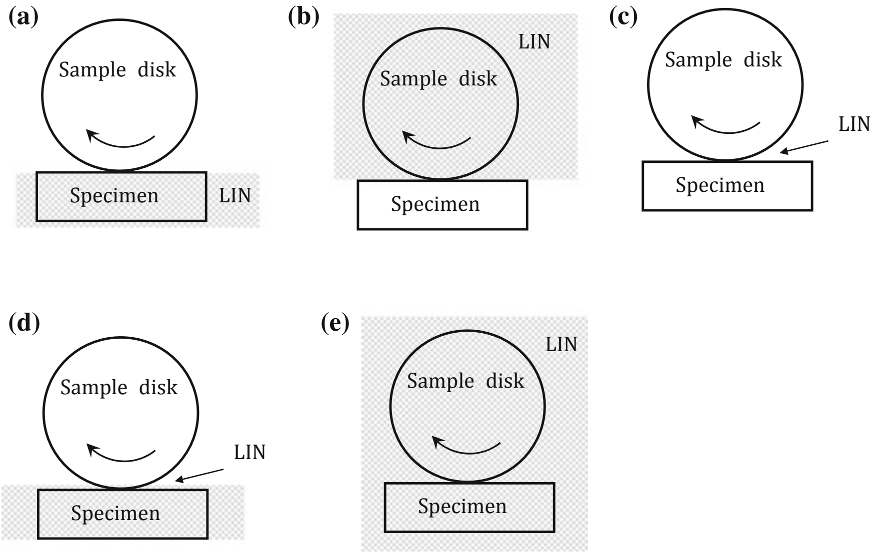


Fig. 15 Study of five cases for LIN application among both substances for different oiling methods: **a** specimen surrounded by LIN material; **b** sample disk surrounded by LIN material; **c** LIN inserting among both parts; **d** inserting LIN only on specimen; and **e** both surrounded by LIN material exclusive of inserting on boundary of both [41]

carbide insert. LIN lubrication ability improved due to low temperature which influenced via objects' couple. LIN gave minute coefficient of friction by producing hydrodynamic which is not depended on couple type.

4.5 Influence of Cryogenic Conditions on Cutting Forces

Cryogenic cooling helps to enhance the machining force because workpiece turns out to be tougher and stronger at low temperature. Although, low cutting zone temperature reduces the length of the sticky zone and therefore, reduction in the frictional force between tool-chip interface occurs. An improved method of cryogenic cooling is to control the flow of the coolant within the tool-chip interface, it may protect the workpiece from unwanted cooling. LIN is imposed to tool–chip boundary by initial nozzle and locates the chipbreaker such that it may raise the chip. Hong et al. [16] have experimentally demonstrated a relationship between different cooling approaches with various forces as shown in Fig. 16. Cooling on both (flank and rake) has enhanced the force required very less as compared to other cutting processes.

Bermingham et al. [32] have found that main cutting force reduced due to the application of cryogenic coolant on flank face directly by flank nozzle.

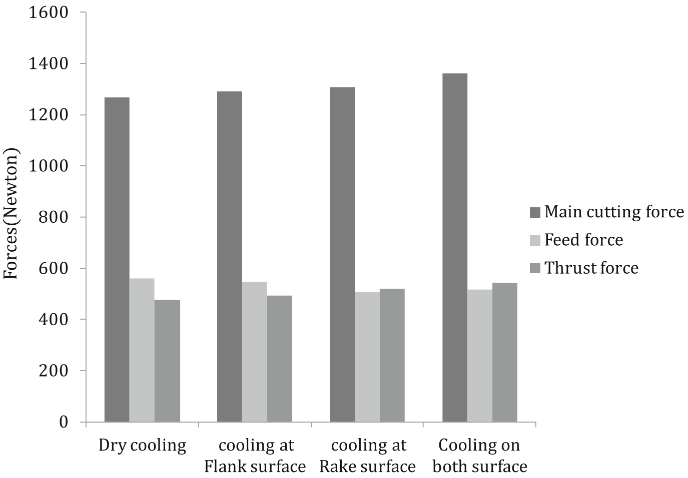


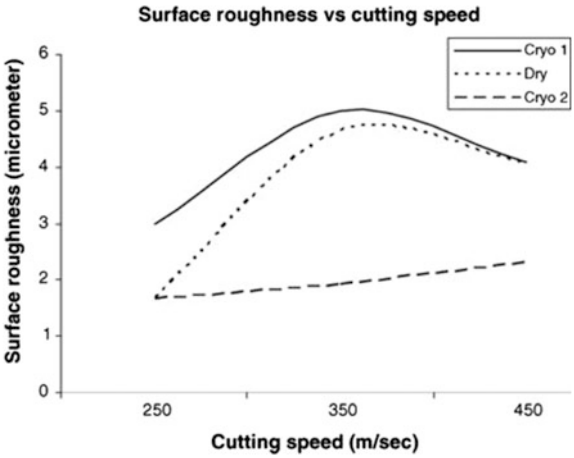
Fig. 16 Effect on cutting forces due to change in cooling approaches [16]

Meanwhile, they concluded that thrust force is always greater compared to feed force. Yuan et al. [40] have found that by cryogenic cooling, lower cutting forces can be attained than dry cooling and MQL. Huang et al. [42] have investigated the effect of jet LIN cooling on cutting forces for 7075-T6 aluminum alloy. When they applied LIN to machining region in the path, it supports to remove the chips, cutting forces appreciably decreased, and however, the edge forces enlarge. Busch et al. [43] investigated that the methods of high-pressure cutting fluid controlling procedure lean on the delivery direction and pressure, comprised of diverse potential through cutting zone. Method which is usually employed for machining inserted high-pressure coolant jet between rake surface and chip. This approach has a great effect on chip-breaking actions. The radius of chip curvature is decreased due to high pressure of the coolant, and the chips split into minute parts which are easily detachable, and thereby decreased in cutting force.

4.6 Influence of Cryogenic Machining on Surface Finish and Dimensional Precision

Cordes et al. [12] have found improvement in surface quality for milling process by using CO_2 as a cryogenic coolant as adhesion of atoms increased. In the study, Pu et al. [44] sprayed LIN between the cutting faces of tool and AZ31B magnesium alloy, thus eliminating the strong adhesive effect between them which is present during dry machining. Therefore, surface roughness is decreased by 20% through cryogenic machining as compared to dry machining. In another study, Paul et al. [29] have found that cryogenic jet cooling for AISI 1060 steel provides better

Fig. 17 Variation in surface roughness versus cutting speed with different cooling processes [48]



surface finish than dry and wet machining. In a study, Wang and Rajurkar [45] have machined hard-to-cut materials like ceramic, titanium alloys, Inconel alloys, and tantalum. They noticed great surface finish in case of cryogenic cooling.

Cryogenic cooling with liquid nitrogen on γ-titanium aluminides is raised as a better option to limit surface and subsurface defects by Klocke et al. [46]. Especially, reduction in surface roughness and subsurface microstructure is noticed during their cryogenic cooling, hence improvement in surface quality. In machining of Kevlar composites, Bhattacharya et al. [47] have flooded LIN on workpiece to get enhanced surface finish. However, they concluded that indirect cryogenic cooling provides better surface finish than dry cutting and cryogenic chip cooling. Mia and Dhar [33] have observed that the main cause for defective surface quality is generation of high temperature during machining. Due to high machining temperature workpiece melts near tool tip and forms built-up edge, which further caused to decrease the surface finish and high cutting forces. Ahmed et al. [48] have shown effect of three different machining processes with variation in cutting speed on surface roughness. They have used two methods of application of LIN named cryo 1 and cryo 2. In cryo1, gas was injected to cutting edge which increases chip brittleness, while, cryo 2 was done without insertion of gas results decrease in chip brittleness. Figure 17 shows the results observed by them with different machining processes for variation in surface roughness and cutting speed.

4.7 *Effect of Cryogenic Temperature on Microstructural Change of Tool and Workpiece Material*

Bensley et al. [49] have performed experiment for improving En 353 residual stress distribution by modifying its microstructure by cryogenic treatment process.

Table 1 [49] Percentage of retained austenite seen by X-ray diffraction method

Type of treatment	Retained austenite
CHTUT	28.1 ± 3.5
CHTT	28.5 ± 6.1
SCTUT	22.0 ± 7.6
SCTT	22.8 ± 5.9
DCTUT	14.9 ± 5.8
DCTT	14.3 ± 4.1

They have used six different ways for cryogenic treatment, viz. conventionally heat-treated untempered specimen (CHTUT), conventionally heat-treated tempered specimen (CHTT), shallow cryogenically treated untempered specimen (SCTUT), shallow cryogenically treated tempered specimen (SCTT), deep cryogenically treated untempered specimen (DCTUT), deep cryogenically treated tempered specimen (DCTT). They noticed a certain change in percentage of retained austenite in sample as shown in Table 1.

It has been concluded that shallow cryogenic treatment and deep cryogenic treatment provide greater result if applied after tempering. Due to cryogenic treatment, reduction in temperature occurs which enhances the lattice imperfections and thermodynamic unsteadiness of martensite. Consequently, this treatment supports carbon and alloying elements toward imperfections. These imperfection groups perform as a source for the development of superior carbides on later tempering process. Therefore, greater residual stress released by deep cryogenic process because of carbon particles shifts to a small area to split into identical crystal part or further imperfections and using this they construct ultra-fine carbides [49].

Perez and Belzunce [50] have done an experiment on H13 steel with four different conditions in the following sequence: firstly, austenitizing sample at 1020 °C for 30 min after that gas or oil quenching, then cryogenic treatment of sample at −196 °C for 12 h, and at last triple tempering of sample at 590 °C for 2 h. They have found that cryogenic-treated and oil-quenched carbides are finer, homogeneously scattered, and at higher quantity inside H13 steel in comparison with other three processes. Due to homogeneity of carbide atoms inside the sample, toughness of steel increased significantly. Figure 18 shows microstructure of sample for four conditions observed by Perez et al. after experiment performed on H13 steel.

Pu et al. [51] have done experiment on AZ31B–O magnesium alloy and noticed microstructural changes in SEM and optical microscope images. They concluded that it is possible to modify microstructure of AZ31 Mg alloys by using different machining situations. With cryogenic machining, white layers can be generated where grain formation may not be distinguishable and these layers' hardness enhanced by 60% in comparison with whole material. In the layer, new grains could be formed which consist of nano-crystallized grains. It is observed that white layer enhances corrosion resistance property of the sample.

In the experiment of Ti–6Al–4V alloy as sample, Bordin et al. [39] have seen subsurface microstructural modification in shape of extended and distorted atoms

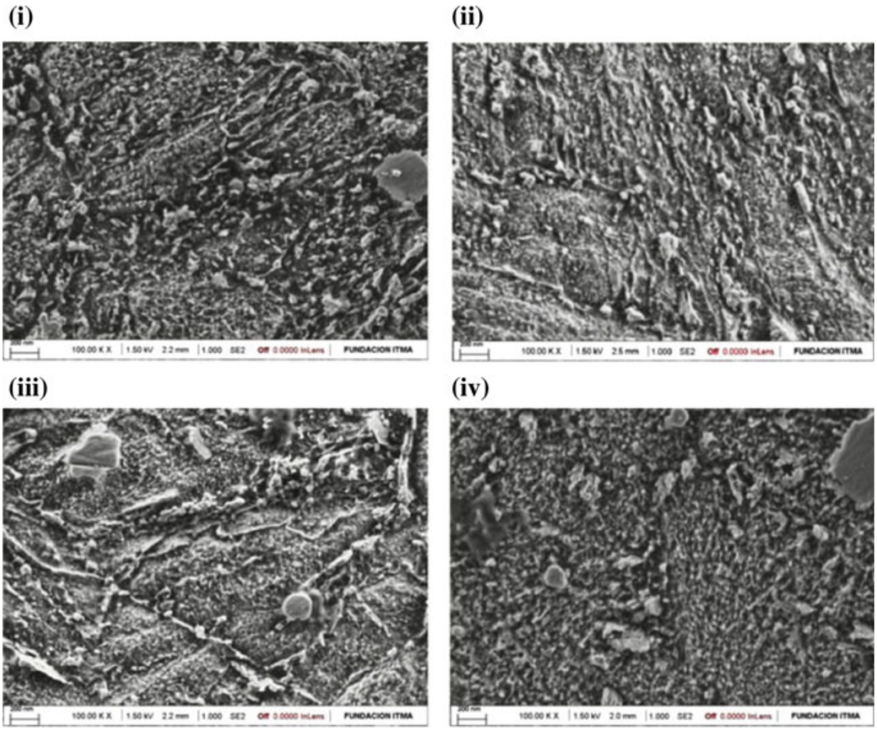


Fig. 18 Microstructure for H13 steel at 100,000 × magnification by FEG-SEM for four different processes: **i** HT1, **ii** HT2, **iii** HT3, and **iv** HT4 [50]

on workpiece during dry machining, while there is no change on workpiece microstructure during cryogenic machining for even harsh cutting parameters. In an experiment, Podgornik et al. [52] have done deep cryogenic treatment on steel and found an increase in steel properties due to generation of advanced spike-type martensite and martensitic modification with plastic deformation of primary martensite.

5 Comparison Between CO_2 and LIN Cryogenic Cooling

Some common differences between cryogenic machining by CO_2 and LIN as a coolant material are as follows.

- It is seen from observations that when higher feed rate and high cutting velocity used for machining, increment in material removal rate occurred, and hence machining temperature enhanced. LIN machining cools down temperature 9–34% and 3–17% better in comparison with CO_2 machining and wet machining, respectively [53]. The reason behind this difference in cooling was deviation in their boiling point temperature; hence, LIN (−192 °C) reduces temperature more than CO_2 (−78.5 °C).

- Basically, cryogenic material opposes friction generation between chip and tool surface. Hence, it offers excellent softening and cooling effect which causes reduction in cutting forces to better level. Cryogenic machining through CO_2 reduces forces 17–38% and 2–12% than wet and LIN machining, respectively [53]. CO_2 offers better result as compared to LIN because it is used as a pressurized jet and entered deeper in cutting region between tool and chip boundaries than later one.
- Due to lower temperature of LIN than CO_2, surface hardness of LIN cooling sample is higher than CO_2 cooling which is an additional cause of minor increment in cutting force value of LIN cooling.
- It is observed by Jerold and Kumar [53] on SEM images that tool taken out from CO_2 cryogenic cutting has less damaged faces and edges than LIN cryogenic cutting for constant feed rate.
- Crater wear seen by Jerold and Kumar [53] was 68 and 118 μm at 94 m/min for CO_2 cooling and LIN cooling, respectively, and it increases with increase in cutting velocity. Therefore, it can be concluded from results that CO_2 coolant opposes wear of tools superior to LIN coolant.
- Change in surface roughness for deviation in cutting velocity and feed rate is observed. Due to less wear observed on CO_2 than LIN machining, surface finish obtained by CO_2 cooling is superior to LIN machining. However, at extremely high cutting velocity, surface roughness obtained by both machining processes is the same [53].
- Chip shape plays a significant role in the economical aspect of machining because lengthy and continuous chips' removal is costly. It is observed that CO_2 machining gives enhanced chip form than LIN machining due to excellent penetration effect [53].
- LIN is easily available and cheaper than liquid CO_2 because LIN is a by-product of many industries.
- LIN forms nitrogen on vaporizing which is less harmful compared to vaporized form of CO_2.

6 Conclusion

Cryogenic machining is emerging as a cost-effective, eco-friendly, and advance sustainable manufacturing process for difficult-to-cut materials. Cryogenic materials fulfill the need of coolant as well as lubricant with enhancement in various desirable characteristics of the sample. Therefore, researchers and scientist are more focused specifically on developing method for machining superalloys used in aerospace industries, nano-crystalline surface regeneration, and inducing desired properties to any material. Liquid nitrogen is the material used in most of the machining cases as cryogenic fluid. In the machining process, it cools tool as well as workpiece. Cooling of the tool makes it harder by altering its microstructure and reduces wear. In turning operation, cooling is done by rake face, flank face, and rake–flank together. It is reported that the maximum tool life is achieved by putting cryogenic fluid through the rake face and flank face together. Workpiece cooling may not be useful at all the time because it makes the workpiece harder and therefore increases the cutting forces. Most of the analysis is done on turning and orthogonal process; however, few are done in other operations like milling/micro-milling. In a milling operation, the tool comes in contact with the workpiece for half of the time in its rotation and half of the time it rotates freely without contacting the workpiece. Therefore, the cryogenic fluid was provided to the back of the milling tool which reduces the workpiece pre-cooling and showed efficient cooling to the tool. Further, research work can be focused on minimizing the force required to cut the sample, until now cryogenic material in common cases enhances force required to cut the material; therefore, energy consumption increased for machining; hence, machining by CMQL process needs improvement for reducing force required and makes cryogenic machining more economical from perspective of energy consumption. The major issue with the cryogenic material is its handling. A better-controlled flow of the cryogenic fluid can reduce volume of the liquid as well as the reduction in the reach of the liquid into the workpiece material; so that, increase in the cutting force can be controlled. It is finally concluded that cryogenic cooling is a sustainable substitute of conventional wet cooling and has the potential to significantly enhance the machinability of difficult-to-machine materials.

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Sustainability Issues in Electric Discharge Machining

Janak B. Valaki, Pravin P. Rathod and Ajay M. Sidpara

Abstract Electric discharge machining is a well-known advanced machining process extensively used for difficult-to-machine materials, microparts and precision engineering components for various biomedical, scientific and industrial applications. In spite of EDM's special characteristics, this process suffers from major limitations as regards to sustainability. High specific energy consumption, hazardous emissions, operator health and safety risk, generation of toxic waste and sludge, etc., are the major issues. This chapter introduces EDM, highlights and discusses inherent sustainability issues, and suggests possible solutions. An experimental study based on the use of sustainable dielectrics is the main part of this chapter. The effects of EDM parameters on material removal rate, surface roughness, and other surface integrity characteristics under the influence of sustainable dielectric fluids are discussed. The chapter ends with the conclusions and possible avenues of future research.

Keywords Sustainable manufacturing · Wet EDM · Dry EDM
Near-dry EDM · Sustainability · Vegetable oil

Notations

EDM	Electric discharge machining
PAH	Polycyclic aromatic hydrocarbons (PAH)
BTEX	Benzene, toluene, ethylene–benzene and xyle

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HAZOP	Hazard and operability analysis
W/O	Water-in-oil
BD1	Jatropha oil-based biodielectric fluid
BD2	Waste vegetable oil-based biodielectric fluid

1 Introduction

Electric discharge machining (EDM) is one of the most popular machining processes [1]. It uses discrete electrical discharges in the form of sparks to ionise the dielectric media and generates plasma between electrode gaps which results in generation of extreme temperatures as high as 8000–12,000 K [2]. The material removal in EDM is based on localised heating, melting and vapourisation of workpiece due to striking high energy sparks [3] as shown in Fig. 1.

The dielectric fluid used in the EDM process ionises and deionises at high frequencies as per the controlled voltage regulating mechanism of the process. Each cycle removes a certain amount of material. However, due to large number of process variables involved, EDM process behaviour is highly dynamic, stochastic and very complex to predict. High temperature, pressure waves and decomposition products of dielectric fluid involved in EDM process generate various unwanted end products like air emissions, eroded metal particles, heat, spark causing radiation and noise as summarised in Fig. 2.

Precisely controlled melting and evaporation of material surface produce dimensionally and geometrically accurate and precise surface profiles on hard-to-machine materials. EDM is mainly used in machine tools industries to manufacture dies, punches and cutting tools [5]. Recent advances in EDM process have extended its applications to surface texturing, precision and micromachining [6].

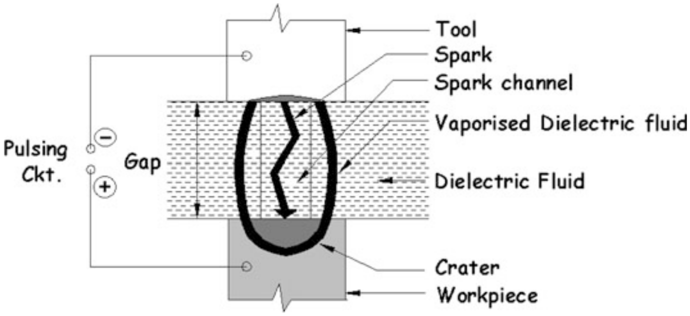


Fig. 1 EDM spark description

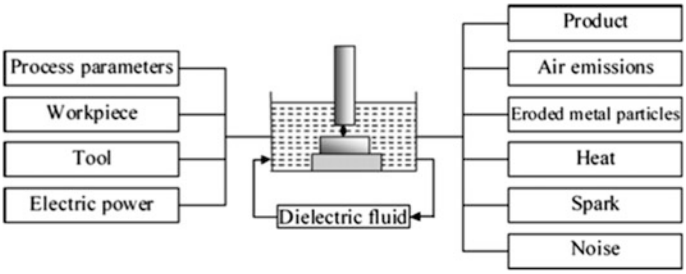
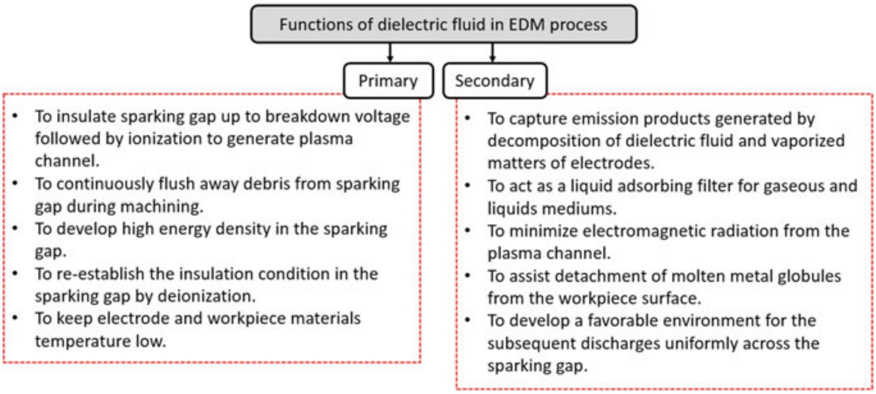


Fig. 2 Input–process–output diagram for EDM process [4]

2 Dielectric Fluid in EDM

The dielectric fluid is very important with regard to productivity, economy and quality of the parts [6]. Dielectric fluid performs many functions during EDM process. Based on the importance of the function in EDM physics and material removal, it is categorised into primary and secondary functions as given in Fig. 3 [7].

The complex set of properties of dielectric fluid and process physics together makes EDM one of the most complex machining processes. In order to define and evaluate sustainability of the EDM process, it is imperative to understand the role of various properties of dielectric fluid on process behaviour. During the ionisation–deionisation of dielectric fluid, EDM produces emission of solid metallic particles, aerosols, toxic gases, waste dielectric, which are hazardous to the operator and environment [8]. Apart from that, toxic emission, fire/explosion, electromagnetic radiation, etc., are potential health hazards during the process [9]. Figure 4 highlights the desired properties of dielectric fluid for stable and efficient material erosion cycles [10].



- To insulate sparking gap up to breakdown voltage followed by ionization to generate plasma channel.
- To continuously flush away debris from sparking gap during machining.
- To develop high energy density in the sparking gap.
- To re-establish the insulation condition in the sparking gap by deionization.
- To keep electrode and workpiece materials temperature low.

- To capture emission products generated by decomposition of dielectric fluid and vaporized matters of electrodes.
- To act as a liquid adsorbing filter for gaseous and liquids mediums.
- To minimize electromagnetic radiation from the plasma channel.
- To assist detachment of molten metal globules from the workpiece surface.
- To develop a favorable environment for the subsequent discharges uniformly across the sparking gap.

Fig. 3 Functions of dielectric fluid in EDM process

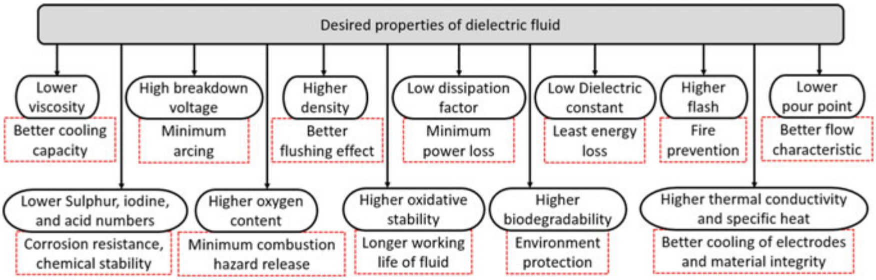


Fig. 4 Desired properties of dielectric fluid for EDM

2.1 Dielectric Supply Methods

EDM process is significantly affected by the selection of dielectric fluid and the way it is supplied to the machining zone [11]. EDM process is carried out with three modes like wet, dry and near-dry EDM as shown in Fig. 5.

In wet EDM, liquid dielectric is used and supplied in the working gap from side or through tool electrode. Both the electrodes (tool and workpiece) are submerged in the dielectric fluid during operation. *In dry EDM*, dielectric is supplied in the working gap in the form of pressurised jet of air, gas or mixture of air and gas. This mode reduces pollution as compared to wet EDM by minimising emissions released to hydrocarbon-based compounds [12, 13]. Furthermore, the machine does not require bulky dielectric circulation and cooling system. *In near-dry EDM*, dielectric is supplied in the form of mist or spray of the mixture of fluid and gas in a specific proportion. It was first demonstrated in 1989 by Tanimura et al. [14]. However, mist or spray of dielectric results in electrolysis corrosion on the workpiece and also pollutes the environment.

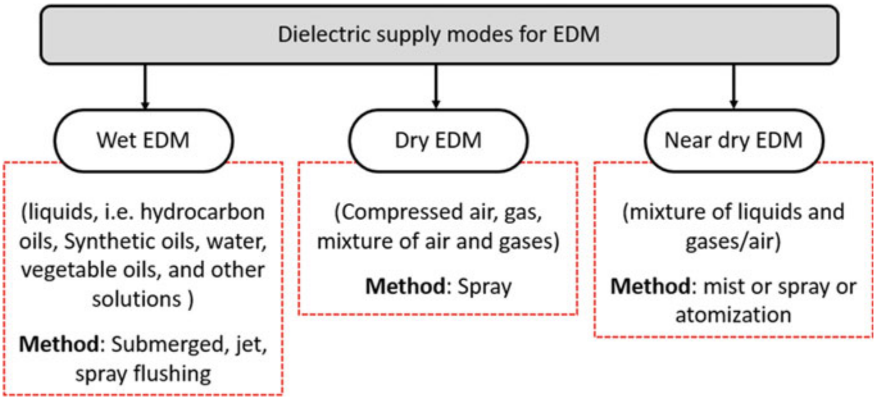


Fig. 5 Dielectric supply modes for EDM

3 Sustainability of EDM Process

The Department of Commerce (USA) defines sustainable manufacturing as "the creation of manufactured products that use processes to minimise negative environmental impacts, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers" [15]. Sustainable manufacturing is a branch of sustainability that deals with economic, environmental and social objectives of manufacturing activities. Sustainable manufacturing processes produce the minimum quantity of wastes, improved environmental performance and energy efficiency while ensuring high operational safety and personal health [16].

Manufacturing can significantly contribute to the sustainable development goal as it is directly related to products, processes and services which affects the three pillars of the sustainability via environment, social and economic sustainability [17]. Various sustainable manufacturing practices such as environmentally conscious/green machining, lean manufacturing practices, enterprise resource planning systems, product life-cycle management systems and recycle and remanufacturing are some of the significant means that strengthen the three pillars of the sustainability [18]. Increased market competitiveness, go green attitude of consumers, increased social awareness and corporate social responsibility (CSR) and the requirement to comply ISO 14000 series standards have compelled manufacturing organisations to adapt the norms laid down by the international organisations to identify and implement sustainable manufacturing practices.

3.1 Impact of EDM Process on Environment, Health and Safety

EDM with liquid dielectric fluids is very popular for commercial applications. However, liquid dielectric fluids are responsible for some serious economic and environmental concerns such as slow machining rate, uneven electrode wear, high specific energy, poor surface characteristics, toxic waste, sludge generation, hazardous emissions, risk of fire explosion.

The sludge, dielectric waste and deionised resin produced at the end of the EDM operation need to be disposed appropriately to minimise the land and water pollution [19]. End-of-life treatment is an imperative process performed on waste oils to minimise its hazard potential before it is disposed. Personal health concerns of manufacturing activities are associated with the effects of toxic and volatile emission products from the manufacturing operations on the health of operators. During EDM operation, the operator is exposed to highly toxic and hazardous elements near operator working zone. As a result, compliance with the maximum permissible emission values is critically required [20]. Prolonged exposure to hazardous gases, toxic aerosols and finely suspended metallic particles is considered as serious health

Table 1 Drawbacks of dielectric fluids used in EDM process

Hydrocarbon-based oils	**Dry/gaseous dielectrics**
• Release of hazardous emission products • Carburisation • Toxic and non-biodegradable waste generated • Fire explosion • High specific energy consumption • Electromagnetic radiation	• Poor flushing • Poor debris detachment • Poor surface finish • Reattachment of debris • Unstable sparking • Poor dimensional and geometrical accuracy
Water-based dielectrics • Corrosion of EDMed surface • Electrolysis of the dielectric • Decarburisation • Microcracks formation on the EDMed surface	**Mixture of wet and dry dielectrics (Near dry)** • Release of aerosols • High concentration of aerosol in the operator breathing zone

hazard to the operator [21, 22]. EDM process has some of these problems due to the presence of dielectric fluid of different properties [23].

Table 1 presents a summary of drawbacks of the dielectric fluids used in EDM operations. It is possible to control the physics of melting and evaporation by proper selection of dielectric fluid and the way it is supplied in the working gap.

In wet EDM, electrolysis corrosion occurs when water is used while toxic by-products are produced when hydrocarbon-based dielectric is used [24]. Therefore, environmental regulations have to be strictly followed for their proper disposal [25]. Land and water pollution occurs due to the disposal of EDM wastes such as sludge, filter cartridges, dielectric waste [26]. Furthermore, toxic substances in the form of solid, liquid and gaseous forms also create health and environmental problems [27]. Not regulating or controlling the above problem results in respiratory, carcinogenic and occupational dermatitis-related diseases [28]. Gaseous dielectric fluids also create unhealthy operating environment by microdebris, bad smell of burning of dielectric fluid, etc. Environmental, health and safety concerns of the EDM process are summarised in Fig. 6.

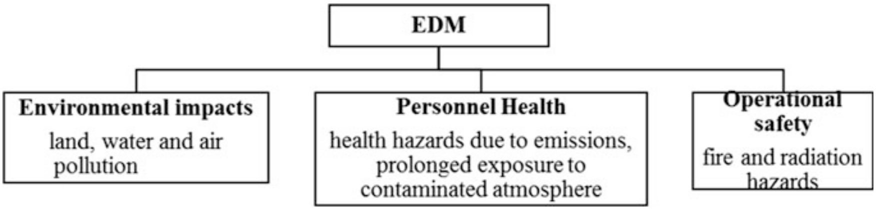


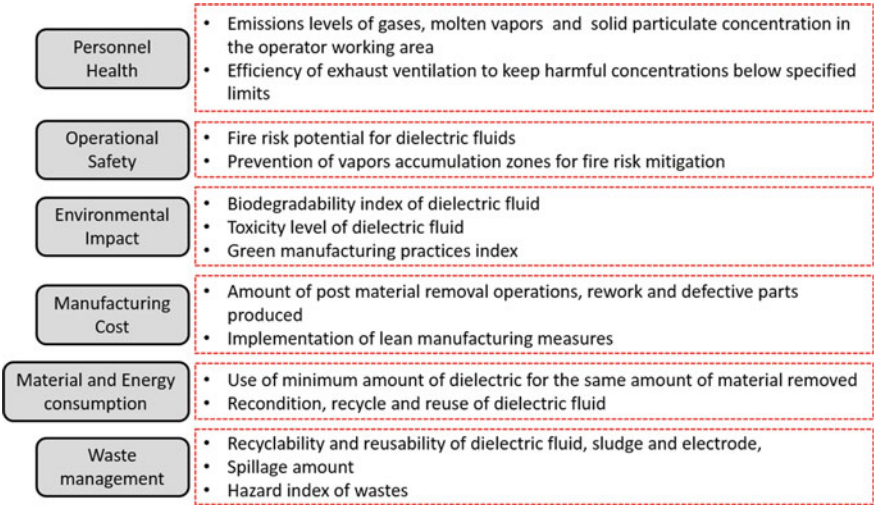
Fig. 6 Environmental, health and safety concerns of EDM

3.2 Technological and Economic Concerns of EDM Process

The EDM process consumes 30–50 times more energy and produces 50–60 times slower output (machining rate) than conventional machining processes [29]. EDM with deionised water results in 50% less carbon content on the machined surface than that of the base material, while in case of hydrocarbon-based dielectric fluid, carbon content is four times more on the top surface than that of base material [30]. Near-dry EDM also has some serious problems such as electrolytic corrosion, suspending aerosols, blackish and rugged machined surface, ejection of debris to nearby places [31]. Oxygen-mixed water-in-oil emulsion may minimise the possibilities of fire-related problems [32]. Dielectric plays certain functions in EDM for efficient operation. However, it is observed that all three modes of dielectric supply cause problems related to working environment, by-product disposal, etc. Final machined surface is subjected to variable hardness, cracks, resolidified material, etc. These characteristics are attached with the dielectric fluid and its mode of supply.

3.3 Sustainable EDM

Manufacturing processes are assessed using six sustainability indicators, viz. personal health, safety, environmental impact, cost, material and energy consumption and waste management [33]. Assessment of the sustainability of EDM process can be done through key performance indicators (KPIs), as shown in Fig. 7 [34].



Personnel Health	• Emissions levels of gases, molten vapors and solid particulate concentration in the operator working area • Efficiency of exhaust ventilation to keep harmful concentrations below specified limits
Operational Safety	• Fire risk potential for dielectric fluids • Prevention of vapors accumulation zones for fire risk mitigation
Environmental Impact	• Biodegradability index of dielectric fluid • Toxicity level of dielectric fluid • Green manufacturing practices index
Manufacturing Cost	• Amount of post material removal operations, rework and defective parts produced • Implementation of lean manufacturing measures
Material and Energy consumption	• Use of minimum amount of dielectric for the same amount of material removed • Recondition, recycle and reuse of dielectric fluid
Waste management	• Recyclability and reusability of dielectric fluid, sludge and electrode, • Spillage amount • Hazard index of wastes

Fig. 7 Key performance indicators for sustainable EDM [34]

4 Green or Biodielectrics for EDM

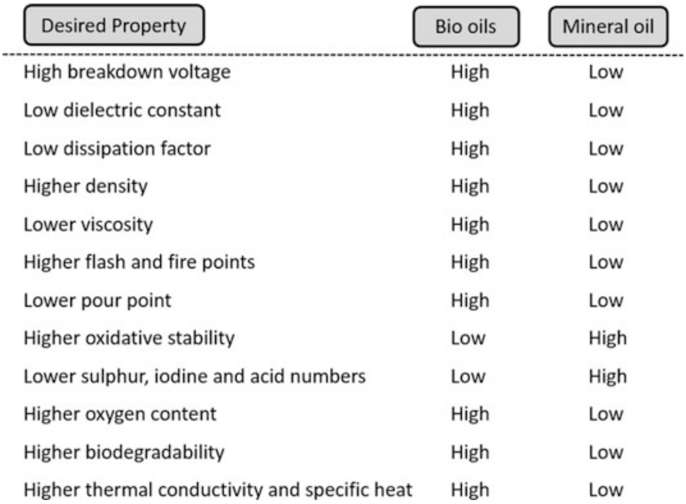
One of the research areas identified for better sustainability of EDM process is the use of green dielectric fluid as an alternative to conventional fluids. Being vegetable plant-based natural product, sustainability index of vegetable oil is the highest amongst all the dielectric fluids. Refined and transesterified vegetable oils have similar dielectric properties to that used in EDM [35]. Hence, they have potentials to replace conventional dielectric in EDM process. Reconditioning and reuse of vegetable oils would have a convincing impact on sustainability index. The characteristics of vegetable oil-based dielectric fluids for EDM are summarised in Table 2 [36]. Vegetable oil-based dielectric fluids offer significant advantages in terms of sustainability point of view. Hence, its application in industrial practices is likely to improve sustainability indices of the processes. Qualitative assessment of suitability of bio-oils as a dielectric fluid for EDM is given in Fig. 8.

Jatropha curcas and waste vegetable oil (WVO) have been identified as potential vegetable oils as feedstocks for biodielectric fluids for EDM. Jatropha curcas oil, non-edible oil due to the presence of highly poisonous toxalbumin curcin, does not affect the food chain. Jatropha seeds contain 30–40% oil by weight, and Jatropha seed oil has excellent mechanical, thermal and chemical properties and comparable dielectric properties compared to hydrocarbon-based kerosene.

Due to the abundance availability, low cost, sustainability impact, and ease of esterification and transesterification, WVO has been found as a potential alternate dielectric fluid for EDM [34]. WVO has the highest potential to influence sustainability amongst the available vegetable oils due to low cost, high conversion ratio and economical treatment [37–39]. Furthermore, WVO usage may reduce land, water and air pollution.

Table 2 Characteristics of bio-oils and its effects on sustainability criterion [34]

Characteristics of bio-oils	Effect on sustainability criterion
Higher flash point	Higher operational safety due to fire prevention and risk mitigation
Excellent biodegradability	Lower environmental impact
Higher oxygen content	Better personal health due to minimum harmful emissions
Low carbon atom chain (17–18)	Lower manufacturing cost due to minimum metallurgical deterioration
Nontoxic	Better personal health due to negligible health hazard
Higher breakdown voltage	Better process efficiency
Lower volatility and toxic emission	Higher operational safety



Desired Property	Bio oils	Mineral oil
High breakdown voltage	High	Low
Low dielectric constant	High	Low
Low dissipation factor	High	Low
Higher density	High	Low
Lower viscosity	High	Low
Higher flash and fire points	High	Low
Lower pour point	High	Low
Higher oxidative stability	Low	High
Lower sulphur, iodine and acid numbers	Low	High
Higher oxygen content	High	Low
Higher biodegradability	High	Low
Higher thermal conductivity and specific heat	High	Low

Fig. 8 Qualitative assessment for suitability of bio-oils as EDM dielectric [36]

4.1 Experimental Methodology

Three dielectric fluids (kerosene, jatropha curcas and WVO-based biodielectric fluids) are selected to evaluate operational and technical feasibility with reference to material removal rate, surface roughness and surface hardness. Various physical, chemical and thermal properties of selected biodielectric fluids are listed in Table 3.

Conventionally, EDM process is performed by submerging the workpiece into the dielectric bath. However, as hydrocarbon and synthetic dielectric fluids are volatile and exposed to intense heat, frequent topping up is required to compensate loss due to evaporation. Also, after the end of life, the entire volume of used dielectric is required to be changed with fresh fluids. It is uneconomical practice and harmful for operator and environment as well. In order to improve the sustainability of EDM process, harmful dielectric fluids are to be replaced with emphasis given to minimise the use of dielectric by supplying dielectric fluids using different methods like side jet flushing, submerged flushing, spray/mist flushing as shown in Fig. 9.

The experiments have been performed using P20 Plastic Mould Steel with Electrolytic Grade Copper. Independent process parameters were current, pulse-ON time, pulse-OFF time and gap voltage. Table 4 shows the process parameters and its range used for the experiment.

Surface roughness (SR) and surface hardness (SH) have been used as the response parameters. Lower SR is desirable for economical production as higher SR demands more subsequent surface finishing operations to be performed which adds cost to the material processing. Higher SH is desirable for improved wear resistance of the surfaces to have enhanced life of dies, punches and toolings. Average surface roughness (Ra) was measured using surface roughness tester (Make: Mitutoyo,

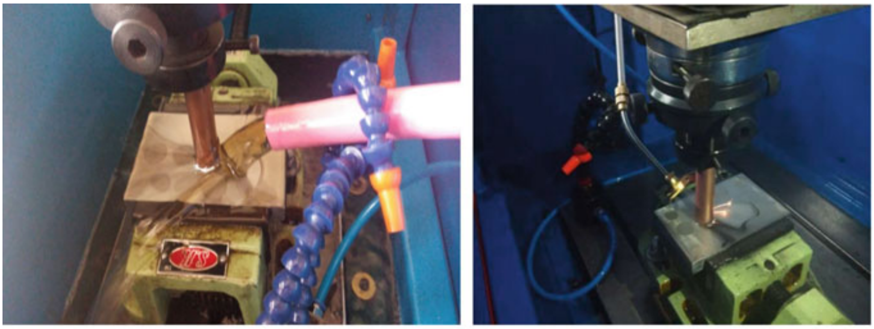
Table 3 Physical, chemical and thermal properties of selected fluids

Sr. no.	Properties	Test procedure	Kerosene	Jatropha oil (BD1)	Waste vegetable oil (BD2)
1	Kinematic viscosity at 27 C cSt	(ASTM D 445-2003)	1.2199	6.5836	8.8766
2	Dielectric breakdown voltage (BDV) kV (rms)	ASTM D 877-2000 Procedure-A	48	26	35
3	Relative permittivity (dielectric constant) at 27 C	ASTM D 924-2003	2.113	3.238	3.367
4	Density at 27 °C mg/ml	ASTM D1298-1999	802.3	870.2	870.2
5	Total acid number mg KOH/g of oil	ASTM D 974-2007	0.02	0.07	0.09
6	Flash point (COC), °C	ASTM D 92-2002	54	170	158
7	Copper strip corrosion test at 100 C for 3 h	IP: 154/78	L1a	L1a	L1a
8	Total carbon (% w/w)	ASTM D 5291	92.38	85.32	89.53
9	Oxygen content % w/w	ASTM D 5599	0.05	1.11	0.09
10	Thermal conductivity (W/m K)	ASTM D2717-95	0.129	0.147	0.154
11	Specific heat (kJ/Kg K)	ASTM D2766-95	2.20	1.90	1.67

Japan). Surface hardness was measured using portable hardness tester (Make: Wilson, Germany). Scanning electron microscope (SEM) (Make: Pemtron Corporation, Korea) with energy-dispersive spectrometer for X-rays (Make: Oxford Instruments, UK) was used for elemental analysis and structural analysis of the machined surface.

5 Performance Analysis of Biodielectric Fluids for EDM

The technical feasibility of biodielectric fluids is investigated for EDM process with jatropha oil, waste vegetable oil-based derivatives. The performance results are shown in Fig. 10a–d and discussed in the section given below.



(a) Side Jet Flushing (b) Spray or mist flushing

(c) Spray flushing (d) Submerged EDM

Fig. 9 Methods of dielectric supply

Table 4 Experimental parameters and its levels

Parameters	Levels
Pulse current (A)	3, 6, 9, 12, 15, 18
Pulse-ON time (μs)	21, 50, 100, 200, 400, 600
Pulse-OFF/interval time (μs)	6, 11, 20, 30, 40, 75
Gap voltage (KV)	30, 40, 50, 60, 70, 80
Polarity	Positive (electrode +ve)
Machining time (min)	10
Flushing type	Single jet side flushing
Duty factor (%)	60–70

5.1 Effects on Material Removal Rate (MRR)

MRR is machining time per unit volume of material removal which is directly related to the production cost. Higher MRR indicates improved productivity and economical production. Moreover, for the same energy input, higher MRR indicates better energy utilisation ratio. Minimum waste of energy and resources also contributes to increased sustainability.

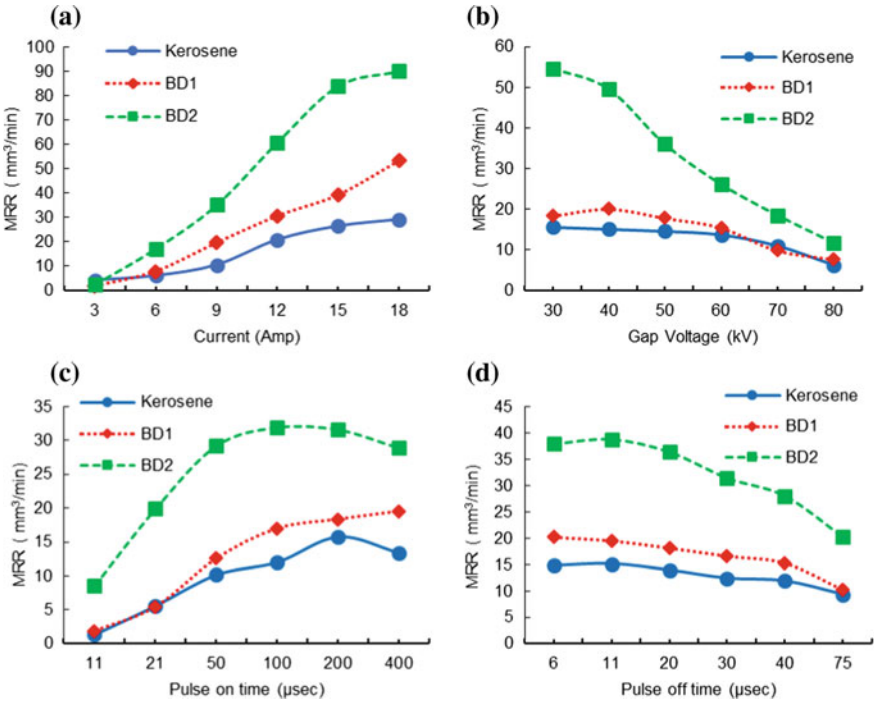


Fig. 10 Effect of **a** current, **b** gap voltage, **c** pulse-ON time and **d** pulse-OFF time on MRR

Parametric trends indicate that for any current value, highest MRR has resulted in waste vegetable oil (BD2) followed by jatropha oil (BD1) while kerosene resulted in lowest MRR as shown in Fig. 10a. This can be attributed to lower breakdown voltage and higher oxygen content of BD1 and BD2 compared to kerosene. Low breakdown voltage prolongs the sparking time and high oxygen content generated higher average plasma temperature, which in turn results in efficient sparking cycles [25, 40]. The combination of higher viscosity and higher thermal conductivity of BD1 and BD2 restricts plasma channel expansion to narrow area and increases the spark energy density [41] which facilitates higher melting and vapourisation. Furthermore, MRR also increases due to higher oxygen content which helps in uniform dispersion of discharge energy [42]. Because of higher thermal conductivities of biodielectrics than kerosene, heat possessed by molten debris globules, electrode and work material is taken away as rapidly as possible to ensure fresh sparking environment for subsequent sparks.

From Fig. 10b, it can be observed that MRR decreases, with an increase in gap voltage for all the dielectrics. Increase of the gap voltage widens the sparking gap. Therefore, the spark energy density decreases which leads to low MRR. The decreasing trend is attributed to the fact that lower gap voltage indicates lower sparking gap, rapid voltage built up across the gap allows earlier dielectric breakdown, and hence material removal starts at an early stage of sparking cycle. Because of better energy distribution and increased sparking efficiency, more amount of material is removed. However, with increasing gap voltage, delay in dielectric breakdown confines spark energy and results in poor spark efficiency which decreases MRR. Higher MRR for BD1 and BD2 is due to lower breakdown voltage, which allows longer sparking cycles. Furthermore, early breakdown and higher oxygen content maintain higher temperature to remove more material [41]. Substantially higher MRR is reported for BD2 followed by BD1 and lowest for kerosene. This is attributed to the reason that at same gap voltage level (sparking gap), BD2 has longer effective material removal cycles than kerosene, and also higher density and thermal conductivity result in higher MRR. Longer and effective material removal cycle results in better energy distribution because of confined discharges due to lower breakdown strength and higher viscosity.

Figure 10c shows the influence of pulse-ON time (T_{on}) on MRR. The behaviour of biodielectric fluids for the influence of T_{on} on MRR is well in line with that of kerosene and commercial grade EDM oil as reported in the literature [43–53]. Increase in T_{on} indicates longer spark duration and more time for melting and evaporation cycle. It results in high MRR for all the dielectric fluids [54, 55].

With an increase in T_{on}, pulse discharge energy is available for a longer time, allowing deep energy penetration into the work material surface leading to large crater formation, which eventually results in higher MRR. But for high pulse discharge time, work particles which come out from the crater did not get effective expulsion and hindered the erosion phenomenon resulting in lower MRR. The amount of molten material which can be flushed away at the end of each discharge is dependent on the plasma flushing efficiency. Plasma flushing efficiency decreases as T_{on} increases. The reason for this phenomenon could be justified as increase in T_{on} caused decrease in the energy changing rate and increased plasma diameter. Lower average temperature of the plasma channel decreases the pressure in the gap and its pulsating nature. So, as per the mechanism of bulk boiling phenomena, molten material is ejected from the molten material crater at the end of discharge decrease [56]. As T_{on} increases, the plasma channel becomes wider and positive ions become more active to attack the workpiece surface. This causes improved melting and evaporation and increased MRR. However, with further increase of T_{on}, the energy transferred to workpiece surface reduces and decreases MRR gradually [57].

Figure 10d indicates that MRR decreased for all the fluids with increase in pulse-OFF time (T_{off}). Moreover, the trends of the fluids are well in line with that of kerosene and commercial grade EDM oil reported [46–48]. High T_{off} results in less energy transfer per pulse and narrow plasma channel. Therefore, less area will be available for bombarding of ions on the workpiece [50]. Furthermore, high T_{off} facilitates proper deionisation of dielectric fluid which increases the energy requirement for reionisation of dielectric for the next cycle [49]. Because more energy is expensed in reionisation of dielectric fluid, less energy is left for melting and vapourising of material, which tend to reduce MRR [42, 50]. Therefore, MRR decreases due to less spark energy available for melting and vapourisation of the material.

Comparative trends of the biodielectric fluids indicate that for the same value of T_{off}, BD2 produced significantly higher MRR followed by BD1 and the lowest for kerosene. This is attributed by the reason that at the same pulse pause duration, higher viscosity and higher thermal conductivity of BD2 and BD1 result in intense and confined plasma channel [41]. This, in turn, resulted in higher MRR for BD2 followed by BD1 and kerosene. Moreover, higher breakdown voltage and higher viscosity of BD2 demand more energy for repetitive reionisation of dielectric for material removal. Hence, results which in turn, produces lower MRR than BD2.

5.2 *Influence of Current on Surface Roughness and Surface Hardness*

Surface roughness (SR) is associated with an average roughness of the surfaces produced, and it is related to surface quality generated during machining. Lower SR is desirable for better accuracy and tribological performance; lower SR is desirable to maintain a lubricating layer for a longer period to have longer service life. Higher surface hardness (SH) is desirable for improved wear resistance of the surfaces which produces increased life of dies, punches and toolings. This Comparative study is intended to analyse the influence of current on the response behaviour of SR and SH.

Figure 11a shows that SR increases with current for all the fluids. BD1 generates low SR than kerosene for the selected range of parameters. However, BD2 generates low SR at higher current values. BD1 results in 23% lower SR than kerosene (77%), while BD2 produced 5% higher SR than kerosene. Figure 11b shows that with an increase in current values, SH reduced for all the dielectric fluids except at 18A. BD1 results in 6% higher SH, while BD2 produces 13% lower SH than kerosene (87%) under the influence of current.

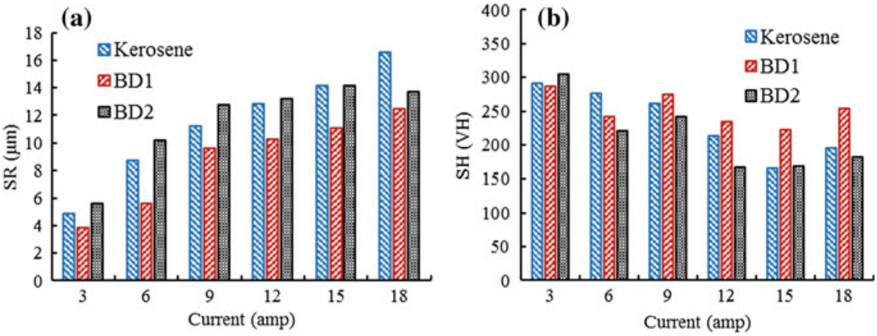


Fig. 11 Comparative analysis of influence of current on **a** SR and **b** SH

5.3 Influence of Pulse-ON Time on Surface Roughness and Surface Hardness

Figure 12a shows the relative influence of T_{on} on the SR for different dielectric fluids. It can be seen that with an increase in T_{on}, SR increases for all fluids. However, BD1 produces lower SR while BD2 results in higher SR than kerosene. Comparative analyses indicate that BD1 produces 13% (87%) and BD2 generated 33% higher SR than kerosene. Figure 12b shows the relative influence of T_{on} on SH for different dielectric fluids. It is seen that with an increase in T_{on}, dielectric fluids produce an overall decreasing pattern of SH. However, BD1 produces 7% higher SH, and BD2 produces 12% (88% to kerosene) lower SH than kerosene.

5.4 Metallurgical Structure Analysis

Surface integrity and characteristics of the machined surfaces are to be analysed using SEM and EDS analyses. Presence of oxide layers, microcracks, decomposition products on the machined surface require post-EDM operations on the work material which affect productivity by demanding more energy and resource consumption. It also helps to determine the quality of the dielectric fluid during the process and helps to determine the control the dielectric quality for the safe disposal of waste dielectric fluid.

During EDM process, the material gets transferred between electrodes in solid, liquid and gaseous states simultaneously due to the high thermal state of the process [58]. Due to the possible addition of compositional elements from electrode material, dielectric decomposition and elemental segregation in the crater, resolidified deposits and white patches may exhibit the change in the surface composition of the material.

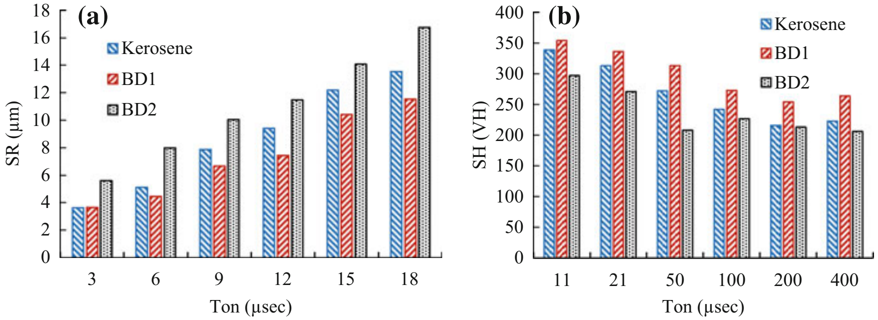
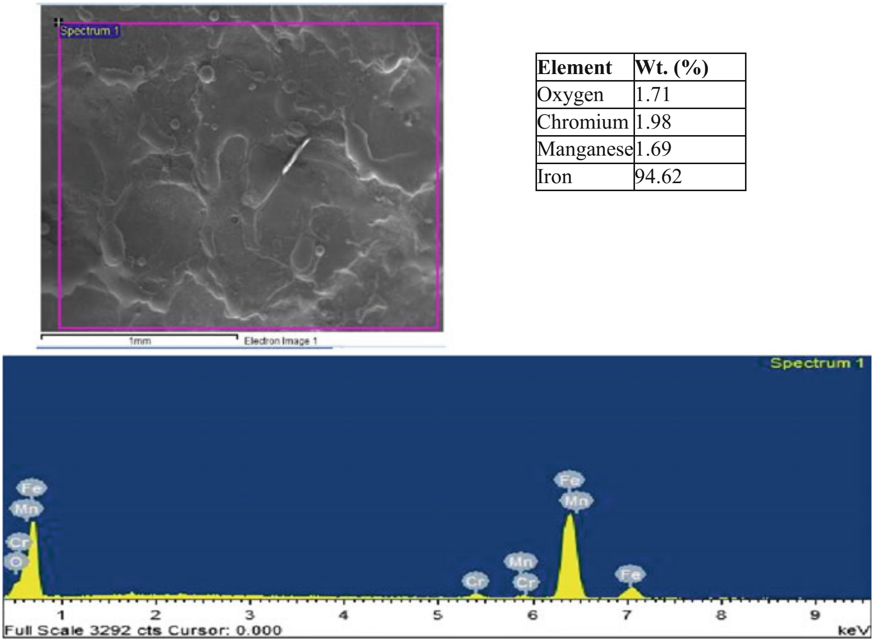


Fig. 12 Comparative analysis of influence of pulse-ON time on **a** SR and **b** SH

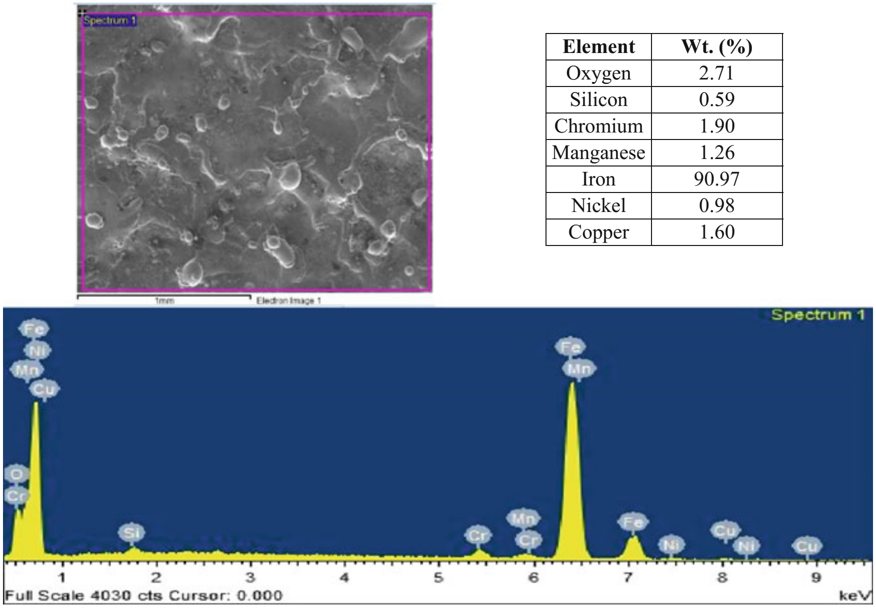
EDS micrographs are taken at 60x magnification for 2 × 2 mm area on the specimen, which is used to measure the elemental spectrum and element content. EDS micrographs and spectrums of the surfaces machined with kerosene, BD1 and BD2 at current—18 A, T_{on}—200 µs, T_{off}—20 µs and GV—50 kV are shown in Figs. 13, 14 and 15.

EDS indicates the presence of oxygen content in all three samples including kerosene. It is an indication that at higher energy state, work material would have undergone oxidation due to the decomposition of dielectrics and forms oxides on the material surface [59]. Moreover, a correlation between higher oxygen content and lower iron content has been found in all the samples. It is an indication of the presence of iron oxide in all the three samples machined. Moreover, the presence of copper particles has been traced for BD1 and BD2 samples which indicate migration of copper from the electrode to workpiece surface. At higher energy state, high oxygen content and thermal conductivity of BD1 and low specific heat of BD2 would increase the average temperature of the plasma channel. Higher average temperature might have allowed migration of copper elements from an electrode to a work surface. The samples machined with BD1 and BD2 have shown higher nickel content indicating transfer of nickel from tool electrode. Smaller discharge time and higher viscosity of BDs would increase the thermal load on an electrode to



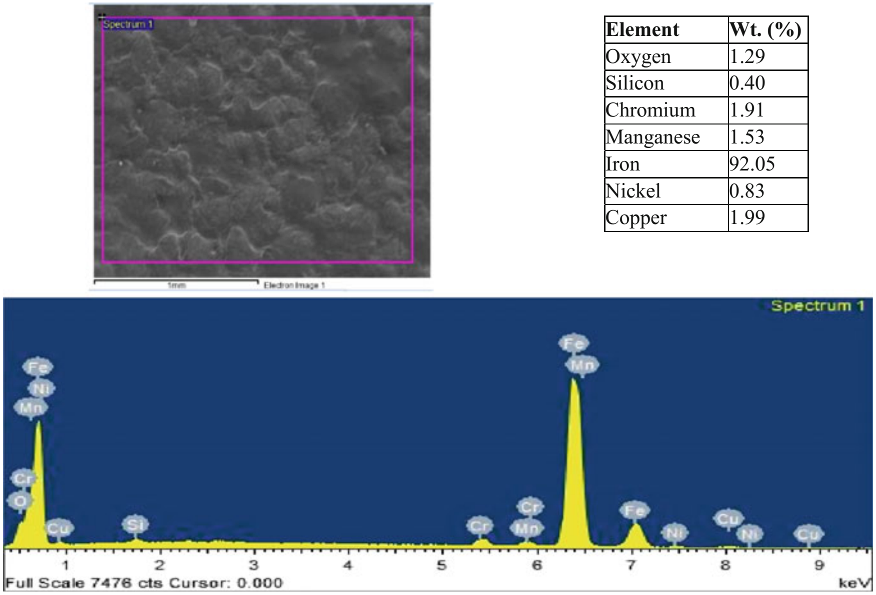
Element	Wt. (%)
Oxygen	1.71
Chromium	1.98
Manganese	1.69
Iron	94.62

Fig. 13 EDS micrograph, elemental spectrum and element content for kerosene at current—18 A, T_{on}—200 µs, T_{off}—20 µs and GV—50 V



Element	Wt. (%)
Oxygen	2.71
Silicon	0.59
Chromium	1.90
Manganese	1.26
Iron	90.97
Nickel	0.98
Copper	1.60

Fig. 14 EDS micrograph, elemental spectrum and element content for BD1 at current—18 A, T_{on}—200 µs, T_{off}—20 µs and V—50 V



Element	Wt. (%)
Oxygen	1.29
Silicon	0.40
Chromium	1.91
Manganese	1.53
Iron	92.05
Nickel	0.83
Copper	1.99

Fig. 15 EDS micrograph, elemental spectrum and element content for BD2 at current—18 A, T_{on}—200 µs, T_{off}—20 µs and V—50 V

erode at a rapid rate, which allows nickel ingression on material surface from an electrode.

During EDM process, the material removal takes place by melting followed evaporation assisted by flushing using dielectric fluid. The area from where material is removed from workpiece forms a crater and spherical debrises. The size, shape and nature of the crater govern the surface quality produced. Analysis of the surface generated using biodielectrics and kerosene is shown in Fig. 16.

The SEM micrographs of the EDMed surface reveal valuable information about the surface modification, structural changes and crack formation in the workpiece. EDM surface produces irregular topography and defects such as globules of debris, spherical particles, varying size craters and microcracks. The machined surface is characterised by an irregular fused structure, beads of debris, shallow craters and micropores [59, 60]. The dark area represents the presence of deep craters, the greyish area represents the presence of shallow crater with heat-affected zone,

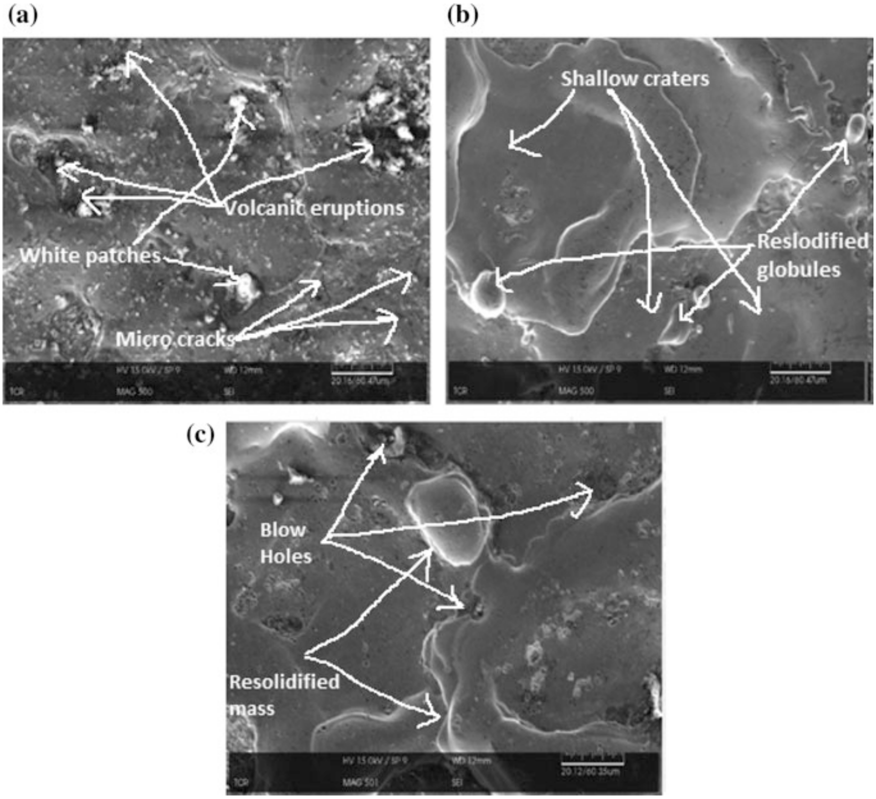


Fig. 16 SEM micrographs for **a** kerosene, **b** BD1 and **c** BD2 at current—18 A, T_{on}—200 µs, T_{off}—20 µs and V—50 V

and the bright area represents the resolidified mass. Moreover, black spots indicate the carbides presence and white spots indicate oxides [61, 62].

At higher pulsed current, the dielectric undergoes frequent cracking and more melt expulsions; also, the severe impact of the discharge energy on the material surface increases the SR [63, 64]. Micrographs of kerosene revealed more darkish area, large number of blowholes, narrow and deeper craters shown in Fig. 16a. A continuous conglomerate of resolidified molten material created an uneven surface morphology which might have resulted in higher SR. The existence of volcanic eruptions and the uniform greyish area indicated that material removal phenomenon would have existed for a limited period only and hence results in uneven melting and produces more SR. Also, the presence of microcracks has been observed.

However, SEM micrographs of the BD1 and BD2 indicated lesser darkish but more greyish area indicating shallow and wide craters, which could have resulted in lower SR as shown in Fig. 16b, c, respectively. For higher current, SEM micrograph of BD1 represented an interesting phenomenon. More material was melted but splashed could not been detached and resolidified covering a larger area. SEM image of the BD2 represents river bed-type wide craters with adjacent resolidified globules, which might have resulted in higher SR.

6 Conclusions and Future Directions

Vegetable oil-based biodielectric fluids are operationally and technically feasible alternatives to conventional and non-sustainable hydrocarbon-based dielectric fluid for EDM process. The tested biodielectric fluids are clean, green, safe and sustainable solution to improve sustainability of EDM process by improving environmental friendliness, operational safety and personal health issues of the process.

Adopting sustainable manufacturing practices is a proven major socio-cost benefit component for manufacturing industries due to growing awareness amongst society. It would also help to implement ISO 14000 series environmental management standards in EDM industry and carry out life-cycle impact assessment for parts manufactured by EDM process.

It is observed from the reported work that very limited research has been done related to sustainability issues of EDM process. Some of the relevant areas for sustainable EDM operation are given below.

1. *Selection of tool, workpiece and dielectric fluid*:

It plays an important role in the emissions and wastes generated. A systematic study on prediction and characterisation of emission products and other wastes is necessary for keeping their level within the limit using optimum process parameter setting.

2. *Evaluation of operator risk*:

EDM operators are susceptible to fire explosions, toxic and hazardous wastes which increase the operator risk potential. Hence, a systematic and scientific model is required to set, monitor and control in-service parameters so that operator risk can be minimised by keeping the risk potential parameters below its set limit.

3. *Life of dielectric fluid*:

Quality of dielectric fluid deteriorates with time and usage. Toxicity of wastes and emissions increases with prolonged use. Study of the effective life of dielectric fluid will help to avoid inefficient machining operation and health-related issues.

4. *Power consumption*:

Very high amount of energy ($\sim 70\%$) is consumed by various dielectric circulatory systems in handling and conditioning. Hence, optimisation of power consumption will reduce the energy usage.

5. *Environmental impact*:

Impact on environmental by wet, dry and near-dry EDM needs to be assessed. It will ensure the least life-cycle cost and minimum environmental impact.

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Energy-Efficient Casting Processes

Emanuele Pagone, Konstantinos Salonitis and Mark Jolly

Abstract Metal casting is one of the most energy-intensive manufacturing processes that have developed along the evolution of mankind. Although nowadays its scientific and technological aspects are well established, in the context of future resource scarcity and environmental pollution pressures, new studies appear necessary to describe the "foundry of the future" where energy and material efficiency are of great importance to guarantee competitiveness alongside environmental protection. In this chapter, both managerial and technical good practices aimed at implementing energy-efficient casting processes are presented alongside a few examples. The "Small is Beautiful" philosophy is presented as a systematic approach towards energy resilient manufacturing and, potentially, sustainability in the long term. Thus, this chapter aims at providing an overview of the different aspects comprising the state of the art in the industry and examples of research themes in academia about energy-efficient casting processes.

Keywords Casting · Foundry · Sustainability · Energy efficiency

1 Introduction

Shape casting is a manufacturing process characterised by its energy-intensive nature (i.e. the use of a large amount of energy per unit product for the core activities) and a long tradition where technological improvements progressed alongside the history of mankind [1]. This work aims at discussing the future of the foundry industry while dealing with resource scarcity and environmental pollution pressures: two important future challenges. Energy efficiency addresses, in the first

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instance, these challenges although a more comprehensive approach is envisaged in the longer term where sustainability is implemented in metal casting and will include economic, environmental, and societal aspects [2].

The UK metal casting industry can be broadly representative of the energy efficiency in a typical developed country with £2.2 billion turnover and 17,000 jobs [3] in 422 foundries (intended as production units active in 2015) [4]. In comparison, for example, France and Germany show a comparable number of production units (namely, 413 and 588) [4]. Furthermore, the ratio of inhabitants per metal casting production unit I_f results fairly constant among several developed countries like the mentioned UK, France, Germany, USA and Canada (Table 1).

A study conducted in the UK showed that although aggregate data of energy and material consumption is recorded in foundries, most often there is no protocol to monitor the energy consumption along the process [7]. The mentioned aggregate data are usually used to control utility billing, to analyse broadly the performance of the plant, and to learn what practices are more effective. One of the main reasons for such practice, as identified by the mentioned study, is that a significant number of foundries do not measure the energy consumption of their installed systems comprehensively [7].

On the other end, the UK Government (through the Department of Energy and Climate Change) has set a target for the foundry industry in terms of specific energy consumption of 25.7 MJ/kg by 2020 although the average figure for the sector in 2013 was 55 MJ/kg [7]. Significant improvement in terms of energy efficiency is thus expected in the short term by the sector.

In this chapter, the fundamentals of a generalised cast shaping process are presented in Sect. 2. Sections 3 and 4 will discuss how energy efficiency can be achieved though (respectively) management practices and technological improvements. Finally, Sect. 5 will present real-life examples of energy-efficient metal casting and Sect. 6, the “Small is Beautiful” philosophy, is developed taking into account material and energy resilience in casting manufacturing processes. The content makes the reader able to understand the fundamental problems, the

Table 1 Thousand of inhabitants per metal casting production unit I_f in some developed countries (2015 data)

Country	Population (thousands)	Number of metal casting plants	I_f
UK	65128.86	422	154.33
Germany	81686.61	588	138.92
France	66624.07	413	161.32
USA	320896.62	2380	134.83
Canada	35848.61	183	195.89
Italy	60730.58	1085	55.97
Spain	46447.7	128	362.87
Japan	127141	2085	60.98

The UK appears to be broadly representative of developed countries with a significant foundry industry showing a comparable I_f factor to Germany, France, the USA and Canada
Data Source Population [5], plants [6]

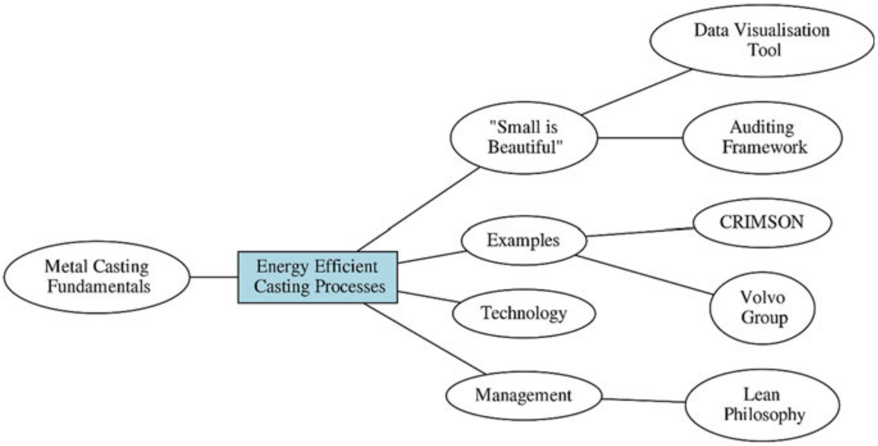

Fig. 1 Main sections comprising this chapter

industrial state of the art and examples of the on-going academic research about energy-efficient casting processes. Figure 1 summarises broadly the content of this chapter.

2 Metal Casting Fundamentals

Modern metal casting includes different types of processes with specific characteristics that can be classified in different ways. One example of broad classification is identifying two main groups of processes based on the condition whether the liquid metal fills the mould with or without the effect of additional pressure exerted externally (besides gravity) [1] or if the mould is expendable or permanent [8, 9]. Analysing all the casting processes from an abstract point of view, a number of generic, common sub-processes can be identified as depicted in Fig. 2.

The first process step is melting the charge and any other forms of recycled metal from later processes. A proportionally large amount of energy [10] is required to

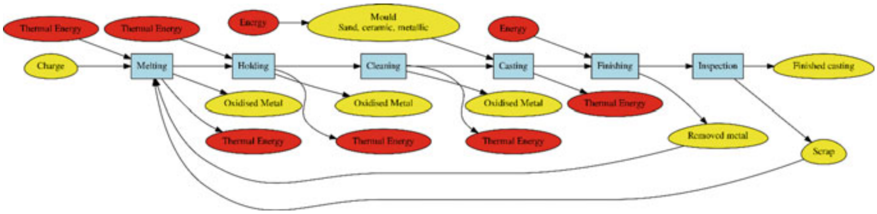

Fig. 2 Generalised shape casting process steps (in light blue) with the relevant main material (in yellow) and energy flows (red)

bring the metal beyond the melting point to a "superheat temperature" that is usually a compromise between optimal fluidity, a sufficient margin to certainly fill the mould before solidification and generation of oxides or dissolved gases [1].

Another energy-intensive process (although not always necessary) is holding the liquid metal to accommodate different production rates or to allow the cleaning of the melt from impurities, oxides and dissolved gases. Although cleaning is conceptually another process, it may take place in the holding furnace. In parallel, a mould (made of sand, metal or ceramic material) needs to be prepared for the casting phase when the liquid metal is poured into it. During the previously described steps, a non-negligible amount of thermal energy is rejected into the environment alongside a variable quantity of metal oxides that inevitably are generated.

With "finishing", a number of possible operations are intended. Finishing includes certainly the removal of the gating, runners and risers (i.e. fettling) necessary by design to create a sound product with minimal shrinkage and inclusion defects. The relevant metal removed may be recycled in the melting furnace. However, also machining is sometimes performed at this stage of the process and is another example of operations included in the general definition of finishing.

Before the finished product can be shipped, it is usually inspected in different ways with a relevant fraction of scrap that can be internally or externally recycled.

3 Energy Efficiency Through Management

As well as technical means (described in Sect. 4), management good practices are another, complementary, effective way to reduce waste and improve the metal casting process in terms of energy efficiency. This section presents initially the management practices in the context of foundries and then focusses on the discussion of the promising lean-thinking philosophy. Finally, practical examples are provided in the last subsection.

3.1 Management Practices in Foundries

Profit margins are usually relatively small in the metal casting industry, limiting the opportunities to invest in more efficient equipment [11]. For this reason, better foundry management practices are often even more desirable than technological improvements. Moreover, although significant research efforts have been directed towards energy efficiency measures, there is still a substantial potential in research about management of resource efficiency [12]. Similar energy efficiency management practices are applicable to companies of different sizes, but the relevant skills available and goals determine a different decision-making process.

Smaller firms (that represent a significant proportion of foundries) have limited knowledge of energy efficiency measures [13, 14], and small and medium enterprises (SMEs) do not consider investments with a payback time longer than 2–3 years [14]. On the other hand, larger enterprises have been found to struggle more to effectively implement energy management practices in general [15]. Barriers hampering such enhancements comprise difficulties to easily communicate with the high-level management and complicated production processes and organisational structures [15].

Beyond these considerations, it appears that management practices in energy-efficient casting are not well developed. For example, a research conducted in Sweden showed that almost half of the Swedish foundries do not have a long-term energy plan and that energy management can be considered successful only in about one-quarter of them [16]. Next section will discuss one prominent management technique significantly popular also within foundries, the lean manufacturing philosophy, and it will be followed by some examples of its practical implementation in the metal casting industry.

3.2 Lean Manufacturing Concepts in Foundries

The introduction in the scientific literature of the lean manufacturing philosophy can be traced back to 1990 with a study by Womack in the automotive field where a set of techniques adopted by Toyota Motors, focussed on quality and productivity, were highlighted [17]. This philosophy that is meant to encompass every part of the enterprise aims at boosting competitiveness reducing costs, maximising quality and minimising waste and lead time [18]. Waste is considered under several different aspects according to the "lean" point of view: defects, waiting, unnecessary processing, overproduction, movement, inventory, unused employee creativity, and complexity [19]. All these aspects are targeted by lean thinking.

The further popularity of the lean paradigm in many different types of industry and service has as a common trait, besides the mentioned principles, the "lean culture" that must permeate fully the enterprise (and the mindset of all its employees) rather than being a mere set of tools to be applied on the shop floor [20].

In the context of the foundry industry, it is possible to identify all key aspects of the lean philosophy. Considering waste, for example, defects are products scrapped, replaced or reworked not only during the final inspection phase, but anywhere along the process described in Fig. 2. Waiting can be represented by the holding phase if it has been introduced to accommodate capacity bottlenecks, but generally speaking it can be the result of unbalanced lines, stock-outs or equipment downtime [19]. The typical unnecessary processing in metal casting is the fettling of sub-optimal gating and risers or as a result of far from net shape forming processes. Overproduction can be generated by the temptation to take advantage of economies of scale and manufacture products for which there are no orders to avoid the long set-up times (with the associated costs and additional energy consumption) required in foundries with intermittent production. Excessive movement can occur in foundries with sub-optimal layout that can waste substantial amounts of energy in sensible heat while increasing also the lead time. Inventory “waste” is typical of traditional foundries where a large amount of stock is present [21, 22] mostly to avoid intermittent production and its long set-up times. The lack of involvement of employees and their creativity is a general problem that has no peculiar manifestation in metal casting industries. Holding time can be in some cases a good example of complexity “waste” in foundries.

Moreover, efficient production and environmental impact (of which energy consumption is a considerable contributor) are linked together by the energy-intensive nature of the process that is also strictly regulated [11]. Thus, although the implementation of environmental-friendly technologies does not add direct value to the product (and, for this reason, it would be in contrast with the lean philosophy) [23], the synergistic role of lean and environmental actions has been proven successful for the competitiveness of foundries [24]. The combined approach towards quality and environmental protection has been observed also by statistical observations where adopters of the ISO 9000 standard were more inclined to implement also ISO 14000 (that standardises Environmental Management Systems—EMS) [25]. Moreover, in 2011, ISO 50001 was published to establish the requirements for energy management systems (EnMSs) and it was structured in a similar way of ISO 14001 to allow the potential integration of EnMSs within EMSs [26]. The implementation model of EnMSs follows a simple sequence of tasks in a flow chart fashion, as shown in Fig. 3.

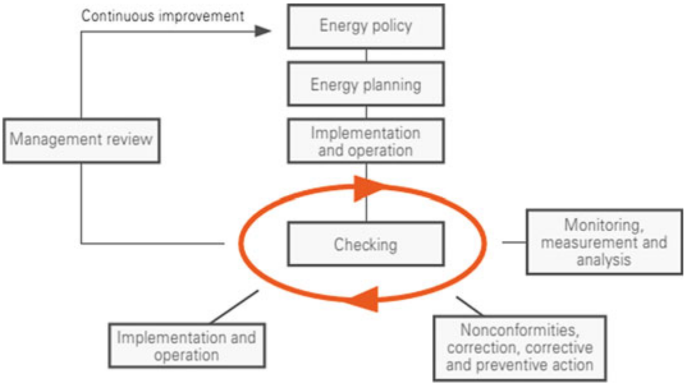

Fig. 3 Implementation model of ISO 50001:2011 [26]

3.3 Examples of Lean Implementation in Foundries

The practical implementation of lean philosophy in metal casting industries can vary significantly considering the various unique combinations of products and processes typical of this industry. For example, Torielli et al. proposed a framework for the synergic implementation of lean and environmental (i.e. "green") practices [11]. Figure 4 shows the relationship between the different elements comprising the framework.

Consistently with the "cultural" spirit of the lean paradigm, at the base of the framework sits the organizational philosophy that must involve employees at any level and must become the natural mindset. Four pillars are based on the mentioned philosophy: throughput improvement, energy efficiency, innovative technology and community partnerships.

Improved throughput is achieved minimising scrap and processes that do not add value to the product, e.g. making scrap repair or welding unacceptable and, thus, unavailable in the foundry. This does not only streamlines the process steps (reducing operating costs, energy consumption and operating time) but also promotes the early detection of issues that generate scrap. Another means to improve throughput is the maximisation of operational material efficiency (OME) that is the ratio between the mass of shipped castings to the customer over the mass of melted metal over a representative time span [27]. Such maximisation can be achieved making sure that the process is under control and designing to the nearest net shape possible, optimising size and location of risers and gating [28, 29]. To accomplish this last task, accurate computer simulation programs are very useful. Any improvement of OME will not only have a positive impact on the finishing and melting phases of the foundry process but, in an environmental perspective,

Fig. 4 Arrangement of the elements comprising a framework to implement lean and green practices [11]

also reduce the embedded energy of the final product that includes also the energy necessary from mining onwards [11].

Energy efficiency can be pursued tracking the energy flows in the process. Interestingly, it has been confirmed that improvements in the energy consumption, alongside other lean manufacturing measures, determine a reduction in costs [14, 30].

Innovative technologies may be necessary to improve significantly the added value or the efficiency of the foundry (see Sect. 4). Financial sustainability of such measures is sometimes a barrier to their implementation or an important factor in the decision-making process among a number of options [11].

Community partnerships are described as the process with the highest potential concerning environmental performance. They can help meet regulations as well as identify synergies with other industries that use waste products for their processes [11].

Another example of implementation of the lean philosophy in a foundry has been described by de Oliveira and Pinto [31]. The plant considered is a sand casting process melting ferrous alloys located in Brazil and producing parts for infrastructures, mining and cement industry as well as transport. After having mapped the process, a model in simulation software has been created and validated against the mass of castings produced in one month. Then line balancing and layout improvements were sought using the created model [31].

Also Hari Priya et al. applied lean principles to a sand casting plant aiming at reducing lead time [32]. The goal has been reached using value stream mapping (VSM): a material flow representation that highlights the locations where waste is produced [11]. VSM usually does not represent waste streams or ancillary material flows although it includes also the flow of information [11, 33]. When the full material streams in conjunction with the energy flows are represented, VSM takes the name of Green Value Stream Mapping (GVSM). This is a powerful tool to understand and analyse thoroughly the process or to communicate with partners or stakeholders. A further extension of GVSM would be the inclusion of embedded energy streams that allow to perform lifecycle analyses [11].

The analysis by Hari Priya et al. implemented also 5S in the foundry [32]. 5S contributes to the lean paradigm in organising systematically every part of the shop floor (i.e. “the right thing in the right place at the right time”) [11] to easily identify waste as well as make evident any oversight or malfunction. 5S stands for Sort, Straighten, Shine, Standardise and Sustain (although also Safety it is usually added as sixth element) [11].

Using VSM, 5S Hari Priya et al. identified the opportunity to eliminate a thermal cycle aimed at stress relief and extended the cooling time of the castings in the mould. An improvement in rationalising the number of material grades available was also identified [32].

From the examples presented, it is clear that lean manufacturing techniques are effective and essential contributors to the development of an energy-efficient foundry industry that preserves its competitiveness. The various lean tools can be chosen and adapted (also in the form of comprehensive frameworks) to the large variety of unique implementations of metal casting enterprises, maximising the benefits of technological improvements (if present) that will be described in the next section.

4 Energy Efficiency Through Technology

Plant technical improvements are sometimes one of the first methods considered to increase energy efficiency or comply with environmental regulations. Although it is possible to obtain significant improvements by means of management actions in the foundry (as exemplified in Sect. 3), there are cases where technical enhancements are necessary to achieve certain levels of energy efficiency.

With reference to Fig. 2, the first main process in metal casting is melting. Furnaces usually adopted to perform this task are cupola, induction, gas tower or gas crucible furnaces. Cupola furnaces extract heat from the combustion of coke, whereas electric induction furnaces induce a variable magnetic field through the charge that generates eddy currents dissipated into resistive heating. Finally, gas tower and gas crucible furnaces are both based on the combustion of natural gas with the former designed to accommodate higher production rates. The different types of furnace determine a different impact on the total energy consumption. For example, a study performed in Italy and focussed on the steel industry has revealed that cupola furnaces contribute to about 50% of the overall foundry energy consumption, whereas electric induction furnaces account up to 70% [34]. At the same time, surveys and case studies have confirmed that induction furnaces are more efficient than cupola furnaces in the steel industry [10, 35].

A fundamental step of the metal casting process is pouring molten metal into the mould to shape it as necessary. Liquid metal must be brought at the correct temperature to ensure good fluidity and adequate filling of the mould. Both liquid metal quality and the pouring technique are important aspects to control, minimise or eliminate defects in the castings [1]. Metal fluidity is generally proportional to the liquid temperature, and the necessary “superheating” (i.e. heating the alloy beyond its liquidus temperature) must be reached before pouring. Typical problems stemming from insufficient superheating are the incomplete filling of the mould, misruns, blow holes and chills. However, too high superheat temperatures will determine excessive shrinkage of the casting, penetration of the metal into the mould (in sand casting processes), veining and scabbing [9]. An optimal superheating temperature has, thus, a twofold benefit: a reduction of defective castings and a reduction of energy consumption [34].

Considering that melting is typically the most energy consuming phase of the entire process [10], relatively small improvements determine significant energy savings. As previously explained, the superheat temperature (and the relevant fluidity of liquid metal) has a significant influence on the castings soundness, and therefore, although it has a notable impact on the energy consumption of the melting phase, it cannot be easily reduced.

Metal preheating is not a necessary step, but it can improve the energy performance of the entire process. Not only it provides a direct reduction of energy consumption [27], but also it can be used as the first, easier step to implement waste heat recovery. A typical industrial example of practices that take advantage of preheating is recovering thermal energy by cooling the hot, flue gas of the furnace to preheat the charge [27]. Usually, preheating involves relatively low-grade heat recovery that can provide a tangible benefit to the overall performance of the plant when designing the preheating and melting processes as physically close as possible.

Among the different types of melting furnaces, the electric induction is usually the most efficient with reported melting efficiencies near 75% [27]. However, coreless units are more suitable for primary melting because channel induction furnaces require a liquid metal charge [9]. Considering that a significant part of foundries is SMEs, their typical production method is batch or semi-batch production where coreless induction furnaces perform well [34]. One method to improve the efficiency of induction furnaces is increasing their operating frequency provided by the utility network, because it determines a consequent increase of power density. In turn, this enables the usage of smaller crucibles reducing heat loss.

Investing some energy (with the other relevant costs) to clean the scrap before re-melting is a good practice when considering the consequent energy savings to obtain good quality of liquid metal. In fact, the quality of material used to charge the melting furnace has been found to have an important impact on the overall energy consumption [34, 36] both by improving the furnace performance and the OME. Another good practice is to minimise the time and operations to open the furnace to reduce the sensible heat losses. Moreover, this represents another opportunity to recover waste heat [27, 34].

Similarly, the necessary cooling of electric induction furnace coils (usually at about 40–45 °C) is another opportunity to recover heat for preheating purposes. Better insulated furnaces also have considerable impact on energy consumption [34]. Correctly trained operators can also improve efficiency in the region of 10% [27].

Holding liquid metal is not necessary and depends on the plant layout and on the process. It is another energy-intensive step that requires to supply heat for a prolonged time to keep the charge at the desired temperature before pouring. Minimising the holding time is an important energy-efficient measure and, if possible, it should be brought down to zero removing this unnecessary step according to a lean-thinking approach (as given in Sect. 3.2). In the cases when it is not possible to remove a holding phase, furnaces with advanced insulating materials and well maintained can contribute significantly to reduce energy consumption [34].

In expendable mould processes, mould making requires notable quantities of energy input. It has been estimated that the whole sand system can contribute to about 20% of overall energy consumption in a foundry [34]. Improvements, such as novel sand CNC machining that does not require patterns to generate moulds [37], can clearly reduce energy consumption and cycle time. Automation is another option to improve productivity and energy efficiency keeping the process under control and potentially reducing material waste.

Fettling (i.e. removing risers and the gating system) when considered together with machining, can generate as much as 75% of the total scrap [27]. However, machining is an optional process (sometimes not carried out “in-house”), and generally, fettling dominates clearly in terms of material loss between the two phases. As discussed in Sect. 2.3, the OME has a significant impact on the energy efficiency of the process, first of all because the material removed had been already melted. Hence, any design optimisation of the risers and gating system has a significant impact on energy and material efficiency.

Also the heat treatment phase is not necessary and is dictated by the mechanical properties of the product and the foundry equipment. Also in this case, heat treatment can be carried out by third parties. There is a significant variability in the characteristics of heat treatments and the relevant energy consumption can change notably. Moreover, a sub-optimal control on this process phase can generate defects with relevant rejections [1].

As mentioned previously in this section, surface cleaning is important for the recycling phase determining significant benefits in terms of energy consumption. Moreover, this phase is necessary also to obtain the required level of quality of the finished product.

Factory services necessary to run the production are another cause of energy consumption that can be analysed [34]. Heating and cooling of the environment, compressed air systems and lighting are all common auxiliaries in foundries.

A significant reduction of energy consumption can be obtained with relatively modest improvements in these auxiliaries, despite their smaller contribution to the overall energy consumption [38]. For example, compressed air systems, although often adopted in manufacturing plants, are not well understood in terms of cost and, thus, on energy consumption [12]. Leaks are the major cause of supply losses in compressed air systems and it has been estimated that as little as 10–20% of the compressor input energy reaches the point of use [12, 34]. Improvements in this area comprise leak repair, upgrading the piping to a more efficient system or correct compressor sequencing. It has been identified that some metal casting firms do not realise the significant impact of auxiliaries on the overall performance [38].

Lighting often offers opportunities for energy efficiency improvements. Natural illumination should be maximised and the complementary role of artificial lighting should be promoted using state-of-the-art solutions like LED (that can determine up to 70–80% of reduction in costs [34]).

5 Examples of Energy-Efficient Casting Implementations

A first example of energy-efficient casting system is the CRIMSON process, currently developed at Cranfield University. The Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) process was designed with the purpose to minimise energy losses while improving the quality of the final product [39]. One peculiarity of this system is that the charge is sufficient only to fill a single mould and it is melted within a crucible in an induction furnace. Then, the crucible is quickly transferred to the computer controlled up-caster (located close to the furnace) where the mould is filled counter-gravity controlling accurately the flow regime of the liquid metal.

The system is designed for energy-efficient operations with minimal heat losses, no holding time and a high-efficiency induction furnace. The quick and simple procedure minimises oxide formation and gas dissolution that together with the controlled filling process produces castings of excellent quality as well as does not require additional steps to clean the liquid metal. Another important peculiarity of CRIMSON is the use of high-quality, pre-alloyed metal as charge. Moreover, the gating system is significantly reduced in comparison with a conventional process with no need for the pouring basin and the down sprue (Fig. 5). This turns into a significant advantage during the fettling and machining processes (as discussed in Sects. 2 and 3).

Moreover, thanks to computational fluid dynamics (CFD) simulations, it is possible to quantify and observe the advantage of the CRIMSON process in comparison to a conventional pouring method (e.g. gravity sand casting) in terms of metal flow regime while filling the mould (Fig. 6).

Volvo Group has developed an energy-efficient metal casting process tailored to produce automotive cylinder heads with ferrous alloys. A new foundry was built near Skovde (in Sweden) designed to maximise energy efficiency. “Foundry G2” has an area of 9600 m^2 with a capacity of 20,000 ton/year and 15 operators per shift [40]. The Future Process for Casting (FPC) is the name of the advanced sand casting process, patented by AB Volvo, that uses a combination of chill steel and pressurised water-cooled sand to achieve a quick and controlled cooling of the molten metal. The system keeps the mould stable to avoid defects in the cylinder-heads, whereas the pouring system is controlled by fully automated ladles. Volvo claims to increase strength of the product by 10–15% retaining good

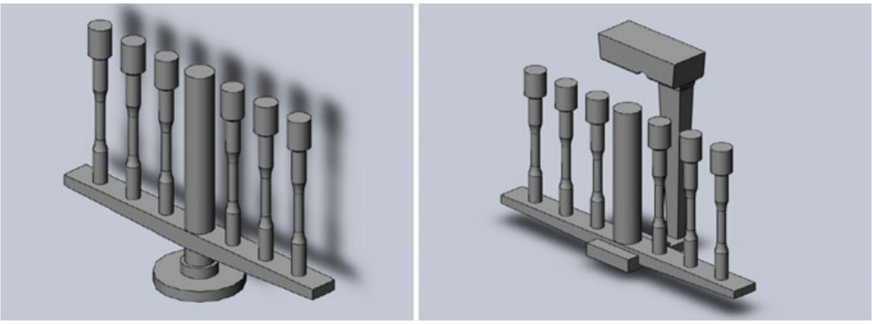

Fig. 5 Comparison of the casting systems of the CRIMSON process (left) and a conventional gravity sand casting (right) to produce a set of tensile bars [27]

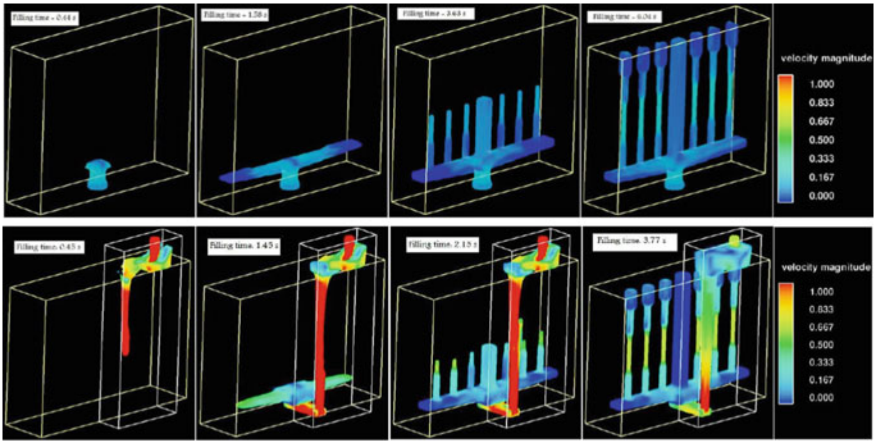

Fig. 6 Comparison of the velocity magnitude at different times of the CRIMSON process (top) and a conventional gravity sand casting (bottom) to produce a set of tensile bars [27]

castability and machinability, 85% of the core sand is recycled, and approximately 50% energy consumption reduction is obtained recycling the cooling water and the total specific energy consumption slightly above 2 MJ/kg. Such remarkable result in terms of energy efficiency is achieved thanks to a very advanced design where heat recycling does not require any extra equipment to heat the building and the choice of materials does require minimal effort for cleaning. [40]

6 “Small Is Beautiful” Approach

“Small is Beautiful” is a new philosophy that intends to tackle the contemporary challenges of the metal casting industry incorporating resource efficiency (both in material and energy terms) and flexible production since the beginning of the design process. In addition to the mentioned characteristics, other critical aspects, such as profitability and responsiveness to market needs, are considered. Energy resilience is identified as the first step to address the mentioned challenges considering the energy-intensive nature of metal casting. In the longer term, a more comprehensive and holistic approach implementing all aspects of sustainability is envisaged.

The first steps in defining this new philosophy were focussed on capturing practices and comparing energy and resource efficiency studying 80 foundries, contacting 60 and visiting 10 of them. About 100 enterprises and industry experts were interviewed, and general energy data were collected. As a result, the need for a structured energy auditing framework and an effective visualisation tool of measurements able to integrate with existing manufacturing systems has been identified [7]. A concise overview of the key aspects comprising “Small is Beautiful” follows.

The interested reader is invited to check the cited references to deepen his or her knowledge in this respect.

6.1 Auditing Framework

A complete auditing framework of the energy consumption in the plant is essential to drive the optimisation process towards energy efficiency. Usually, conventional manufacturing processes are audited measuring the energy consumption of the machine tools used that results significantly higher than the theoretical minimum [27]. Ancillary systems could increase considerably further the energy consumption, and thus, the monitoring procedure should be designed with care because it may not be possible to measure individually or in isolation such additional systems.

To address the mentioned issues, three major phases are designed (Fig. 7):

- Preparation: the audit is structured and tailored to the peculiarities of the foundry to be analysed.
- Measurement: after a calibration phase (with no actual casting happening), the measurements are collected.
- Analysis: the energy consumption of each phase is calculated and all the other indirect metrics are calculated both at local and system level.

Performing a Pareto analysis of the phases ranked according to the energy consumption (or their associated cost), it is possible to choose the areas with the highest return.

The described framework is well suited for its integration with lean philosophy tools (described in Sect. 3.2).

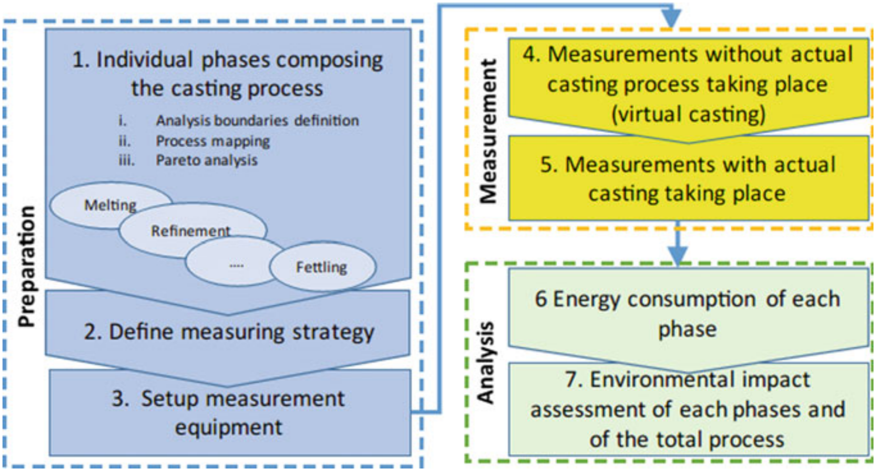

Fig. 7 Energy consumption audit framework [27]

6.2 Data Visualisation Tool

A software to visualise clearly foundry energy and material flows has been developed as a response to an industrial necessity captured within the initial activities of “Small is Beautiful”. The computer program makes possible a clear analysis of the foundry process in its entirety at a flexible level of data granularity. This analysis is intended to help decision-makers in considering different scenarios with improvements in various areas and rapidly evaluate their performance with the help of a graphical representation (e.g. using process flow or Sankey diagrams). The analysis aims also at discovering synergistic opportunities hidden in the complete production chain. Furthermore, it is possible to include in the analysis also the supply chain (e.g. mould or die suppliers, inserts manufacturers) and will be able to link to product design software [41, 42].

A general representation of the program workflow is depicted in Fig. 8 and comprises three major steps.

In the first instance, two textual input files are necessary to start with the analysis. It is compulsory for the user to prepare a file that describes the metal casting factory (called “Plant file” in Fig. 8). Optionally, some configuration features can be specified in the “Config file”, and this information will override the default settings.

A minimal excerpt of the previously defined “Plant file” (in YAML format) and of the configuration file is provided in Figs. 9 and 10. An additional graphical user interface (GUI) to substitute the textual inputs is expected to be included in future releases.

The second major step of the program workflow is the generation of an internal data structure. In this phase, the information provided in the “Plant file” is

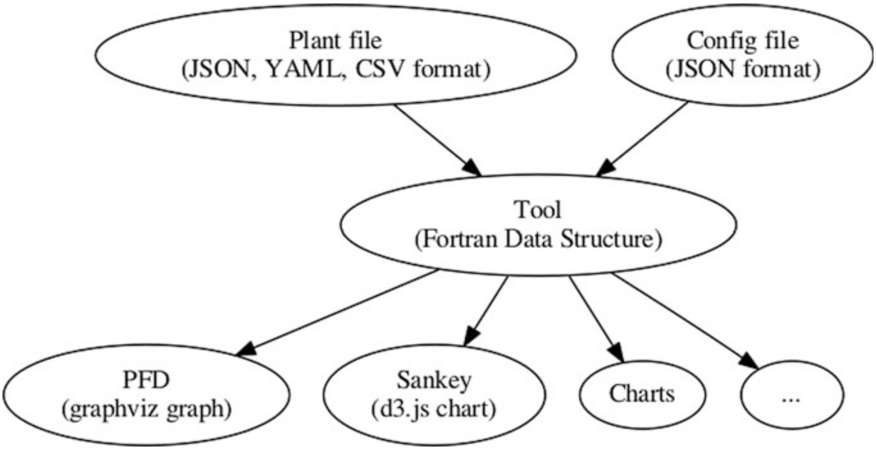

Fig. 8 High-level workflow of the “Small Is Beautiful” data representation tool [42]

Fig. 9 Excerpt of the presented tool input file describing the foundry specifications in YAML format [42]

```
...
start component: Melting Furnace
output um_mat_q: kg
output um_en_q: GJ
Components:
  - name: Melting Furnace
    flows:
      - name: Charge
        categ: mat
        dir: in
        qtity: 100
        um_q: kg
      - name: Thermal
        categ: en
        dir: in
        qtity: 20
        um_q: GJ
      - name: Oxidised Metal
        categ: mat
        dir: out
        qtity: 2
        um_q: kg
      - name: Thermal
        categ: en
        dir: out
        qtity: 10
        um_q: GJ
    next comp:
      - name: Holding Furnace
  - name: Holding Furnace
...
```

converted into a conveniently flexible format that can be efficiently handled with a programming language.

The internal data structure is used in the third, last step, to transform the information about the factory inserted by the user into different graphical outputs. The program is designed modularly to handle a variety of final diagrams and charts, and currently, it can produce automatically process flow diagrams (PFDs) invoking the graphical library graphviz [43] alongside Sankey diagrams calling a specific plug-in of the javascript library d3.js [44].

```
{
  "config verbose": false,
  "input file": "input.yaml",
  "categ analysis": "all",
  "graphviz": {
    "comp shape": "box",
    "mat shape": "septagon",
    "en shape": "ellipse",
    "comp foreg colour": "lightblue",
    "mat foreg colour": "yellow",
    "en foreg colour": "red2",
    "show comps lbl": true,
    "show flows lbl": true
  },
  "sankey": {
    "colour path": true,
    "d3 lib path": "rCharts_d3_sankey/libraries/widgets/d3_sankey",
    "d3 templ path from lib": "/layouts/chart.html",
    "width": "960",
    "height": "500"
  }
}
```

Fig. 10 Example of the configuration file used by the tool presented in this work (JSON format) [42]

Looking at Fig. 9, it can be noticed that the required description of the foundry process is basically a list of phases that can be entered in any order but that must specify a connection of one phase with the others. The phases are called "Components" in the "Plant file" and to each of them it can be attached, optionally, a flexible number of input or output energy or material flows.

The implementation of object-oriented features in the program provides some benefits associated with this type of design. For example, the amount of material and energy content processed at each phase is internally calculated applying conservation laws and analysing the input data of the flows with the connection among process phases. Although the calculations to perform at each process phase are different from each category of streams analysed (i.e. material or energy), the algorithm to traverse the entire data structure has been coded only once as a polymorphic object. This design permits to reuse the same algorithm for every type of action (implemented in a procedure) to be performed to the entire data structure representing the foundry [41, 42].

An example of the Sankey diagrams of material and energy flow produced by the program is reported in Fig. 11.

Furthermore, the program has been designed to integrate with "legacy" manufacturing systems already established in the industry. When integrated, this tool can perform further tasks alongside energy and material flow analysis. These additional tasks have been categorised according to six scenarios and summarised in Table 2.

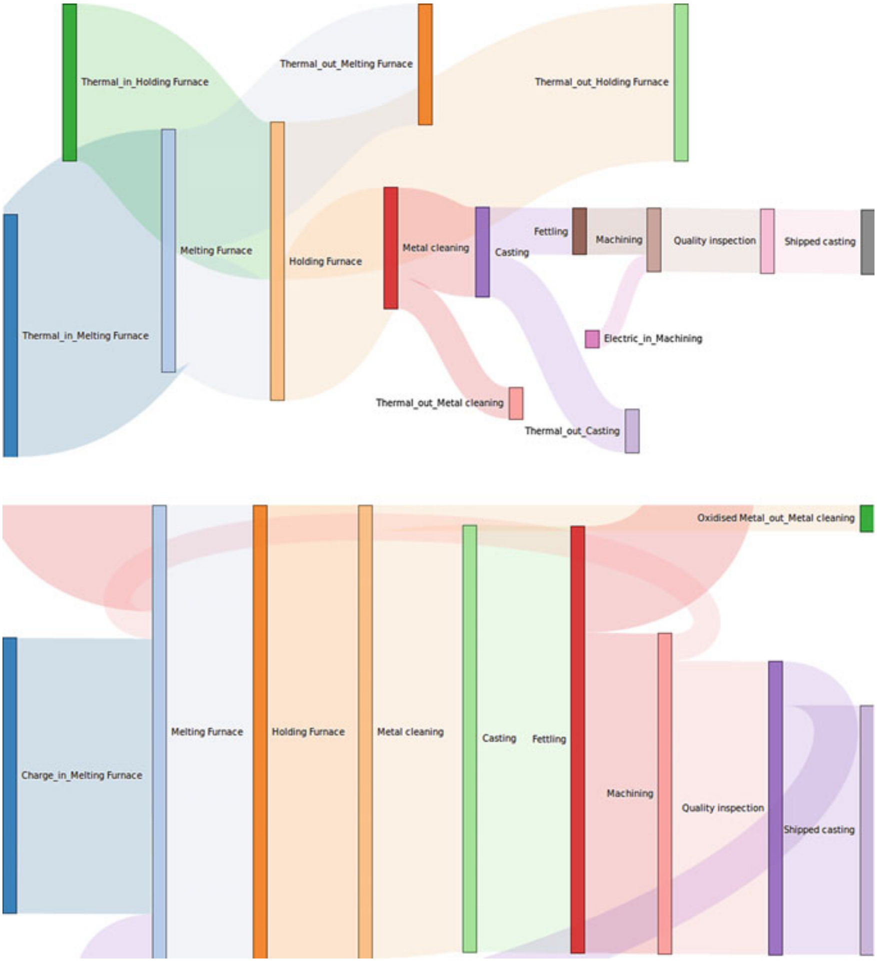

Fig. 11 Example of material (top) and energy (below) flows in Sankey diagrams of a metal casting foundry. The diagrams have been generated by the computer program developed for the "Small Is Beautiful" project [42]

One option would be to interface the program with computational fluid dynamics (CFD) codes for metal casting modelling to add a more detailed layer and analyse specific process phases while investigating alternative design options or improvements to the current product. In this last case, data collected during audits can be used to link the tool to CFD codes, whereas a database of manufacturing processes is necessary to serve the same purpose while designing new products. In these scenarios, automatic optimisations can be implemented with profit [42].

Table 2 Scenarios to integrate the tool with existing manufacturing systems [42]

Scenario	Input	Additional benefit
Production improvement	Audited data	Accurate specifications (via interfaced tools, e.g. CFD)
Product design	Manufacturing processes database	Accurate specifications (via interfaced tools, e.g. CFD)
Benchmarking	Reference plants database	Basic Pareto analysis (i.e. find "low-hanging fruits")
Process monitoring	Real-time data	Process monitoring tool (via Internet of things)
Training	Real-time data	Personnel didactic tool (via Internet of things)
Lifecycle assessment	Materials lifecycle database	Product lifecycle analysis

Alternatively, the foundry performance can be benchmarked against a database of reference plants, leading to suggestions to improve the aspect that will guarantee the highest return on investment [42].

Another option is monitoring the performance of the foundry using the tool visual capabilities with real-time data. This can be achieved using networking protocols when the equipment in the factory is connected according to a modern, "smart foundry" paradigm. In such a scenario, the program can become also a didactic tool to improve the behaviour of the factory personnel that has been often observed to have an important impact on the good performance of manufacturing plants. Furthermore, inverting the direction of the data flow from the program to the production equipment, it is possible to control the process in real time [42].

Finally, the design of the program permits a relatively simple implementation of embodied energy or CO_2-footprint flows if lifecycle databases are made available. This scenario would allow an analysis of the whole life cycle of the foundry products [42].

7 Foundries of the Future: A Short Conclusion

Among the challenges that the foundry industry will have to tackle in the future short and medium term, there is undoubtedly resource scarcity with even tighter environmental regulations. In this context, energy-efficient casting studies are of great value and interest to preserve competitiveness and environmental protection. Both managerial and technical improvements can contribute to enhancements towards this goal although so far they have been considered with different priorities. The foundries of the future will have to consider as an important activity to control their processes, a thorough analysis of material and energy flows together with a culture inspired by the lean manufacturing paradigm. These main aspects have been described in this work showing examples of energy-efficient casting implementations. In particular, as a philosophy well aligned along the mentioned goals, “Small is Beautiful” has been presented. A potential extension of its current framework to encompass the entire sustainability spectrum appears feasible in the near future.

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Research Framework of Sustainability in Additive Manufacturing: A Case of Fused Deposition Modeling

Tao Peng

Abstract Additive manufacturing (AM) has taken off for a steadily fast development, as it enables design flexibility and capability of increasingly complex, highly personalized products with enhanced performance and functionality. More importantly, it is claimed to hold great potentials in improving sustainability. However, how to fulfill such potentials is weakly supported by the scattered research. To better outline, connect, and coordinate the efforts toward a sustainable future of additive manufacturing, a research framework with six successive parts is proposed. Fused Deposition Modeling (FDM) is a relatively mature and widely applied process. Considering its scale, the sustainability issues in FDM are first attended. To demonstrate how the proposed research framework is utilized, a life cycle energy analysis of FDM processes has been conducted, including filament production, FDM printing, post-processing, and auxiliary services. Three research projects are presented and performed with the guidance of research framework. The common motivation is to understand the energy characteristics, key influential factors, and energy-saving opportunities in the FDM printing processes. The topics are (1) how the key parameters influence the process energy consumption; (2) the relation between energy consumption and surface roughness using different printers; and (3) how to minimize the overall printing time, correspondingly printing energy, of a multi-component complex part. It is hoped that with the proposed research framework, the future studies on sustainability in additive manufacturing can be consistent and comparable, and the data integration and cross-disciplinary data analysis can be facilitated.

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Keywords Additive manufacturing · Energy consumption · Environmental impact Fused deposition modeling · Life cycle · Sustainable manufacturing

1 Introduction

Living a sustainable way of life has been accepted and respected by a wider public. On September 25, 2015, the 194 countries of UN General Assembly adopted the 2030 Development Agenda titled "Transforming our world: the 2030 Agenda for Sustainable Development" [1], which outlined 17 Sustainable Development Goals (SGDs) [2]. Each goal has specific targets to be achieved over the next 15 years. Predictably, continuous reinforcement of sustainable production and consumption will be focused by many industrialized countries.

Advanced manufacturing, a pillar industry to provide people with various products and services, has been revitalized. Strategic programs were launched worldwide, at both regional and global levels, such as "Advanced Manufacturing Partnership" in the USA, "Industrie 4.0" in Germany, "China Manufacturing 2025". Germany has also outlined its holistic climate protection plan 2050 in response to the SDGs [3]. All these programs aim to develop cutting-edge technologies, to meet the needs of higher intelligence for autonomous production, flexibility for personalized products, and environment-friendly performance. Research attentions have been paid to the sustainability issues in traditional manufacturing intensively [4, 5]; likewise, these issues are essential for advanced manufacturing.

Additive manufacturing (AM), also known as 3D printing, is a global-featured advanced manufacturing technology. Its emergence and 30-year development promises a more intelligent, sustainable, and cost-effective way of making highly personalized products. A formal definition of AM is given by American Society for Testing and Materials (ASTM) Committee F42 as "*a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*" [6]. A family of AM technologies was developed, including material extrusion (e.g., Fused Deposition Modeling—FDM), binder jetting (BJ), powder bed fusion (e.g., Selective Laser Sintering—SLS, Selective Laser Melting—SLM), vat photopolymerization (e.g., Stereo Lithography Apparatus—SLA), and directed energy deposition (e.g., Laser Engineered Net Shaping—LENS) [7]. AM technologies are not intended to replace conventional manufacturing, but utilized as an additional tool to fabricate complex parts in a more cost-benefit manner. They promise better environmental characteristics, since they are highly resource-efficient and reduce the buy-to-fly ratio drastically. However, support structure and material recycling loss are inevitable in fabricating complex parts. There are five primary benefits in terms of sustainability as follows [8]:

1. Reduced amount of raw material required in the supply chain;
2. Reduced need for energy-intensive manufacturing processes and wasteful/harmful materials;
3. Flexibility to design more efficient components with better operational performance;
4. Reduced product weight, contribute to carbon footprint improvement in service on the vehicle into which they are integrated;
5. Reduced transportation as parts could be manufactured closer to the point of consumption.

A recent hypercycle for 3D printing indicated a steady expansion into commercial and industrial production as well as a promising increase of new application areas [9]. Although more extensive adoptions of AM are expected, current research focuses primarily on new materials and processes, while over-optimistically rely on its self-sustainable development. Instead, thorough research on the sustainable development of AM must be conducted, to address its accumulated impacts on economic, social, and environmental aspects. In this chapter, FDM is used as an example, because of its wide application and closeness to individual user. First patented in year 1989, FDM was formally referred to as one of the material extrusion processes by ASTM. Year 2007 was a turning point for FDM, when the open-source RepRap project began to gain attentions [10], and the patent expiration of FDM in year 2009 triggered the commercial competition. Since then, FDM has been the most popular and easy-to-use AM technology worldwide. With capability of dealing with geometrical complexity and small volume cost-effectiveness, enables the fast fabrication of prototypes, FDM has become an increasingly important tool ranging from creative design pieces, educational works, to fully functional parts [11].

A schematic diagram of a FDM printer is illustrated in Fig. 1, where a part is typically built in a layer-by-layer manner, using plastic filament or metal wire

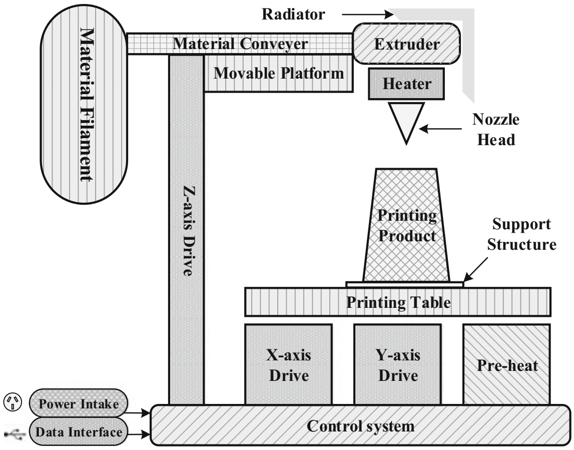

Fig. 1 A schematic diagram of a FDM printer [15]

unwound from a coil. The move mechanism used is often an *X*-*Y*-*Z* rectilinear design, resembling three-axis CNC machine tools, while other mechanical designs are also available, e.g., delta-robot-type printers. A typical FDM process involves eight stages: (1) 3D model generation, (2) printing file conversion, (3) on-machine parameter settings, (4) support creation, (5) part slicing, (6) tool path generation and optimization, (7) fabrication, and in most cases, (8) part post-processing [12]. According to Wohlers Associates, the market for 3D printers and services was worth $2.2 billion worldwide in 2012, up 29% from 2011 [13]. In 2015, more than 278,000 desktop printers were sold [14]. Among which, over 44% were FDM type [13]. With such a significant and steady increase, the sustainability issue of this technology is no longer negligible.

Additionally, the supply chain for FDM printing has formed rapidly and spontaneously, including material innovation, filament production, printer manufacturing, material recycling, and printing services. However, a proper organization and coordination among different processes is missing. Thus, available data to support sustainability analysis are lacking and limited to a specific domain. Without comprehensive data, no life cycle or multiple objective analyses could be conducted to guide a sustainable industry. Moreover, a research on the issue of sustainability should be conducted along with the advances in materials and processes [16]. For example, surface quality of FDM parts has been intensively studied, while the resource efficiency and energy consumption are overlooked.

The needs of further research on FDM are obvious, particularly a research framework to help guiding and shaping the future research. This chapter is dedicated to this topic. The remainder of this chapter is organized in four sections. In Sect. 2, sustainable AM is elaborated from a life cycle perspective, and a brief literature review is presented. A research framework of sustainable AM is proposed in Sect. 3, consists of six research activities. Section 4 presented three proof-of-the-concept research cases on (1) how FDM process parameters influence printing energy consumption; (2) whether energy savings and better surface roughness conflict on different printers; and (3) how to schedule printing jobs of complex parts among several FDM printers for printing time minimization. Finally, some discussions, concluding remarks, and outlooks are provided in Sect. 5.

2 Life Cycle Perspective

Before introducing the research framework, it is essential to consider life cycle. Life cycle assessment is a comprehensive and systematic evaluation approach, covering the entire life cycle of a product, in many cases, from raw material acquisition, through material production, part manufacturing, to use phase, and end of life treatment and disposal. For FDM-printed products, thermoplastics are normally used. Taking polylactic acid (PLA) as an example material, it is an excellent biodegradable plastic produced from starch, can be easily shaped between temperature 190 and 230 °C. Compared to traditional manufacturing, FDM only impacts on manufacturing phase, which can be divided into three stages, i.e., filament production, FDM printing, and post-processing [17]. The raw material is PLA granule for filament production, which is commonly accepted by a FDM printer. FDM printing consists of extruding a softened thin filament through a heated nozzle, depositing and fusing onto a previous layer before the filament cools and hardens. Post-processing is normally required for support structure removal, cleaning, and surface polishing.

Sustainable AM should be studied from a life cycle perspective; however, to collect the relevant data in every stage to form a Life Cycle Inventory (LCI) is the most challenging task. This needs collaborative efforts. An initiative known as Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) coordinates international efforts to analyze and improve the environmental impact for a wide range of emerging manufacturing processes with respect to their direct and indirect emissions. In the framework, Kellen et al. pointed out that quantitative analyses of environmental impact are still limited and proposed a systematic LCI data collection approach [18, 19]. Figure 2 illustrates the three analyzing dimensions, energy, material, and time, respectively. In a FDM printing process, electrical energy is transformed into thermal energy and mechanical energy and discharged as heat loss. Primary material refers to the required material of a part, and support structure or binder material is generally considered as auxiliary materials. The "waste" material sometimes can be recycled and reprocessed. For instance, the filament can be

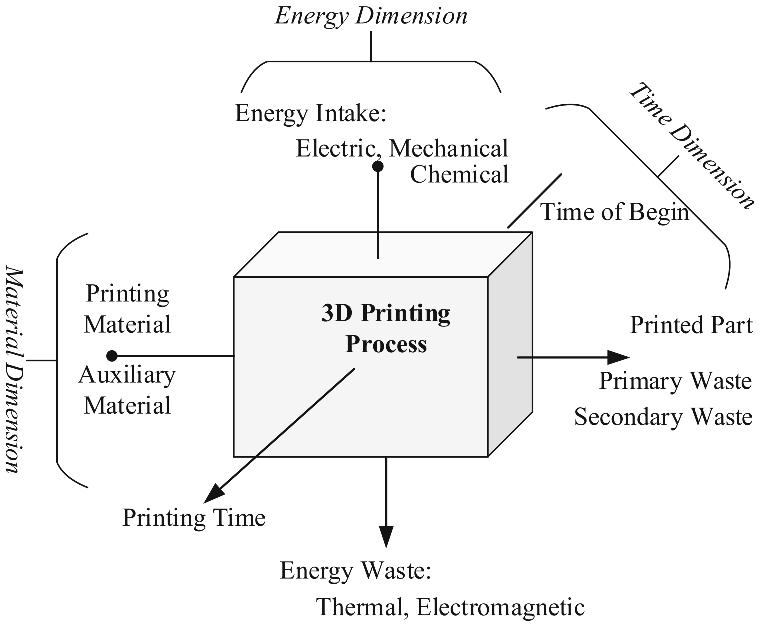

Fig. 2 Three analyzing dimensions of 3D printing [15]

fabricated from post-consumer plastic waste, besides from virgin resins. The meaning of printing time is straightforward.

Existing research toward sustainable AM can be found but scattered. Considering the family of AM technologies, literature review conducted by Huang et al. [7] confirmed many positive impacts, including reduced environmental impact, but also identified that more research is needed, such as to accurately evaluate the energy consumption. Drizo and Pegna [20] provided a comprehensive review of environmental impact assessment of existing AM technologies. They discussed some important unresolved issues, specifically with respect to materials, due to the lack of available data. Gutowski et al. [21] showed that emerging processes were capable of working to finer dimensions and smaller batches but at lower rates, which resulted in very large specific energy requirement. Their statement that "the seemingly extravagant use of materials and energy resources by many newer manufacturing processes is alarming and needs to be addressed" clearly pointed to AM technologies. They recently reviewed the process rates and energy intensities of various additive manufacturing AM technologies, particularly laser powder bed fusion process [22]. Le Bourhis et al. present a new methodology where material, fluids, and energy flows consumed are all considered [23]. A predictive model integrated in the design step was then proposed for environmental impact assessment. Mognol et al. [24] investigated optimal parameter selection with the purpose of reducing energy consumption. They tested various parameter combinations, part orientations, and positions in three representative printing systems and concluded that minimizing manufacturing time is critical to reduce energy consumption, but there is no general rule for energy optimization for all systems.

Focusing on FDM, existing literature suggests that part surface finish and productivity attract most attentions. This concerns largely on economic aspect. Comparably, environmental aspect, energy, and material efficiency are less studied. For surface finish, the staircase effect markedly affects FDM parts because of filament and nozzle dimensions, and some hundreds of microns are the layer thickness normally used. It is higher than other AM technologies, whose layer thickness can be as small as tens of microns [25]. Thinner layers [26], selected build orientation [27], and surface angles [28] would simply result in better surface roughness. Parameter optimization, including printing speed, layer thickness, infill ratio, printing paths, and support structure, is another approach to achieve better surface, dimensional tolerances, and mechanical properties [29, 30]. Other poor surface finish may relate to thermal and mechanical aspects of material during local heating and cooling, which introduces part distortion and residual stresses, and sometimes shrinkage [31]. Considering energy efficiency, thinner layer dramatically increases the printing time and energy consumption, while thicker layer reduces printing energy but leads to secondary finishing operations, such as barrel finishing, bear polishing [32]. This also leads to additional energy consumption. Luo et al. [33] studied energy consumption on four different FDM printers at a macro level. A detailed energy analysis was reported [15], and a unit-weight method was proposed to assist quick estimation of life cycle energy consumption of a FDM part

[17]. Considering material efficiency, studies mainly focused on support structure optimization. Allen and Dutta [34] determined the required support areas based on triangular mesh and build orientation. Huang et al. [35] reduced the volume of support by transforming cylindrical structure into conic. Heide [36] further minimized such a volume by reducing the volume and complexity at lower structure. Strano et al. [37] developed a methodology to design incomplete infill for support structure. Some studies focused on internal support structure optimization for better stability and compressive capacity [38].

Apparently, how to balance different aspects in sustainability for FDM remains a non-trivial task, and requires much more research, particularly from a life cycle perspective. No conclusion can be drawn based on the limited and scattered works aforementioned. A research framework is, therefore, proposed in the following section to direct and facilitate future research in FDM.

3 Research Framework

The FDM market has gone through price competition to quality and function competition. Two facts exist in the FDM industry, one is that most FDM printers, including industrial FDM, have limited functions for energy and material efficiency concerns; the other is that most users of FDM printers have limited knowledge on system configuration and parameter optimization. Now, there is a great opportunity to further research on the sustainability of FDM.

A general research framework guides a researcher since motivation discovery, from theoretical gap or real-life needs, and then formalizes the problem. Methodology is developed creatively to address the problem, and the results will be interpreted carefully. In many cases, actual implementation or prototype is performed, and those results will be re-evaluated to reinforce the conclusions. Such a process is illustrated in blue arrows in Fig. 3. Following this, the research framework for sustainable AM is detailed. The SDGs, specifically Goals 9 (Industry, Innovation, and Infrastructure) and 12 (Responsible Consumption and Production), are the key motivations. The problem formation is based on selectively analyzing sustainability dimensions. To solve the problem, both qualitative and quantitative analyses are performed with knowledge of multiple domains. Experiments and case studies are normally conducted to provide first-hand information. 6R, i.e., Redesign, Reduce, Reuse, Recycle, Recover, and Remanufacture, activities are suggested to continuously improve the sustainable performance during the implementation, and eventually, sustainable practices can be recommended for AM processes.

To demonstrate how the proposed research framework is utilized, a life cycle energy analysis of FDM processes has been conducted. For this example, the motivation is to characterize and optimize energy consumption in the whole life cycle of FDM. Thus, the research starts with scope definition to determine the boundary of a life cycle study (see Fig. 4), then qualitative analysis to divide the

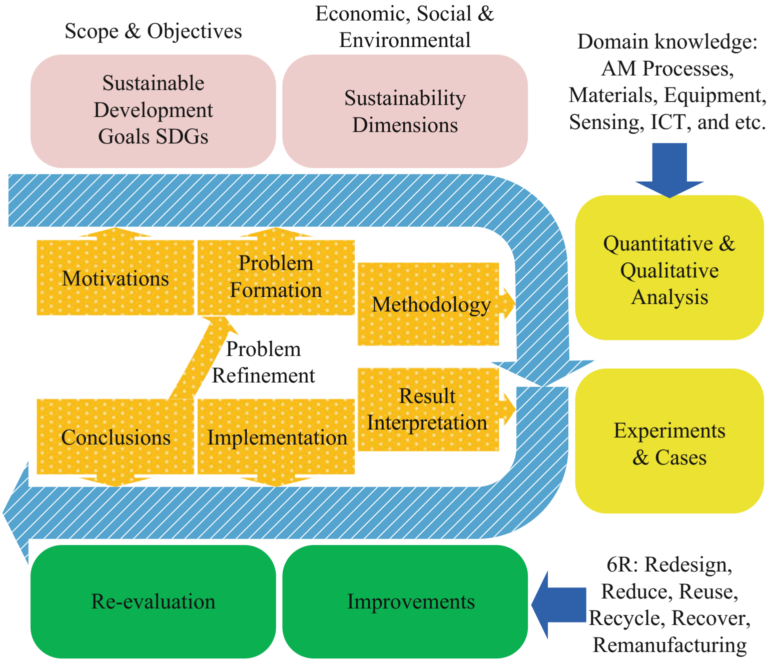

Fig. 3 A research framework of sustainable AM

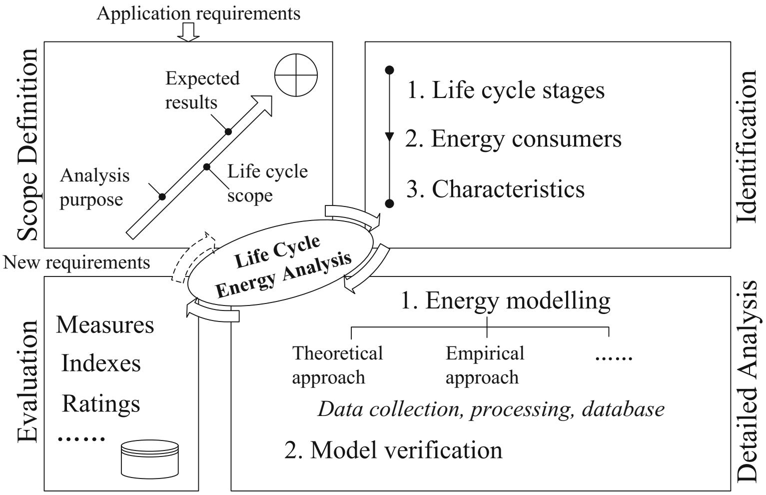

Fig. 4 Life cycle energy analysis of FDM processes

stages and identify main energy consumers is first performed, and energy characteristics can be described. Subsequently, quantitative analysis, more specifically energy modeling and verification, is performed. Different modeling approaches, such as theoretical, empirical, experimental approaches, can be used with the support of various databases. The analysis results can be expressed by different measures, indexes, or ratings. These can be indicators to assist energy performance evaluation.

All energy consumed in raw material production, part manufacturing, and auxiliary services should be included in a life cycle energy analysis. For FDM, this is shown in Fig. 5 with the energy consumers in each process. The first process "filament production" is done on an extruding machine, where eight major components are involved. Blocks with grid pattern are heavy energy consumers, such as heater. Blocks with slash pattern are medium energy consumers, such as material conveyor. Blank blocks, such as roller storage, are light energy consumers. Likewise, the second process "FDM printing" is completed using a 3D printer, which has seven major components. Heater, including nozzle, worktable, and sometimes chamber heating, is again the heaviest energy consumer. The third process "post-processing" requires much less energy, because it involves many manual works, for example, support removal, surface polishing or coloring. Transportation services between different processes are considered a heavy energy consumer.

Once the consumers are identified, energy model for each consumer can be built. More details on energy modeling have been reported in [17]. A unit-weight energy consumption approach was also developed to quickly calculate life cycle energy consumption of a FDM part. These results are useful inputs to a variety of decision-making processes, for instance, printer selection, production planning and scheduling, parameter configuration, and many others. More processes, e.g., material recycling and reprocessing, can be added to Fig. 5 according the different life cycle scopes. To detail the implementation, three case studies have been performed as student research projects, to show how projects can be better organized with the research framework.

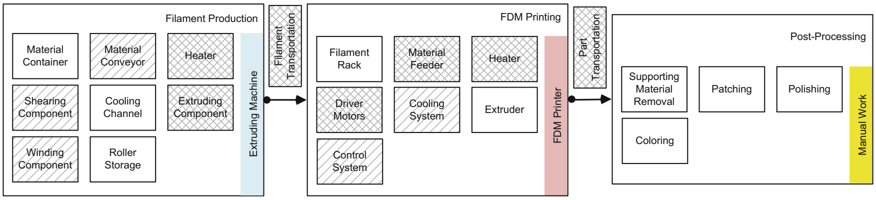

Fig. 5 Energy consumers in a FDM life cycle

4 Case Studies

Three student research projects are presented in this section, which were performed with the guidance of research framework. First of all, the common motivation is to understand the energy characteristics, key influential factors, and energy-saving opportunities in the FDM processes.

Generally speaking, a FDM process can be divided into three stages, warm-up, printing, and finishing. Even for different FDM printers, these three stages can be identified. In "warm-up" stage, the high power consumption at the beginning of all profiles was attributed to nozzle and worktable heating. In the "printing" stage, besides heating, drive motors and auxiliary components, e.g., cooling fan, started to consume energy. In the "finishing" stage, the main activities were axis homing and component cooling. Although the activities are similar in each stage, different printers demonstrate different energy behaviors. For example, Fig. 6 depicts the power profiles measured on three different FDM printers. The power profile in blue fluctuated much stronger than that in red, and the power profile in black had no worktable heating (here, three FDM power profiles are examples only, different from the ones in the following case studies).

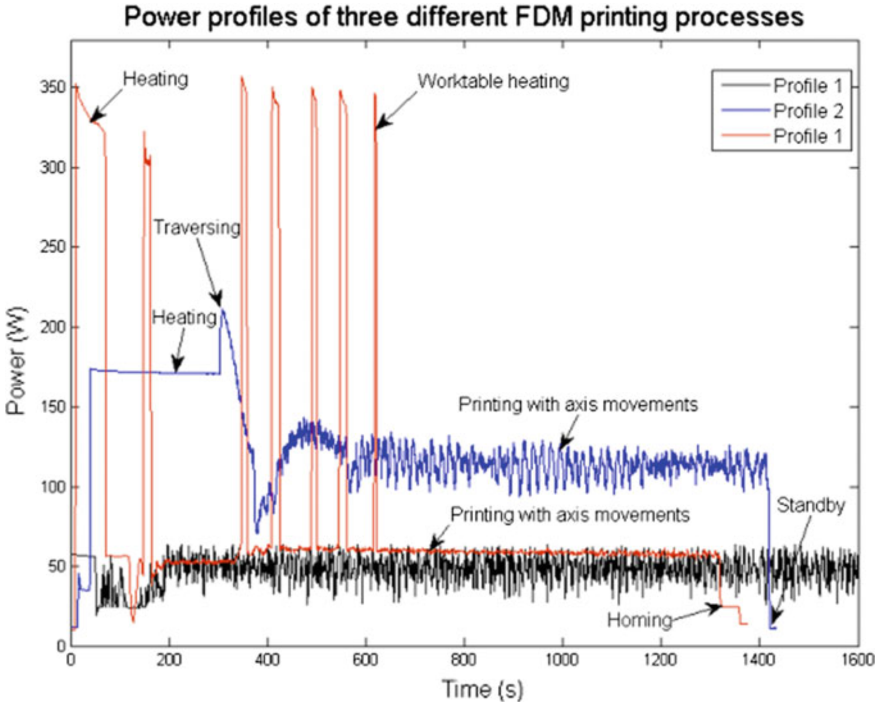

Fig. 6 Power profiles of three different FDM printers

The topics of three case studies are (1) how key process parameters influence the energy consumption; (2) the relation between energy consumption and surface roughness using different printers; and (3) how to minimize the printing time, which affects the printing energy, of a multi-component complex part. Here, the energy consumed in the printing stage was firstly studied, because of experiment resource and data availability.

4.1 Case I

The first case endeavors to find the impact of key process parameters on energy consumption and surface roughness. Various parameters, including layer thickness, printing speed, infill ratio, infill pattern, part build orientation, nozzle temperature, can be configured for a FDM process; however, three of them, layer thickness t (mm), printing speed v (mm/s), and infill ratio η, were selected based on their reported significance in the existing literature and preliminary experiments. They are known to correlate closely with both energy consumption and surface roughness. v is a composite value, averaged from acceleration, deceleration, straight line, contour or corner traverse.

Materials

The material used was PLA because of its excellent biodegradability and can easily be shaped between 190 and 230 °C. Two diameters of the filament were used on different printers, 1.75 and 3 mm, and the slight difference of material properties was neglected, because it has insignificant impact on energy consumption and surface roughness.

Equipment

In Case I, a rectilinear design FDM printer, Creatbot® DX (Cb-DX), was employed. It is worth mentioning that the selection of the printers is depending solely on accessibility, with neither preference nor recommendation. A portable wattmeter HOPI HP 9800 was used to stream online power consumption data, which portrait the power profiles. The fabricated sample parts are shown in Fig. 7. After the samples were collected, surface roughness of selected part surfaces was initially measured using a handheld Roughometer TIME 3200. However, the selected surfaces were not always flat and smooth enough to return a value; hence, a Keyence VK-X150 laser microscope system for 3D and profile measurement was employed to examine surface morphology. VK Viewer and Analyzer software was used to capture the image with a relatively large depth of field and to analyze the surface roughness.

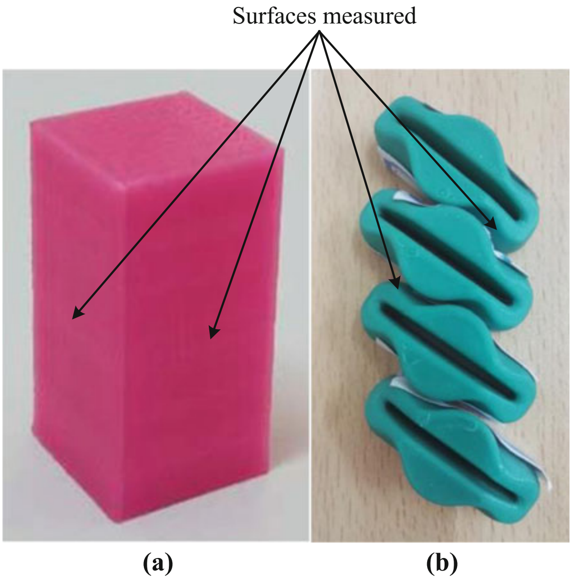

Fig. 7 Samples' illustration and measured surfaces

Experiment design

Since only three parameters were altered to study their impacts, full factorial design was performed in developing parameter sets on Cb-DX (see Table 1). Two levels were determined for each parameter, and overall eight sets were printed. Each set has been repeated three times.

Data processing

Printing energy, expressed as E_p in kJ, relates closely to the selected parameters. It is obtained from the power measurements using the portable wattmeter. Total printing time is denoted as T_p in seconds. The power data of each sample were processed in MATLAB R2012a, to extract the printing energy. The heating energy consumed by the worktable was removed, as it is irrelevant to selected parameters. E_p, therefore, consists of energy consumed by control system, material extrusion, fan cooling, nozzle heating, and all drive motors.

Average roughness Ra in µm, i.e., the arithmetical mean deviation of absolute heights of the profile, was commonly used. Most investigations on the surface roughness of FDM parts were mainly using Ra [39]. But this provides neither distinction between peaks and valleys, nor spatial structure information. Advanced surface characterization is directed to the use of more specialized roughness

Table 1 Levels of parameter used in case I

Level	t (mm)	v (mm/s)	η (%)
1	0.1	20	20
2	0.3	60	60

parameters [40]. In this case, VK-Analyzer is used to obtain the surface roughness Ra and Rz in µm, and line roughness LRa in µm and LRz in µm. All four-side faces of sample (a) and two flat-side faces of sample (b) were measured (see Fig. 7). Figure 8 depicts the VK-Analyzer interface. The line roughness for each measure was represented by the minimum value of ten randomly selected lines.

Results

All values of E_p, T_p, Ra, Rz, LRa, and LRz are summarized in Table 2. The results were plotted in Fig. 9, illustrating the linear relationship between printing energy consumption and printing time using Cb-DX, which indicates that the average power can be considered constant for different printing speeds.

Layer thickness was identified as the most influential factor, followed by printing speed and then infill ratio. This agrees with the findings in existing research. Layer thickness was increased by threefold from 0.1 to 0.3 mm, suggesting nearly one-third energy reduction, however, while the values of surface roughness were worsen less than half. Although differences were expected, the values of Rz and

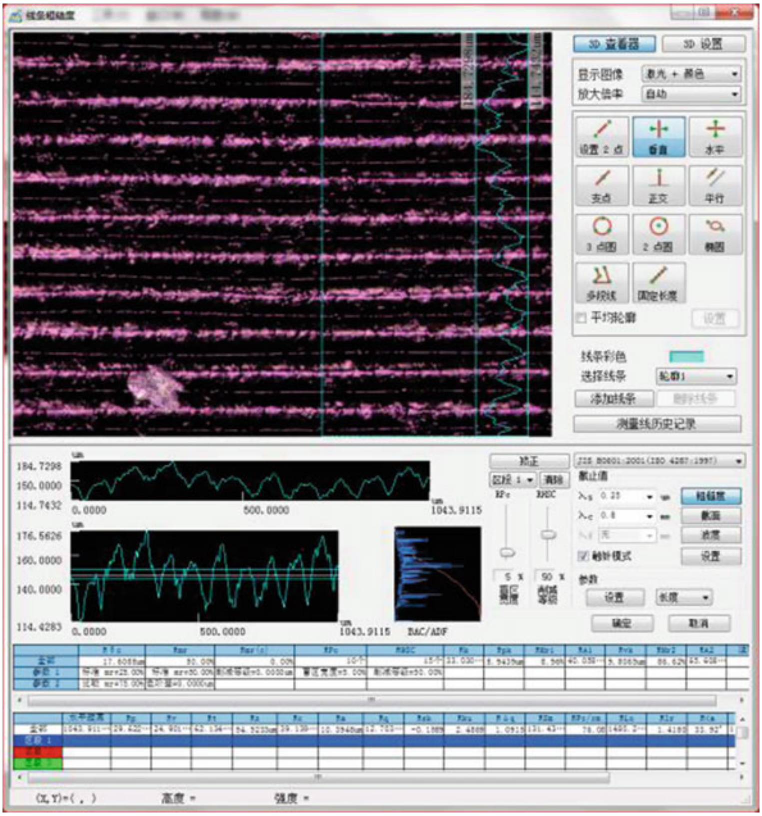

Fig. 8 A snapshot of the VK-Analyzer interface

Table 2 Summary of energy consumption and surface roughness data in case I

No.	t (mm)	v (mm/s)	η (%)	E_p (kJ)	T_p (s)	Ra (μm)	Rz (μm)	LRa (μm)	LRz (μm)
1	0.3	60	20	38.2	650	24.15	204.38	22.19	108.83
2	0.3	60	60	47.1	793	23.94	187.12	21.49	100.85
3	0.3	20	20	77.4	1345	27.29	254.56	24.23	116.10
4	0.3	20	60	112.2	1956	26.31	298.76	23.23	117.37
5	0.1	60	20	98.7	1917	12.90	202.78	9.86	51.84
6	0.1	60	60	126.5	2186	10.76	195.34	8.05	46.15
7	0.1	20	20	194.1	3396	15.26	184.09	10.94	61.19
8	0.1	20	60	311.4	5471	18.96	314.75	14.07	75.09

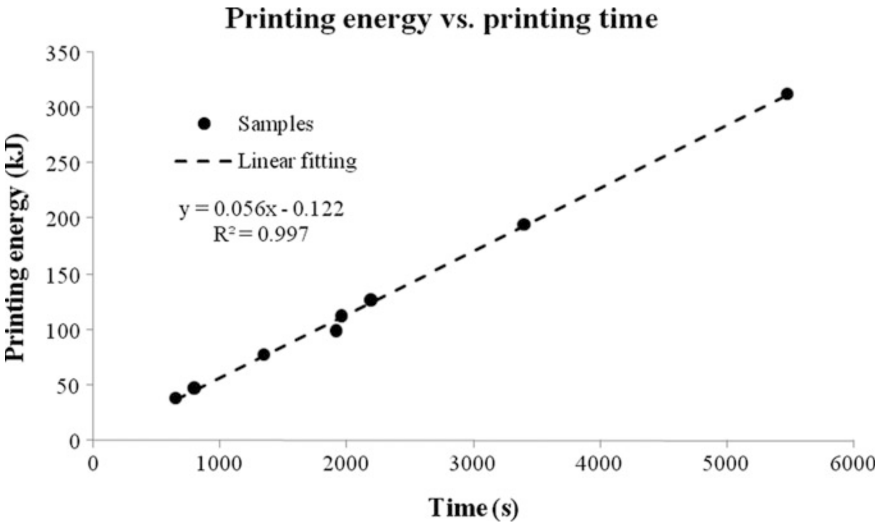

Fig. 9 Linear relationship fitted between printing energy and time

LRz were much larger than corresponding values of Ra and LRa. Layer thickness has opposite impacts on the two objectives, and increasing printing speed can be an effective way to save energy while achieving good surface finish.

A joint analysis on energy consumption and surface roughness has been displayed in Fig. 10. Rz values shown the most irregular and large roughness; thus, a close examination on the surface morphology was performed. Selected 3D images of surface for each parameter set are given in Fig. 11. The surfaces were quite rough with spikes and wavy curves. It has been found that thicker layer and faster speed may lead to more spikes and unevenness. This may be attributed to the material squeezing and spilling due to local overheating, or non-uniform filament thickness.

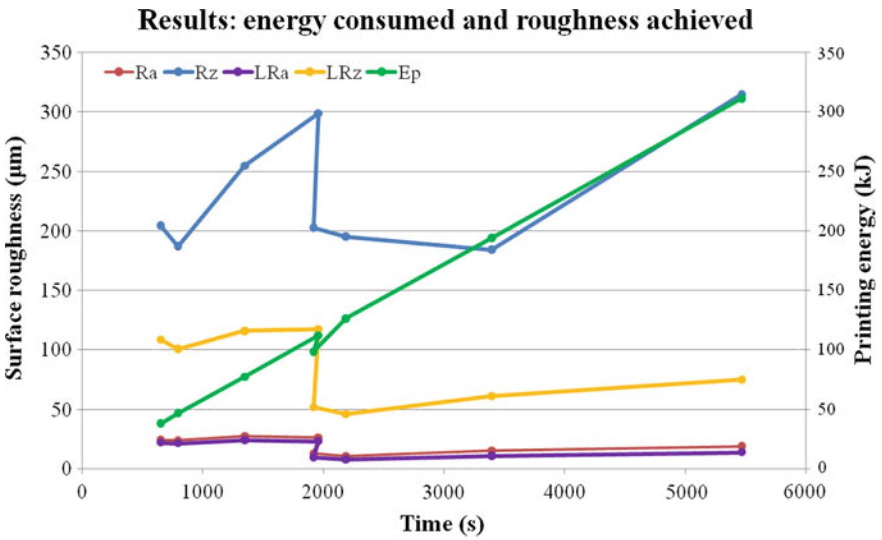

Fig. 10 Joint analysis on printing energy and surface roughness over time

4.2 *Case II*

The second case aims to investigate different FDM printers in terms of printing energy and surface roughness, using various parameter combinations. Here, layer thickness t (mm) and infill ratio η were changed.

Materials and Equipment

Same type of material, PLA, and same data measuring and processing tools were used. Three models of FDM printers were used including the one in Case I. Two other printers were a self-developed delta-robot printer (DR) and a Mbot® Grid II + (Mb-G). Cb-DX and Mb-G are of same type and similar size. The three printers were at different locations, but the differences in experimental environment and operating behavior were neglected.

Experiment design

Since three different printers were used, same values of parameter were adopted. Layer thickness t and infill ratio η were chosen as varying parameters, and each has same two levels of values. The type of printer was also considered on factor. Full factorial design was also performed with the values in Table 3. To note that printing speed v was not changed, because as mentioned in Sect. 4.1, v is a composite value. Therefore, three printers will behave differently at a same given printing speed. To avoid this complexity, v was fixed at 50 mm/s. Besides, nozzle and worktable temperatures were set 210 and 45 °C, respectively, for all the runs. Each set has been repeated three times.

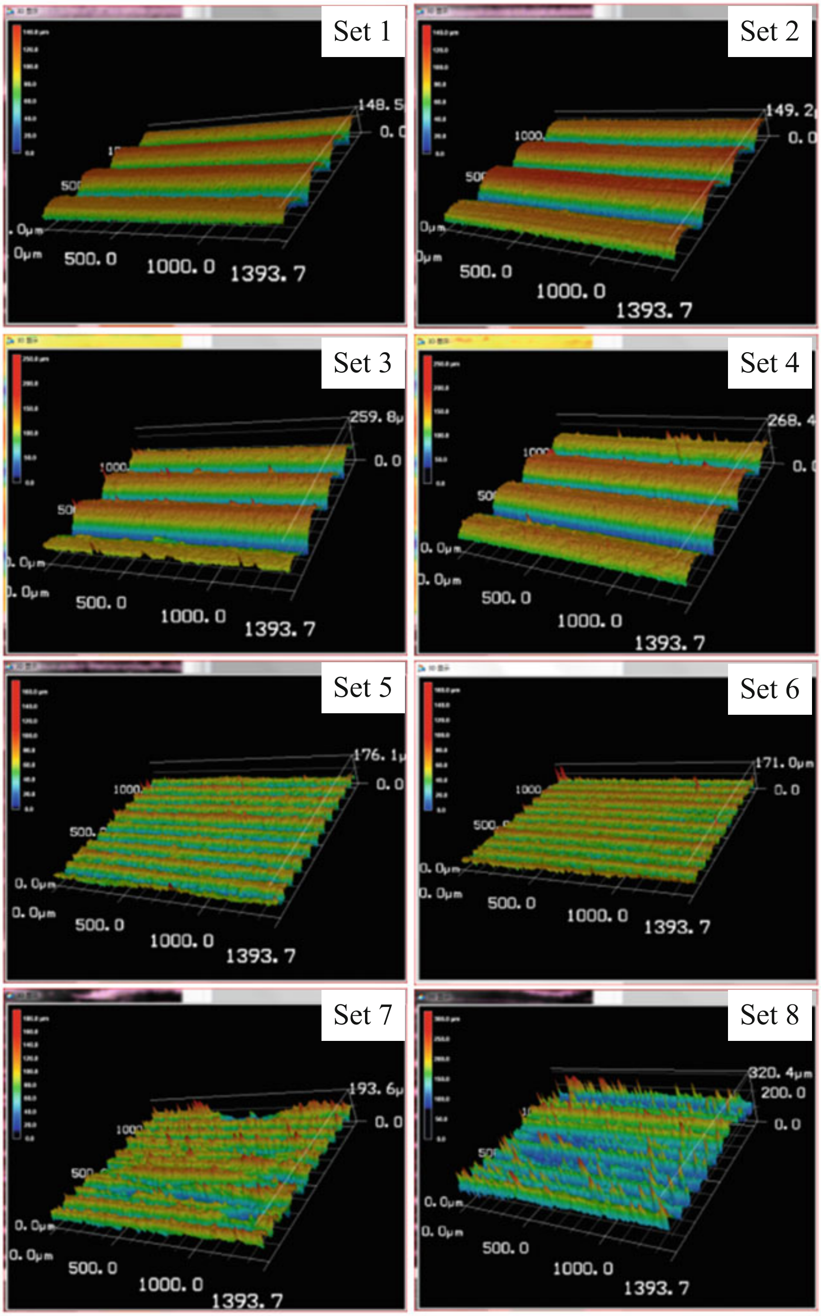

Fig. 11 Selected 3D images of surface morphology for each parameter set

Table 3 Levels of parameter used in case II

Level	Printer	t (mm)	η
1	Cb-DX	0.1	20%
2	DR	0.2	60%
3	Mb-G		

Results

After data processing, the values of energy consumption and surface roughness are presented in Table 4. Obviously, fabricating same parts using same parameters on different printers resulted in different energy consumption and surface roughness. On the whole, with same parameters, Cb-DX produces better surface with moderate energy consumption, and DR consumes less energy, up to 24% energy saving, but produces larger surface roughness as much as 40%.

These data are plotted in Fig. 12, showing that the printing energy values of all three printers were linearly correlated with printing time, however, at different slopes, i.e., average printing power. Surfaces observed by microscope were grouped into two by layer thickness, 0.1 mm in Fig. 13a and 0.3 mm in Fig. 13b. It can be observed that Cb-DX and Mb-G produced near straight-line interfaces between layers, while DR produced wavy interfaces between layers. This is attributed to the parallel mechanism of a delta-robot-type printer that generates stirring movement along with traverse movement.

4.3 Case III

Based on the findings in above two cases that printing energy is positively related to printing time, Case III attempts to investigate the energy optimization opportunity

Table 4 Summary of energy consumption and surface roughness data in case II

No.	Printer	t (mm)	η (%)	E_p (kJ)	Ra (μm)
1	1	0.2	20	70.0	24.16
2	1	0.2	60	86.7	22.78
3	1	0.1	20	117.0	13.34
4	1	0.1	60	158.3	12.71
5	2	0.2	20	64.7	41.28
6	2	0.2	60	83.4	38.96
7	2	0.1	20	114.5	21.83
8	2	0.1	60%	160.4	18.35
9	3	0.2	20	77.3	39.68
10	3	0.2	60	98.3	38.07
11	3	0.1	20	150.2	19.47
12	3	0.1	60	194.0	17.33

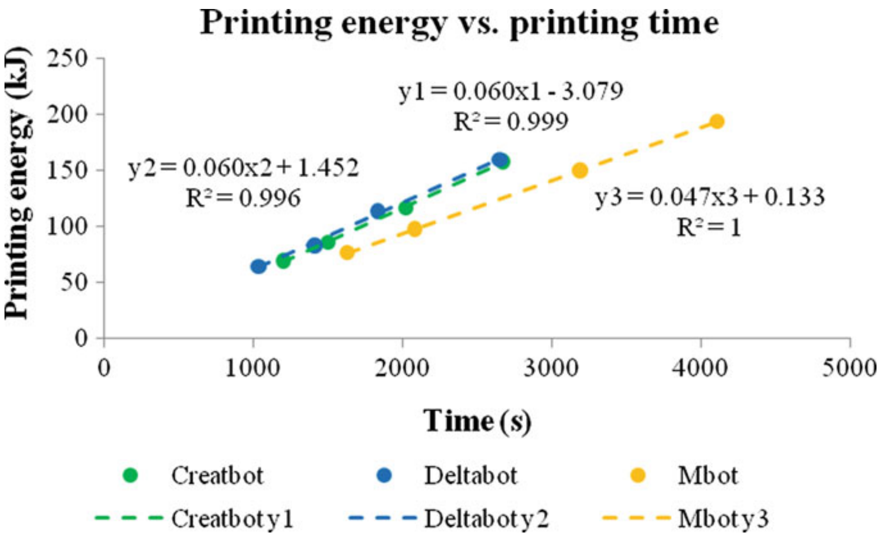

Fig. 12 Linear relationship fitted between printing energy and time

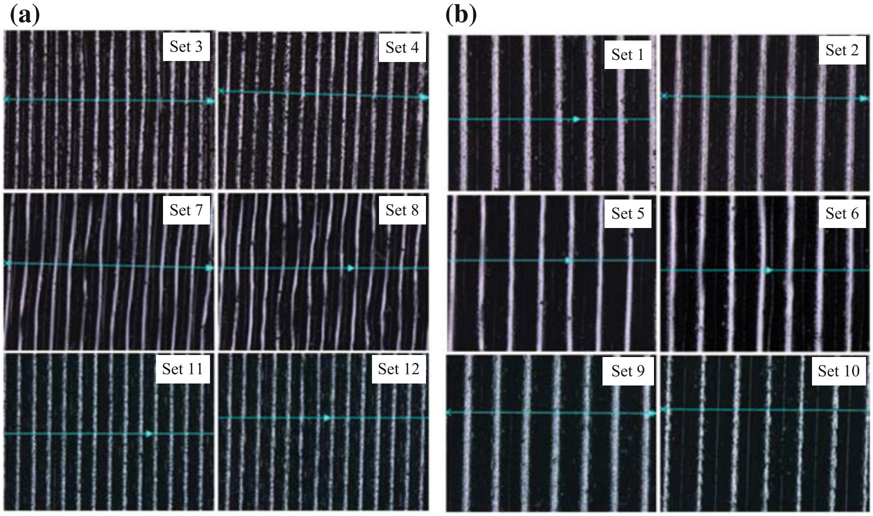

Fig. 13 Layer interfaces produced by different printers at layer thickness of **a** 0.1 mm and **b** 0.3 mm

in production planning. Instead of fabricating same parts using different FDM printers, this case was to print various parts using multiple same FDM printers. How to minimize the printing time, correspondingly printing energy, while meeting the surface quality requirements, was focused.

Materials and Equipment

Material in use remained the same. Five DR printers were considered as a manufacturing unit. The process parameters of each part were determined beforehand according to its surface quality requirements. In this case study, it was simplified by using different values of layer thickness. Currently, only constant layer thickness can be executed in a printing task; this is treated as a constraint.

Optimization model

FDM enables rapid prototyping and fabrication on demand in a make-to-order (MTO) fashion. Considering the fabrication of a complicated part of multiple components, each component can be regarded as a part. The problem becomes how to minimize the finishing time of printing m parts with n identical FDM printers. A mathematical model was developed.

Minimize finishing time of printing T_P is expressed as,

$$\min T_\mathrm{P} = \min(\max(T_{\mathrm{p}1}, T_{\mathrm{p}2}, \ldots, T_{\mathrm{p}n}) + T_\mathrm{handling} + T_\mathrm{assembling}) \tag{1}$$

where T_pi is the printing time of printer i, T_handling is material handling time, and $T_\mathrm{assembling}$ is the assembling time of the complicated part. For such a part, it is assumed that it can only be assembled when all components are ready.

The optimization problem is a minmax problem. As aforementioned, in each printing job, only one set of parameter can be used, particularly, layer thickness. For the m components, they are divided into, at least, g groups based on different parameter sets. Here, it is simply assumed that the printing time of several parts at once equals to the sum of printing times of these parts separately on a same printer. The changeover time is not included in current study, which should be considered in real practices. The limitation of this assumption is discussed in Sect. 5. Therefore, considering the worktable area, the groups are further segmented and re-organized into k jobs, where k is no less than g. Each job can then be produced in one setup on a printer.

$$m = \sum_{j=1}^{k} q_j \tag{2}$$

q_j is the quantity of components in job j. $T_{\mathrm{p}i,j}$ represents the printing time of job j on printer i. Then, the optimization model is described as

$$\begin{aligned} \min T_\mathrm{P} &= \min(\max(T_{\mathrm{p}1}, T_{\mathrm{p}2}, \ldots, T_{\mathrm{p}n})) \\ &= \min(\max(\sum_{N_1} T_{p1,j}, \sum_{N_2} T_{p2,j}, \ldots, \sum_{N_n} T_{\mathrm{p}n,j})) \end{aligned} \tag{3}$$

where N_i is the number of jobs executed on printer i, subject to

$$k = \sum_{i=1}^{n} N_i \tag{4}$$

$$N_1, N_2, \ldots N_n \geq 0 \tag{5}$$

The finishing time of the whole part is dominated by the longest printing time of printer *i*.

Solution

Considering the printers are same, the optimization problem was simplified as an integer linear programming problem. It was modeled using MATLAB R2012a. To solve this, branch and bound method was adopted and executed in MATLAB. Two examples, Napier Deltic Engine and Mechanical Hand (see Fig. 14), were fabricated with consideration of minimizing the overall printing time, correspondingly printing energy. Tables 5 and 6 summarize the input data to the optimization model. The printing time of each component was obtained from the bundled software of the printer.

The solution to the optimization problems gives a total printing time for the Napier Deltic Engine which is 8654 s and the Mechanical Hand which is 13667 s. Once again, this result is based on the assumption that the printing time of several parts equals to the sum of printing times of these parts separately on a same printer.

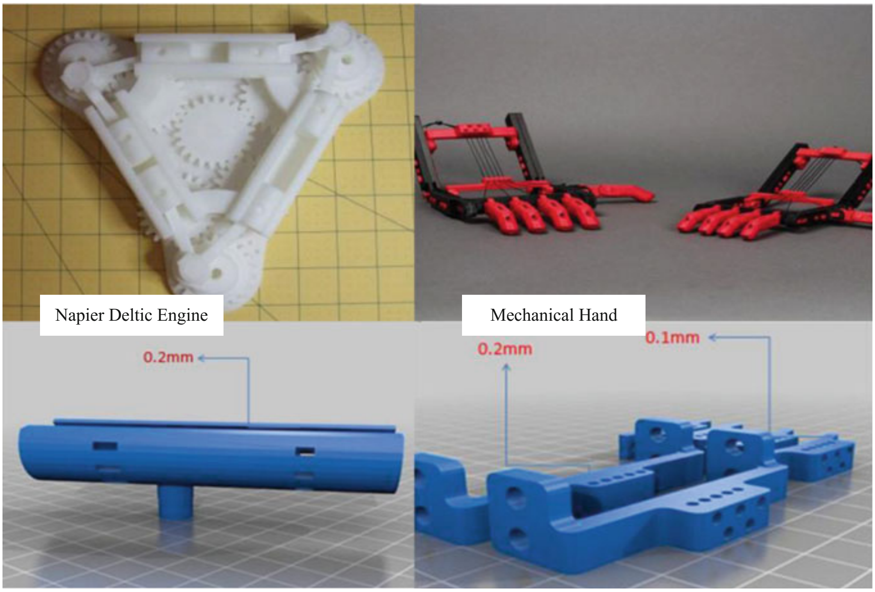

Fig. 14 Two examples of complex parts

Table 5 List of components of Napier Deltic engine, with selected layer thickness and printing time

Component no.	Description	Quantity	t (mm)	Time (s)
1	Base1	1	0.4	3108
2	Base2	1	0.4	3253
3	Base3	1	0.4	3319
4	Plain gear	5	0.2	928
5	Plain gear pin	5	0.2	235
6	Cam	3	0.2	1264
7	Cam Gear1	1	0.2	1081
8	Cam Gear2	1	0.2	1092
9	Cam Gear3	1	0.2	1088
10	Cam gear pin	3	0.2	490
11	Piston	6	0.2	761
12	Single con rod	3	0.2	378
13	Dual con rod	3	0.2	508
14	Cylinder1-2	1	0.2	2384
15	Cylinder2-3	1	0.2	3363
16	Cylinder1-3	1	0.2	1996
17	Gudgeon pin	6	0.1	361
18	Cylinder	3	0.1	695

Table 6 List of components of mechanical hand, with selected layer thickness and printing time

Component no.	Description	Quantity	t (mm)	T_p (s)
1	Snap Pins1	2	0.05	359
2	Snap Pins2	2	0.05	370
3	Snap Pins3	8	0.05	363
4	Snap Pins4	20	0.05	364
5	Finger1	5	0.1	189
6	Finger2	5	0.1	866
7	Finger3	5	0.1	638
8	Bridge1	1	0.2	815
9	Bridge2	1	0.2	756
10	Wrist1	4	0.2	572
11	Wrist2	2	0.2	447
12	Knuckles1	1	0.2	1216
13	Knuckles2	1	0.2	717
14	Knuckles3	1	0.2	539

The changeover time is not included in current study. As discussed in Cases I and II, minimized printing time means minimized printing energy in fabricating a complex part using multiple printers.

5 Discussions and Conclusions

In the real world, a large amount of FDM printers have been put into service in product innovation, rapid prototyping, and manufacturing. Practitioners in this industry still primarily concern the material characteristics, surface quality, and productivity. The issue of sustainability is often overlooked. One may argue that, for example, the energy consumption of a desktop FDM system is much smaller than other manufacturing equipment, but accumulatively, energy saving is not insignificant.

To respond to the research needs, a research framework is proposed in this chapter to guide the further research projects in an easy-connected and well-organized manner. Under the umbrella of sustainability, all aspects, that is economic, social, and environmental, and their balance, can be understood. Qualitative analysis should always be supported with quantitative analysis and verified with experiments or test implementation. Developing proper quantitative measures is another important and interesting topic.

Moving from the development of research framework to the three research case studies, it clearly demonstrated the usefulness of having a research framework in connecting and organizing research projects. Motivated by improving sustainability of FDM processes, Case I investigated the influential parameters on energy and surface roughness of a printer, and Case II studied selected parameters on the different printers. Their results naturally support the minimization of printing time and help in parameter configuration in Case III. This also helps to connect to the results in the existing literature, such as printers produce a same part consumed different energy due to different machine specifications and configurations; thus, careful printer selection is required [41]. Five conclusions can be drawn with the results of all three cases which are as follows:

1. For a FDM printer, the most influential factor on energy consumption is layer thickness, followed by printing speed and infill ratio. Surface roughness is affected by these parameters at the same order, which makes layer thickness the major conflicting factor.
2. In terms of energy consumption, these parameters significantly affect the printing time rather than power. Printing speed is a composite value, which affects energy and surface roughness, but must be carefully studied among different printers. In terms of surface roughness, layer thickness produces staircase effect, but printing speed also introduces vibration at sharp or irregular areas, which produces unexpected wavy surfaces. Engineer to the right required quality and get first part right will reduce the waste.

3. In general, higher printing speed can effectively reduce energy consumption and maintain good surface roughness. Infill ratio may affect the mechanical properties of a part, but most FDM parts are not designed for heavy loads.
4. The study on three different printers indicated distinct energy behavior and surface finish, because of different machine structures and configurations. This provides an energy-saving opportunity by machine selection.
5. Printing time scales with printing volume and build height, and the complexity of the part leads to a compounding effect on printing time. To fabricate multiple parts, a good planning is highly recommended that will improve productivity and energy consumption.

Some limitations exist in current study. First of all, the research framework is not detailed enough to generalize a stepwise procedure; this can be improved with more ongoing research projects. All three FDM printers adopted were low-end editions, which do not have advanced functions to optimize energy efficiency and high deposition accuracy. In case three, the changeover time and hidden cost of printing part change are not considered, which weakens it practicability and may be misleading when the change is very frequent.

Furthermore, the observation of surface morphology suggests that the desktop FDM printers achieve an adequate surface roughness, but the actual surface may contain irregular spikes and unevenness. AM is a family of various unique and powerful technologies; the research on their sustainability is critical. Future work will focus on the refining the research framework and developing quantitative evaluation methods.

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Sustainability in Welding and Processing

Kush P. Mehta

Abstract Sustainable manufacturing considers environmental impact, energy utilization and economic impacts on process of creating product. Welding and processing is one of the most important elements of manufacturing field. Sustainability in welding and processing is the area of concern for today's field of manufacturing. The present chapter elucidates components of sustainability for different welding and processing techniques. The discussions on energy saving, material waste, resources and parameters, environmental benefits and cost-saving capabilities of different welding processes are highlighted. Aforementioned sustainable interventions are addressed under various categories of welding and processing such as fusion arc welding, friction-based welding and processing, laser-based welding and processing, magnetic field-based processes and ultrasonic welding.

Keywords Energy · Environmental impact · Processing · Sustainability Welding

1 Introduction

Welding and processing is one of the most important elements of manufacturing field. Welding is a type of primary manufacturing processes that utilizes heat and/or pressure to obtain the bonding between base materials. The processing of materials uses different manufacturing processes to process the material from raw material properties to desired properties. Welding is used to make assembly of different components of final product. Based on the application of heat, the welding processes are classified such as gas welding processes, arc welding processes, solid-state welding processes and resistance-based welding processes. These welding processes are applied to a variety of materials considering its applications

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in different sector of industries. Similarly, different processing techniques are developed for the range of materials for various applications.

Sustainability is a concept of ability to sustain for a longer period of time considering futuristic social, economic and environmental impacts as presented in Fig. 1. Societal benefits and issues, economic considerations of right from the set-up, maintenance and process operations and environmental impact of manufacturing process as well as manufactured product are generally considered to measure the sustainability of specific manufacturing process. The implementation of sustainability in manufacturing is considered as positive contribution to the society. The sustainable manufacturing adds one more dimension in Fig. 1 that is “technology”. Taking into considerations of these dimensions, sustainable manufacturing is defined by Garetti and Taisch [1] as “the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economical, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life”. Welding and processing is an important part of manufacturing field that plays a major role to manufacture final product. The sustainability in welding and processing is important to understand as it is an essential part of manufacturing industries. Therefore, sustainability in welding and processing is the area of concern for today’s field of manufacturing. Sustainable welding and processing is one of those components of manufacturing in which the product is welded or processed considering its factors of sustainability such as energy consumption, material wastage, applied resources, efficiency, cost-saving, quality, environmental benefits as represented by Mehta [2] (see Fig. 2).

In recent decades, industrial and scientific communities have shown an increase in awareness of environmental impact and the need for sustainability. In such context and analysing the current tendency, selecting the proper welding and processing techniques for a given application certainly plays a key role with respect to the sustainability of product manufacturing. There are various welding and

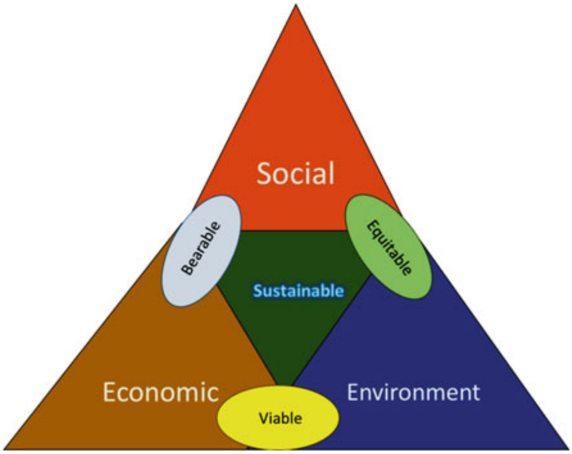

Fig. 1 Dimensions of sustainability

Fig. 2 Factors affect sustainability of welding and processing [2]

processing techniques widely studied, optimized and applied in several industrial fields. However, there is still a lack of knowledge in terms of comparative energy saving and material waste studies. In this regard, environmental sustainability is nowadays a remarkable issue and the main concerns are related to more efficient use of materials as well as energy. From the perspective of a decision-maker, it is also important to take into account the entire set of considerations with regard to resources and parameters, environmental benefits and cost saving related to the sustainability contributions offered in any phase of a welding and processing product life cycle.

Sustainable welding and processes are those processes in which the energy consumption is minimum, process efficiency is maximum, minimum environmental degradation effects, better quality with minimum resources and minimum material waste during process operation. Quantitative analysis on aforementioned factors can provide details on sustainability of welding and processing. It is documented that conventional arc welding processes are lacking in majority of the sustainability elements relative to advanced welding processes. Major concerns of arc welding processes are formation of health hazardous and environmental unfriendly fumes from shielding gas or flux, more energy consumption during process run, more material wastage, defects formation, large resources and process parameters. Hybrid welding processes and solid-state welding processes are reported better in above-mentioned elements of sustainability.

The main objective of this chapter is to give an overview of the most important topics concerning welding, joining and processing issues related to energy and resource efficiency with the aim to stress the principal contributions which may derive from such processes to environmental sustainability [1–6]. This chapter considers available literature on analysis of sustainability elements for different welding and processing techniques considering reader's basic understanding on welding and processing.

2 Fusion Arc Welding

Fusion arc welding is type of welding classification, in which intense electric arc is focused on the workpiece material in order to melt the material that subsequently leads to the joining via solidification after the ejection of arc [7–16]. Fusion arc welding processes generally operate at higher amount of electrical energy, with consumable electrodes (in most of the welding processes) and large number of parameters to operate, shielding gases or flux and post-processing of weld, which adversely affect the sustainability components. Additionally, process incapability for joining different ranges of materials such as dissimilar materials, nonmetallic materials, composites and shape memory alloys limits it to opt for sustainable applications [7–16]. The accountability for sustainable manufacturing in case of fusion welding processes is presented in Fig. 3, based on life cycle inventory phase. As mentioned, electricity is required in the case of fusion welding processes, and therefore, the energy consumption can be decided with measure value and wall plug efficiency with respect to specific process. Secondly, the amount of filler wire consumed to obtain specific length should be measured as input of the process. Next, in the case of arc welding, most of the processes are operated with consumable electrode having a coating of metal or flux. In the case of flux coating, the flux material is wasted in form of slag that should be taken into account while studying sustainability. Flux-coated electrodes result in electrode stub loss as output that is waste of material [14]. The gaseous form of shielding is required to protect

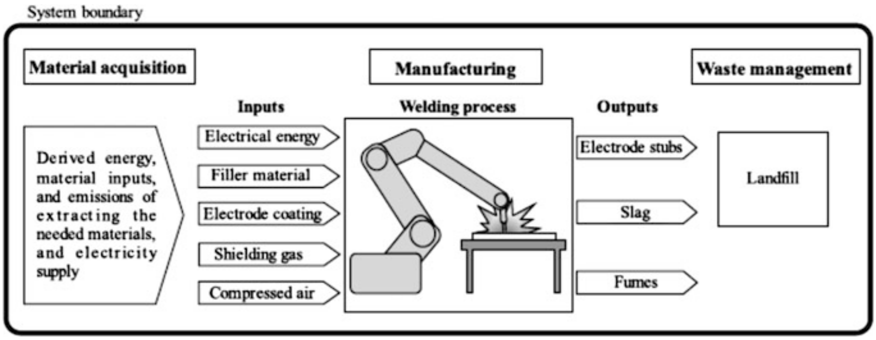

Fig. 3 Inputs and outputs of fusion welding processes for life cycle assessment, with kind permission from [14]

atmospheric contaminations of the weld pool. However, the shielding gases are hazardous and lead to the adverse effects on the environment. On the other hand, shielding through gases generates fumes that have pronounced effects on the environmental damage.

In fact, different approaches of advanced optimization tools, hybrid welding techniques and application of advanced joining and welding techniques are difficult to employ with fusion arc welding processes despite its capabilities on sustainable views. The reasons may be listed as large numbers of process parameters, limitations of workpiece materials, set-up limitations, environmental pollution, higher set-up and operating costs, higher level of energy consumption and so on. Nevertheless, these approaches can be treated as various ways towards sustainability in the case of fusion arc welding processes. Different fusion arc welding processes are discussed as under for different sustainability components such as energy consumption and utilization, material waste, resources and parameters, environmental effects and cost-saving capabilities [1, 2, 7–16].

2.1 Shielded Metal Arc Welding

Shielded metal arc welding (SMAW) is also known as manual metal arc welding as it operates manually through skilled welder. SMAW is operated with consumable flux covered electrode, which is having similar properties of the base material. An arc is established between tip of the electrode and workpiece material. This arc is responsible to give large amount of heat to the workpiece and electrode materials that subsequently melts and causes coalescence by its solidification upon cooling. In order to generate arc, electrical energy is supplied between electrode and workpiece that is not in the contact. Avalanche motion of the electron from −ve charge to +ve charge causes arc by means of initial striking of electrode on workpiece. Hence, electrical current and voltage are most important process parameters of the SMAW. Besides this parameters, the process parameters such as travel speed, electrode diameter, type of electrode, weld joint preparations, arc length and slag removal are additionally influencing the SMAW process. Flux coating of electrode provides shielding at the time of welding that in turn helps to remove the presence of existing atmospheric air from the weld pool area and that is how formation of defects caused by shielding is reduced. The electrode used in SMAW is having limited length, and therefore, multiple electrodes are required to fill the material in case of large weld volume. The use of limited length of electrode leads to create problem in full utilization of that material. Unutilized material of that limited length electrode is called stub loss.

SMAW requires flux-coated consumable electrode, large number of process parameters, multiple numbers of passes and joint preparations of base materials to operate, which in turn adversely affect sustainability [10]. Additionally, the material wastes through stub loss, flux loss as a slag formation, material loss of workpiece during joint preparations and post-welding grinding are maximum among all the welding processes. SMAW is having low-process efficiency as it runs manually that is against of sustainability. Chang et al. [11] claimed that SMAW contributes maximum on environmental effects of global warming potential, photochemical ozone creation potential, acidification, and eutrophication relative to other fusion welding processes of manual gas metal arc welding, automatic gas metal arc welding and automatic hybrid laser arc welding. They additionally noted that the use of filler material and coated flux is very high in case of SMAW compared to of manual gas metal arc welding, automatic gas metal arc welding and automatic hybrid laser arc welding. The health of welder who is working on SMAW process is at risk because of fumes coming out from melting of flux are very health hazardous [10].

2.2 Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW) and Plasma Arc Welding (PAW)

GMAW process uses consumable electrode with continuous feeding to weld pool area with gas shielding. The coalescence is produced with the help of heating the workpiece through established arc between consumable electrode and workpiece. The GMAW process can be automatic or semiautomatic. GTAW process is operated with tungsten electrode, which is nonconsumable. The arc is established in such a way that maximum heat is available at the workpiece and minimum at the tungsten electrode so that electrode remains non consumable. As electrode is non consumable, GTAW cannot result in more than 4 mm penetration (i.e., maximum depth of weld towards the direction of workpiece thickness) in an autogenously operated mode [2]. PAW is a variant of GTAW and operates on same process principle of nonconsumable electrode and workpiece arc establishment, as discussed above. The major difference in PAW is plasma gas that is formed with the interaction of inert gas with an arc through additional set-up in torch. PAW is operated with plasma arc as well as shielding arc, and therefore, its utility of inert gas is maximum relative to other arc welding processes. PAW is leading to constricted arc, and due to the same, the penetration level is enhanced drastically.

GMAW, GTAW and PAW are the types of arc welding processes that are operated with gas shielding around welding electrode in order to protect the weld pool from the atmospheric contaminations unlike flux shielding of SMAW process, in order to obtain better weld bead profile and weld properties. Shielding gases such as argon, helium, CO_2 or multi gases mixture are used in general practice. However, fumes generated from the shielding gases badly affect human health as well as environment. It is reported that most of the fumes generated from the shielding gases are cytotoxic and biotoxic, which increases the possibility of lung cancer to the welder [8–16]. Therefore, different fume extractors and proper ventilation systems are kept at the weld area. However, 100% extraction of those gases is not possible. Other problems highlighted as being fusion welding process associated with SMAW are also presented in case of GMAW, TIG and PAW [8–16]. However, affection towards sustainability is different for all the cases.

Recent technological innovations of fusion arc welding such as activated TIG (A-TIG) welding, hot wire TIG (HW-TIG) welding, key hole TIG (K-TIG), narrow-gap GMAW, tandem GMAW, twin wire GMAW, activated GMAW (A-GMAW), metal-cored arc welding (MCAW) can enhance the factors of sustainability in different ways. A-TIG is an advanced welding process, wherein the layer of liquefied flux is pasted on the workpiece before the welding phase. Liquefied flux is nothing but the mixture of oxide/fluoride flux with acetone/ethanol. A-TIG enhances penetration up to 6–7 mm of weld without the use of consumable in an autogenously operated mode which subsequently saves materials of consumables and reduces energy requirement as well as overall fumes as single pass is enough to obtain 6 mm penetration [17]. Similar to the A-TIG process, A-GMAW is developed by the application of flux before welding phase. In case of A-GMAW, even more than 6 mm weld penetration is possible with the use of consumable electrodes [18]. HW-TIG is operated with additional filler wire. It is a process in which consumable material of filler wire is preheated well before the welding that subsequently improves productivity as deposition capacity (i.e., transfer of melted material into a weld pool) of welding electrode is enhanced [2]. However, preheating of electrode requires extra energy as preheating is applied with the help of electrical energy similar to arc welding processes. K-TIG is a variant of conventional GTAW in which keyhole is formed at the weld pool and consequently increases penetration as well as productivity. K-TIG follows most of the factors of sustainability by having 80% reduction in average welding and fabrication costs along with major advantages of 100 times faster than normal GTAW, low maintenance, weld penetration up to 16 mm in a single pass, massive reduction of in power and shielding gas usages and elimination of grinding or reworking requirements [15]. Narrow-gap GMAW is a type of advanced welding process, which is applied to narrow-gap joint configuration without complicated edge preparations such as V-groove/U-groove/J-groove. Butt joint configuration of narrow-gap weld requires flat edge preparation, and workpieces are kept very close in a narrow gap. Narrow-gap GMAW can save a large amount of materials for thick workpiece materials as no edge preparations are provided. Tandem GMAW and twin GMAW processes are operated with multiple filler wires, which improve energy consumption and weld productivity. It is reported that energy efficiency, environmental effects and welding time can be enhanced by 24, 11 and 50%, respectively, as compared to the conventional GMAW. Results reported by Sproesser et al. [17] are presented in Table 1 and Fig. 4.

2.3 Submerge Arc Welding (SAW)

Submerge arc welding (SAW) is another process in which arc is established between continuous feeding electrode and workpiece. In the processes of SAW, arc

Table 1 Results of single wire GMAW and tandem wire GMAW for sustainability analysis obtained from life cycle assessment model [16]

	Single wire conventional GMAW	Tandem wire GMAW
Number of passes	16	6
Welding time in min	40	18
Energy consumption in kWh	9.1	6.9
Filler material consumption in g	4200	4200
Shielding gas consumption in l	816	664
Direct emission in g	FeO_x: 14	FeO_x: 12
	CO: 6.1	CO: 5
	NO_x: 0.12	NO_x: 0.1
	O_3: 0.4	O_3: 0.3

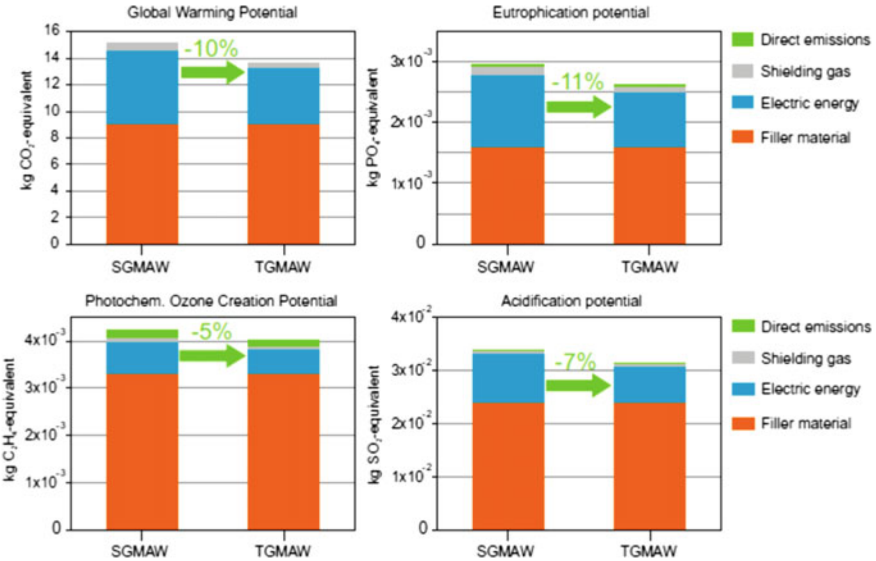

Fig. 4 Environmental effects of single wire GMAW (SGAMW) and tandem GMAW (TGMAW) [16]

is shielded by granular form of flux and process occurs under the blanket of that flux; hence, arc is not visible. As SAW process is operated under the blanket of flux, the problems such as smog, flash and spatter are avoided. SAW is widely used in industries considering its advantages of high productivity and quality welds. Due to this, the cost per unit length of joint made by SAW process is less relative to other arc welding processes. As shielding gases are not required in SAW process, the environmental effects and health issues of welder are in favour with sustainability, which is not the case for GMAW, GTAW and PAW [8–16]. In SAW, the flux powder gets melted and forms blanket over the weld of slag that in turn protects weld and allow to obtain proper shape of weld bead profile [14]. However, after complete solidification, the slag cannot be reused and that is wasted. Besides, nonsolidified flux that is available on the slag layer can be reused after its proper backing. Granular form of flux not allows to adopt process for all the joint configurations and positions with existing typical set-up of SAW. In addition to this, defect such as flux inclusion is a major problem for the multipass SAW process. Very high power supply is required for this process wherein current applied is up to the range of 1500 A that in turn leads to the requirement of high electrical energy compared to other arc welding processes. SAW is operated with a large number of process parameters similar to GTAW, GMAW and PAW. SAW saves material of filler wire as no edge preparations are required under 12-mm-thick workpiece due to process advantage of high current density (i.e., higher current utilization per unit length). This in turn leads to disadvantage that thickness smaller than 4 mm cannot be recommended to effectively weld by SAW in most of the cases.

3 Solid-State Welding Processes

Solid-state welding processes are operated in a solid state of material that means without the melting of the material. The workpiece material is taken up to its deformation through application of heat and pressure together or individual. Friction, mechanical vibrations and high-impact energy are used as different sources of heat energy. As the melting of material is not present in case of solid-state welding processes, these processes have a number of advantages in terms of sustainability relative to fusion arc welding processes as shown in Fig. 5. The issues related to sustainability are limitations of joint configurations, thickness and adoptability for the range of materials need to be worked out. Discussions of sustainability of different solid-state welding processes are presented subsequently in subsections.

3.1 Magnetic Field-Based Welding

Figure 6 shows process principle of magnetic pulse welding (MPW). The electromagnetic forces are produced between the coils and workpiece materials with very short pulses. This in turn produces high amplitude, frequency and current pulses, which consequently generates eddy current towards one of the workpiece side. This in turn leads to create high repulsive magnetic forces and subsequently high magnetic pressure, which causes an impact on another workpiece. In the end, the impact with adequate collision velocity leads to the plastic deformation required for the welding. It is reported that process parameters such as adequate impact

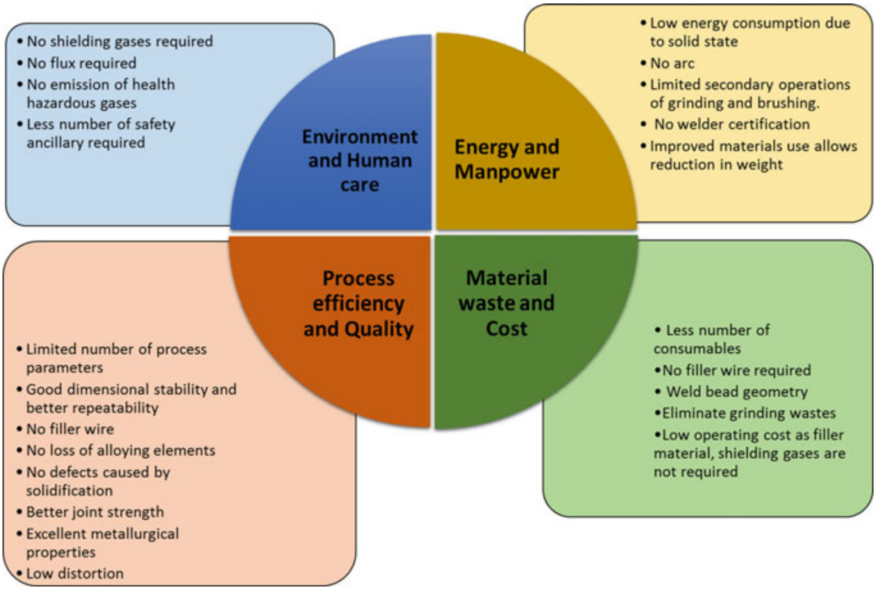

Fig. 5 Advantages towards sustainability of solid-state welding processes over fusion welding processes

velocity, subsonic collision, and pressure are most influenced to the welds, in case of MPW [1, 19–21].

The mechanism of MPW to obtain a weld is similar to an explosive welding as it utilizes impact energy for the material deformation [19–21]. However, the use of chemical explosives is mandatory to obtain a weld in case of explosive welding, which is against the sustainability, whereas no use of chemical explosives makes MPW process more sustainable along with its special advantages of sustainability. MPW process obeys many factors of sustainability as material melting is not involved during welding [19–21]. Shielding gases greatly affect the sustainability as

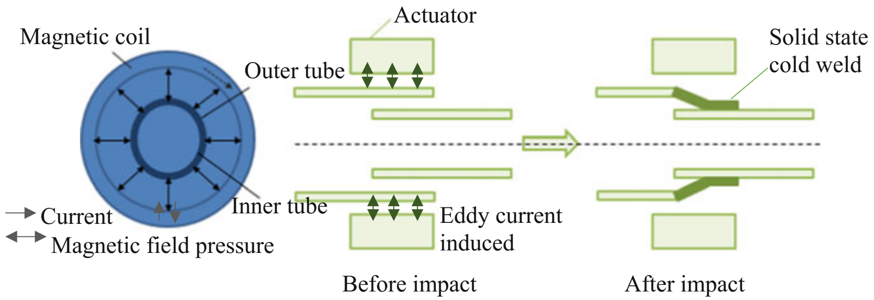

Fig. 6 Process principle of magnetic pulse welding [19]

mentioned above (refer Sect. 2), which is totally eliminated in case of MPW due to its solid-state nature. MPW carries unique characteristics towards sustainability such as high precision, great process repeatability, no consumable filler wire required, and formation of heat affected zone and residual stresses are eliminated [2]. MPW requires minimum post-processing of machining such as grinding and polishing as it is a solid-state welding process. MPW is fast-welding process and best suitable for the mass production. The mechanical strength obtained by MPW can be even stronger than the base material [19–21]. The process efficiency of MPW is higher than the fusion arc welding processes due to higher welding strength, less time operation and process flexibility. The fabrication of components for different geometries of sheet metal products, shafts, and lightweight tubular structures can be easily performed using MPW process [19–21]. MPW can be effectively utilized for joining of dissimilar materials that in turn lead to overall weight and cost reduction benefits. Additionally, MPW is capable to reduce the generation of intermetallic compounds (IMCs) to a great level in case of dissimilar materials joint, which can be seen as improved process performance element [22]. Unlike fusion arc welding processes having a large number of process parameters, MPW has a limited number of process parameters, which can be treated as minimum resources of process. Due to this, process parameters of MPW can be easily adopted with advanced optimization tools for process–property–structure correlation [19–22]. In case of energy consumption, MPW uses less amount of electrical energy relative to the fusion welding processes as the electrical energy is only required to generate electromagnetic forces between coil and workpiece material. However, the consumption of electrical energy must be considered for the sustainability. Despite these advantages, MPW is not so popular in the real applications of different industries [2]. Researchers have investigated MPW in a limited manner compared to the other available welding processes [19–21]. Nonconductive materials cannot be joined with the help of MPW process as electrical conductivity plays a role for the material deformation via electromagnetic field [19]. Statistical investigations on MPW for sustainability are lacking that can provide an exact idea with percentage amount on each factor of the sustainability.

3.2 Ultrasonic Welding

Ultrasonic welding is process in which ultrasonic vibrations are applied to the workpieces under the effect of pressure in order to deform the material in solid state, which consequently leads to the formation of weld [2]. Most common materials adopted for ultrasonic welding are plastics, which is the process extension of materials as the plastics are not so commonly welded by conventional welding processes [23, 24]. Ultrasonic welding is well suited for dissimilar materials due to its solid-state nature. Process parameters such as ultrasonic power, clamping force, welding time, frequency and vibrational amplitude are need to be settled optimum for obtaining sound weld. Limited process parameters are easy to handle and at the same time comfortably adopted in optimization techniques, which actually enhances process efficiency. Ultrasonic welding is also solid-state welding process, and hence, there are no issues of environmental degradation effects [2]. Energy requirement for the ultrasonic welding can be identified by the equation of $E = K (HT)^{3/2}$, where E is electrical energy, H is Vickers hardness number and T is thickness of sheet [25]. Therefore, it can be noted that less electrical energy is required than fusion welding processes, resistance welding and MPW as only solid-state deformation is needed to perform welding [2]. Ultrasonic welded joints are directly ready to use, and post-fabrication of machining or grinding is not required as similar as reported in case of FSW and MPW. No consumables are required for the ultrasonic welding that lead to the material savings [2]. Ultrasonic welding can be successfully applied to the electronic component welding for micro- and nano-applications with better efficiency [1, 23, 24, 26]. Ultrasonic welding has different variants such as ultrasonic seam welding, ultrasonic torsion welding and ultrasonic spot welding that gives process extension for different configurations and applications [23]. Besides, ultrasonic welding is limited to the thin sheets, foil and wires, which is a biggest limitation for the sustainable applications. As per the above equation of the electrical energy requirement of ultrasonic welding, it can also be noted that the increase in hardness of the material leads to increase in difficulty for joining [23–26]. It is reported that the higher hardness material is limited up to 1 mm thickness to obtain a successful weld [2]. Super-hard materials with higher melting point are not recommended for the welding by ultrasonic technique as the deformation is difficult to achieve in that case, which is another disadvantage towards sustainability.

3.3 Friction-Based Welding and Processing

Friction-based welding and processing are depended on frictional heat deformation in a solid state [27]. Friction welding, friction stir welding, friction stir spot welding, friction bit joining, friction stir extrusion, friction surfacing and friction stir processing are examples of friction-based welding and processing techniques [1, 27–31]. Discussions of these processes for their sustainability are presented below.

3.3.1 Friction Welding

Friction welding is shown in Fig. 7 for its process principle. It requires higher amount of frictional heat and pressure for specific time in order to produce successful weld, which needs high electrical energy. However, the energy required is less than the fusion welding processes as the material deformation is only a requisite rather than melting of material [32–34]. After the welding, grinding and finishing need to be performed as it leads to the splashing effect as shown in Fig. 7. Splashing effect occurs due to expelling of deformed material caused by a large

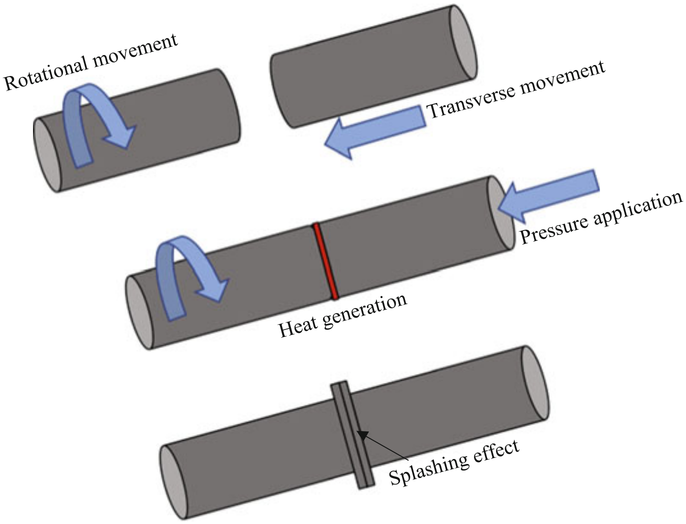

Fig. 7 Process description of friction welding

amount of frictional heating. Wastage of these splashed materials is an adverse effect towards sustainability. In terms of process capability, the friction welding is restricted for specific joint configurations. Asymmetry in joint configuration and complexity of workpiece surface area to be joined are difficult to weld with friction welding.

On the other hand, the elements such as environmental benefits, minimum resources and energy consumption are in the favour of sustainability for friction welding. The reason for this is no shielding gases, fumes and environmental adverse effects are generated from the process. The process parameters are also less than conventional fusion welding processes [34].

3.3.2 Friction Stir Welding

Friction stir welding (FSW) is a variant of the friction welding technique in which a nonconsumable tool is brought into the abutting surfaces of workpieces to be joined [27]. Frictional heat is generated with the help of this tool, and workpiece material is transported by rotational speed and transverse speed of tool (see Fig. 8 for process principle). FSW is very popular as “green process” in the welding community due to its advantages of environmental effects [1, 27]. The FSW is obeying the majority of the sustainability elements. In terms of energy benefits, FSW requires less power to perform successful process. It is reported that FSW needs 2.5% of less power required relative to laser welding technique, which leads to the overall power savings [1, 27]. FSW has proved its excellent potential on different combinations of dissimilar materials such as aluminium (Al)–copper (Cu), Al–steel,

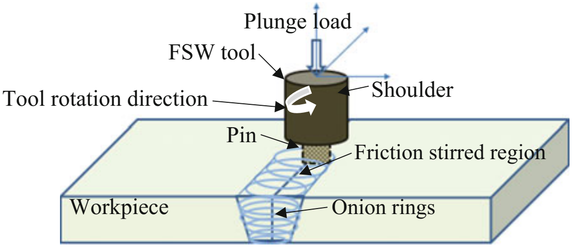

Fig. 8 Concept figure of friction stir welding [2]

Al-titanium (Ti), Ti–steel, Cu–steel, Al–magnesium (Mg) and Ti–Mg, which ultimately provides benefits of cost saving, lightweight and overall efficiency [35–44]. FSW is also applicable to make joints of plastics and polymers that extends process capability. Splashing effect mentioned in the previous section is majorly eliminated by FSW; hence, the material wastage is very low relative to friction welding and also to other processes. FSW is capable to apply on different joint configurations with specially designed fixture [27]. FSW has limited process parameters and required minimum resources even for the reactive materials, which makes it advantages towards sustainability [2].

The sustainability is evaluated in the literature for FSW based on lubricant used in FSW machined, burrs produced during welding phase and heat emitted in the atmosphere during process [45]. It is reported that process parameters significantly influence above-mentioned conditions [1, 27, 45]. Hence, optimization of process parameters is mandatory on the scale of above-mentioned conditions.

It has been narrated that friction welding using external tool on tube to tube-type joint is an eco-friendly method to obtain successful joint relative to GTAW process via mathematical calculations [45]. Friction welding of external tube has proved its superiority on percentage of mass utilization, labour cost, consumable charges and power charges [45].

3.3.3 Friction Stir Spot Welding

Friction stir spot welding (FSSW) works on similar process principle like FSW. In case of FSSW, the travel of tool is not provided as in case of FSW. The tool is inserted in the workpiece material up to some extent and holds for some time that leads to the joint formation. FSSW has replaced resistance spot welding of automotive industries due to its technical and sustainable advantages. It is reported in the book of Mishra et al. [28] that the FFSW can reduce energy consumption up to 99% relative to conventional spot welding process. In addition to this, the installation cost of FSSW can be saved up to 40% approximately compared to the resistance welding process [27, 46]. The process efficiency is high as the process is operated with highly controlled robots [46]. Technological developments of FSSW such as stitch FSW, refill FSSW, rotating anvil FSSW and swing FSSW have eliminated discrepancies of keyhole formation [47–49]. FSSW can be applicable to materials having plastic deformation capabilities irrespective to its conductivity; hence, it increases its capability on number of materials for different applications. Besides, resistance spot welding needs conductive materials to be joined [50].

3.3.4 Friction Bit Joining

Friction bit joining is a technique applied to the workpieces with consumable material of tool, which is inserted and detached after obtaining its bonding with workpiece materials. It is obvious that the energy needed in friction bit joining is higher than the FSSW based on its process principle. Material wastage is also higher than FSSW as it operates with consumable tool [29]. However, the keyhole obtained after FSSW and FSW can be filled by friction bit joining which serves as economic and simple solution for keyhole closure. Friction bit joining is successfully applied to achieve dissimilar joints, which makes overall lightweight structure and cost reduction [29].

3.3.5 Friction Stir Extrusion

Friction stir extrusion is a process of welding, which joins dissimilar materials. The process is advantageous in terms of sustainability as it eliminates formation of IMCs and tool wear relative to conventional FSW [30]. Otherwise, the process is similar to FSW. Nevertheless, friction stir extrusion requires groove or slot at the weld area which needs to be done by machining or some other manufacturing process. This is where the sustainability elements such as material waste, energy consumption and complexity in joint configuration are lacking relative to FSW process [2].

3.3.6 Friction Stir Processing

Friction stir processing (FSP) is a technique to modify the microstructure of the base material with the help of nonconsumable rotating tool. The working principle is same as FSW. Only the difference is workpiece material, which will be of single plate instead of two different plates of FSW [27]. FSP is advantages over other techniques related to microstructural modifications in terms of sustainability elements as it is fast, environmental friendly, less energy to operate, limited process parameters, ability to restrict the process for specific area and can be applicable to the multiple depths [27]. However, some of the issues such as tool wear and high-temperature materials arise, which are not in favour with sustainability. FSP is difficult to apply to high-temperature materials like steels, Ti and nickel as the deformation is difficult to obtain. Tool materials such as tungsten carbide, polycrystalline boron nitride and coated tool steels are required to opt for these higher-temperature workpiece materials, which increase overall cost [27]. The complex geometry requires to improve material flow inside the stir zone is a challenge to provide on these tool materials.

4 Laser-Based Welding and Processing

Laser emits light which is utilized to melt the base materials that leads to the welding after its solidification. Laser welding is a process in which, the heat has its controlled focus on weld area via laser spot [51]. Laser welding has narrow beam and operates at higher welding speed. Laser welding enables higher processing speed and less post-processing that consequently leads to an enhanced productivity [52]. Laser welding is capable to apply on nano-, micro- and macro-components considering it flexibility [26]. It can be applied to nonconductive materials, conductive materials, dissimilar combinations and dissimilar thicknesses [53]. Laser welding saves a large amount of materials relative to conventional welding processes. The energy consumption is less as the heat input is locally concentrated and leads to less emissions of heat too [54]. However, overall energy consumption calculated is found larger than conventional welding processes. The laser welding is rated as eco-friendly process [51]. Laser welding has proved its ability for hybrid welding processes wherein laser is used as trailing process [55]. Laser welding does not require large grove angle which is commonly required in the conventional welding processes. These are the advantages towards sustainability.

Laser is a useful source and successfully utilized for processing of materials through different approaches such as laser sintering process, laser powder welding, selective laser melting, laser. Selective laser melting and selective laser sintering create parts using a thin layer of powder material such as less than 0.1 mm with the help of selective fusion [56, 57]. These processes are sustainable manufacturing processes as the energy consumption is less and material wastage is minimum. There are some design benefits such as unlimited freedom to designer, mass customization of consumer goods, flexibility which are emerging sustainable elements of these processes [56, 57]. However, initial cost, selection of material and mechanical and metallurgical properties are some issues, which are considered as challenge for the sustainability.

5 Summary

The present chapter discusses different factors of sustainability for welding and processing techniques. The summary of sustainability factors for different welding processes discussed in the chapter is presented in Table 2.

Different elements of sustainability such as energy saving, material waste, resources and parameters, environmental benefits and cost-saving capabilities of different welding processes are addressed. Fusion arc welding processes are not

Table 2 Summary of sustainability factors for different welding processes

Welding process	Sustainability concerns	Remarks on solution towards sustainability
Shielded metal arc welding	• High electrical energy consumption • Maximum contribution to environment abasement due to the generation of unwanted gases • Stub loss and flux usage • Low-quality welds • Manual process (low process efficiency due to low accuracy)	• Energy consumption can be reduced with optimized process parameters • Fume extractor can reduced maximum environmental damage • Skilled welder is required to overcome problems of material wastage, low-quality welds and low process efficiency
Gas metal arc welding	• High electrical energy consumption • Cytotoxic and biotoxic fumes generation (shielding through gases) • Spatter formation affects weld quality • Large number of process parameters • Process stability	• Use of fume extractors and proper ventilation systems • Large number of process parameters can be effectively optimized to obtain quality welds • Hybridization of process can reduce overall energy consumption and process stability with increased weld quality
Gas tungsten arc welding	• Low productivity • Low penetration • Cytotoxic and biotoxic fumes generation (shielding through gases) • Large number of process parameters	• Advanced welding techniques such as A-TIG, HW-TIG and K-TIG are developed to overcome problems of low productivity and low penetration • Fume extractor and ventilation can overcome problem of fumes evacuation • Optimization techniques can be applied to optimize process parameters of TIG
Plasma arc welding	• Costly process • Very high electrical energy consumption • High usage of inert gases	• Optimization on usage of electrical energy and inert gases can solve aforementioned problems
Submerge arc welding	• Defects of flux inclusion, hot cracking • Complex set-up • Not applicable to all the weld configurations and positions	• Cleaning in subsequent pass is mandatory to avoid defects and proper disposal of slag • Special arrangements are developed to extend SAW process for some of the positions such as horizontal position and overhead position
Magnetic pulse welding	• Limited to electrically conductive materials • Thickness limitation • Joint configuration limitation • High energy requirement to develop magnetic field	• Optimization on usage of energy to develop magnetic field can solve problem of energy usage

(continued)

Table 2 (continued)

Welding process	Sustainability concerns	Remarks on solution towards sustainability
Ultrasonic welding	• High energyrequirement for higher thickness • Less efficient for high hardness workpiece (process is limited to the thin sheets, foil and wires)	• Workpiece materials like plastics, polymers and aluminium are generally subjected • Higher thickness should not be subjected to USW
Friction-based welding and processing	• Large amount of axial pressure is required • Splashing effect leads to material waste in friction welding • Limited joint configuration adoptability in friction welding • Exit-hole or keyhole formation in friction stir welding, friction stir spot welding and friction stir processing • Tool wear and tool material inclusion are major concerns that affect weld quality	• Optimization of process parameters are required to save splash out material and total energyrequirement • Exit-hole or keyhole remove or filling techniques are developed. • Selection of proper material of tool is required for FSW/FSSW/FSP
Laser welding and processing	• High energyconsumption • Complex and costly set-up requirement relative to conventional weldingprocesses	• Energy consumption can be reduced with optimized process parameters

recommended for the sustainable manufacturing. It can be summarized that solid-state-based welding processes are reported better on the scale of sustainability elements relative to fusion based welding processes. Solid-state welding processes are leading advantages of no presence of arc, fumes, porosity, spatter and solidification defects, low distortion, no filler wire need, no shielding required, less post-machining/-finishing, better dimensional stability, saving of consumables materials, which in turn draws its attention towards the favour of sustainability elements. Novel approaches such as hybrid welding, utilization of optimization tools, recent technological developments and awareness towards sustainable commencement need to be promoted and replaced especially for the factors such as energy savings, minimization in material wastage, enhancement on quality of welds/processed region, less resources and parameters, and maximum overall cost savings.

Considering available literature by keeping focus on sustainability analysis on welding processing, there is a need to develop clear understanding on different welding and processing techniques for all the factors of sustainability as few welding processes are analysed. It is also required to adopt advanced welding processes that are following majority of the sustainability factors in today's industry scenario. Solid-state welding processes can be further analysed and developed towards sustainability as most of it follows majority of the sustainability factors.

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Green Machining of Thin-Wall Titanium Alloy

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Abstract Titanium and its alloys are well known as difficult-to-machine materials due to low thermal conductivity and chemical adherent to cutting tools. Ti6Al4V is most widely used in a thin-wall structure application in the field of aerospace industry. Thin-wall machining encounters vibration and that furthermore increases fluctuations in cutting force. Select the type of machining process that generates sustainability in thin-wall machining is crucial to master. One of the innovations in conventional machining is to promote vegetable oils as the cutting fluids. These cutting fluids offer environmentally friendly cooling as well as lubrication to foster the cleaner production in the aerospace industry. Hence, the capable, sustainable cutting fluid has to be a future of the machining process. Minimum quantity lubrication (MQL) using coconut oil is recognised to be the green machining technique in milling titanium alloy. Coconut oils as nanofluids are attracting considerable attention due to good lubrication properties, non-toxic and biodegradable nature, and easy recycling. Therefore, it is a significant finding to observe the stability, dynamic behaviour, surface quality, and environmental aspects of cutting fluids in milling thin-walled Ti6Al4V. The findings reported in this chapter show

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that the use of coconut oil in the MQL system for thin-wall machining of Ti6Al4V is a promising innovation in the future of aerospace industries. At last, this chapter also sheds light on the treatment of exhausted cutting fluids.

Keywords Thin wall · Titanium alloy · Vibration · Surface quality
MQL · Nanofluids · Sustainable cutting fluids

1 Introduction

Cooling and lubrication are prime requirements in any machining process; therefore, cutting fluids play a pivotal role in machining. Cutting fluids cool, lubricate and thereby reduce the friction and heat generated in the machining zone. Even though cutting fluids have a reasonably low cost, their handling and carrying costs are very high, and their toxic nature and disposal are challenging [1]. It compels to choose the type of processes that are sustainable i.e., productive, clean, and green.

The primary means to control the tool wear propagations are to master the lubrication and heat removal rate in the machining process. One of them is the use of flood-cooling system. Although this system was proven at lower cutting speed, a decreasing performance occurs at higher cutting speeds. This phenomenon is caused by the high amount of heat generated in the critical areas (tool–workpiece interface), which cannot be reached by the cutting fluids; hence, the interface cannot be cooled. Ecological hazards, carbon cycle, operator's health issues, and mineral oils rising cost have brought to the utilisation of vegetable oils [2].

This limitation led to the use of MQL and cryogenic system in machining. The use of MQL, which required the gasification of oil mist, can absorb heat in the cutting area effectively. Another advantage of MQL is economical costs and an environmentally friendly technology. Nowadays, many researchers are trending to shift to use the vegetable oils as the cutting fluids. It possesses a higher boiling point, higher flash point, and excellent lubricity properties, hence lesser loss in the oil mist [2].

Initially, almost all of the research regarding machining on Ti6Al4V all this time were focused on high-speed machining, which followed by the technique, that enables the applying of the dry-cutting condition. Furthermore, the development of machining on Ti6Al4V leads to the utilising of vegetable oils as cutting fluids, mainly palm oil. Unfortunately, the abundance of palm oil could not cover the fact that palm oil contains at least 50% unsaturated fatty acid [3]. The limitation of this property affected the palm oil tends to be oxidative. The result of conventional machining on Ti6Al4V indicated the use of vegetable oil suitable for low and medium speed [4–6].

Current studies in thin-wall machining are focused on the use of finite element method (FEM). This approach was utilised in the analysing of stress distribution, deformation, mechanical vibration, geometric accuracy, and surface quality [7–10].

The important factors such as variable cutting force, tool deflection, and machining stability are not taken into account in the existing FEM models. There is a lack of information concerning the thin-wall machining of Ti6Al4V using vegetable-based nanofluids as a lubricant and the treatment of wasted cutting fluids. Therefore, it is essential to evaluate the performance of thin-wall machining on Ti6Al4V under MQL using coconut oils as nanocutting fluids and the potential treatment of wasted cutting fluid before it delivered to the environment.

Thin-walled structures are common useful part of modern aircraft, such as the integral panel, framework shells, and thin-walled membranes to improve the equipment performance by designers [11]. Thin wall is defined by [12] to mean a typical machining process that forms a piece of specific height-to-depth ratio approximately 15:1 and wall thickness approximately 3–5 mm. Ti6Al4V is the most widely used titanium alloy in thin-wall design requirements.

Titanium materials have received much attention due to superior corrosion resistance and mechanical properties such as high strength, light weight, high wear, fatigue strength, tensile strength, and wear resistance. Hence, these materials are recommended for use in the aerospace and automotive industries. Titanium alloy also has much applications in the field of energy, biomedical, shipping, chemical vessel, turbines, and electrochemical industries because of its higher structural efficiency characteristics [13, 14]. However, the high temperature strength combined with the low thermal conductivity contributes to the poor machinability [15]. Thus, the Ti6Al4V is well known a typical difficult-to-cut material. This problem caused difficulties in dissipating the generated heat in the contact zone. It leads to the very high temperature condition, which occurs in the tool tip and severely impairs their machinability [14].

The first description and evidence of chatter were performed in 1907 by Taylor [16]. However, the regenerative chatter theory reported by Tobias at the 1950s is the first systematic study in this field [14]. Researchers explained regenerative chatter in orthogonal cutting and developed a stability lobe theory for a two-dimensional case in the 1960s. A new analytical form of the stability lobe theory for milling presented in the middle of 1990s. More recently, some research obtaining the stability lobe diagram of a chatter system with consideration of the change of cutting position and the changes of workpiece mass and stiffness during the milling process [17]. For example, [16] obtaining the stability lobes method. Thus a three-dimensional lobe diagram has been developed base on the relative movement of systems.

Low heat conductivity [18] reduced rigidity [11] and complex structure [17] of thin-walled titanium alloy parts are the primary cause of unwanted vibration during the machining process. The limitation in high-speed thin-wall milling of titanium alloy is caused mainly by occurring of a robust regenerative vibration known as chatter. The chatter is the leading cause of the machining process instability, tool wear, and inferior surface finish in the vertical milling of thin-walled Ti6Al4V [14]. Conventionally, the cutting speeds in machining of titanium alloys are often limited to 60 m/min. Thus, it also gives rise to enormously increasing machining cost [14]. Cost efficiency, sustainability, high productivity, and product quality are the major focusing factors in manufacturing industry these days. To fulfil the aforementioned, machining operations should have high material removal rate, energy, and resource efficient, tighter surface tolerances [19].

A central problem limitation which prohibits obtaining high productivity and quality of workpiece is the chatter effect which leads to the chatter marks on the surface, and such a result may be a prominent issue for high-speed and high-precision milling processes [17]. The surface topography indicated by [14] has an association with cutting vibrations. The flexibility of workpiece and system tool was investigated by [16], under the action of the cutting forces that produce a vibration, giving rise to an irregular surface or wavy. The cutting force signals in thin-wall milling analysed using Fast Fourier Transform (FFT) was reported by [14] for detecting chatter phenomenon. The theoretical chatter model proposed by [11] taking the stiffness characteristics of tool and workpiece into consideration aiming at the titanium thin-walled parts. The prediction seems to be a useful approach. Another research was carried out by [18], which propose to study the influence of the tool entering angle on the stability of the process and tool life based on cutting force in milling Ti6Al4V.

Many machining technologies have been focused on reducing the cutting zone temperature, in order to improve the machinability of the materials. In industrial practise, the cutting speed used to machine these difficult-to-cut materials is insufficient. Mainly, MQL and cryogenic machining have been employed to enhance the machinability of the materials through providing lubricity and suppressing high heat generation on the cutting surface during machining process of hard-to-cut materials, respectively [13].

The sufficient cooling system for controlling the cutting temperature in machining is significant for the tool life improvement, especially when dealing with titanium alloys that have low thermal conductivity [13]. The recent development of eliminating both environmental hazards and machining cost has led to the usage of Minimum Quantity Lubrication (MQL). In this chapter, MQL is used to refer to a minuscule amount of lubricant spray (2 up to 50 mL/h) in a mist directly near tool-chip and/or tool-workpiece contact zone to provide the necessary lubricity, which is lacking in dry as well as wet machining. This technique is sometimes known as a near dry lubricating [20]. The use of MQL conducts the gasification of oil mist, which could absorb the generated heat in the cutting area. Another excellence of MQL is ecological friendly and more economy. It was reported that management of cutting fluid or coolant costs at least 16% of the product cost [21]. MQL and cryogenic are classified as green machining techniques.

The machining performance was investigated by [13] using a variety of cooling systems such as flood cooling, MQL, and cryogenic. The investigation was performed using solid end mill on titanium alloy, Ti6Al4V. At the same trials, the cutting force was analysed through the tool breakage detection. Nevertheless, they found that the cutting force for MQL hBN 70 + cryogenic is higher compared to MQL hBN 70 which are 1011 and 865 N, respectively.

Another observation conducted by [15], reported that cutting force increases when high cutting temperatures occur. Thus results in tool life reduction and poor surface quality. Increase in MQL flow rate can reduce the cutting force and tool wear up to a certain extent only. It was found that machining with cryogenic conditions resulted in excessive tool wear and microfracture and increased the cutting forces. Cutting force increased significantly as the Ti-alloy hardens with the application of the liquid nitrogen during the cutting. The cutting force for MQL rapeseed oil and MQL + cryogenic are the same about 1000 N at 47.7 m/min and the cutting force at 76.4 m/min for MQL + cryogenic slightly lower than MQL. A paper reviewed by [21] in 2017 that MQL + $SCCO_2$ is not adequate for cutting force reduction. More concern reported by [13], when conducted deep hole drilling of Ti6Al4V. In this process, the cutting tool can be suffered from strong adhesion due to the lack of lubrication, when only cryogenic cooling employed. He concludes that the lubrication method such as MQL should be added for a better result in deep axial depth-of-cut machining.

Nowadays, many researchers have shifted to MQL using vegetable cutting fluids. Ecological hazards, operator's health, and mineral oils rising cost are important concerns where that vegetable oils can compete with mineral oils. Significant disadvantages of mineral oils are toxic, non-biodegradable, open carbon cycle, and non-renewable. Vegetable oils have a higher capacity to absorb pressure thus have good lubricity properties. They also have a higher flash point, better boiling point, and as a result, there is less loss from misting. Coconut oil has been used for machining AISI 304. The result shows that coconut oil improved the surface finish, reduced tool wear compared to mineral oil [22].

It has been proved that flood cooling, though very useful at lower cutting speed, gets ineffective at higher speeds. This problem caused by the amount of heat generation at the tool–workpiece interface, which cannot be reached by the cutting fluids; hence the interface cannot be cooled [15, 23]. The result from green techniques of milling Ti6Al4V was the power consumption of MQL is lowest followed by dry, cryogenic, laser-assisted machining, and wet machining [21].

During thin-wall milling of titanium alloy Ti6Al4V, the low rigidity can cause vibration. The phenomenon of the vibration is known as a chatter. When the rigidity of the thin-walled workpiece is far lower than the machine-tool system in the direction perpendicular to the machined surface, dynamic milling model of the thinly walled workpiece can be regarded as a 1° freedom system, as shown in Fig. 1 [8, 14].

The dynamic equations for the tool–workpiece system can be obtained as:

$$m_x\ddot{x}_x(t) + \zeta_x\,\dot{x}_x(t) + k_x x_x = F_x(t) \tag{1}$$

where m_{x}, ζ_x, and k_x are the modal mass, damping, and stiffness of the tool-workpiece system in the X-direction. $F_x(t)$ is the cutting force in the x-direction. $x(t)$, $\ddot{x}(t)$ and $x(t)$ are the vibrational acceleration, vibrational speed, and vibrational displacement of the tool–workpiece system, respectively.

The equation of free vibrations for the system by neglecting the damping and the external force can be written as Eq. (2) [24].

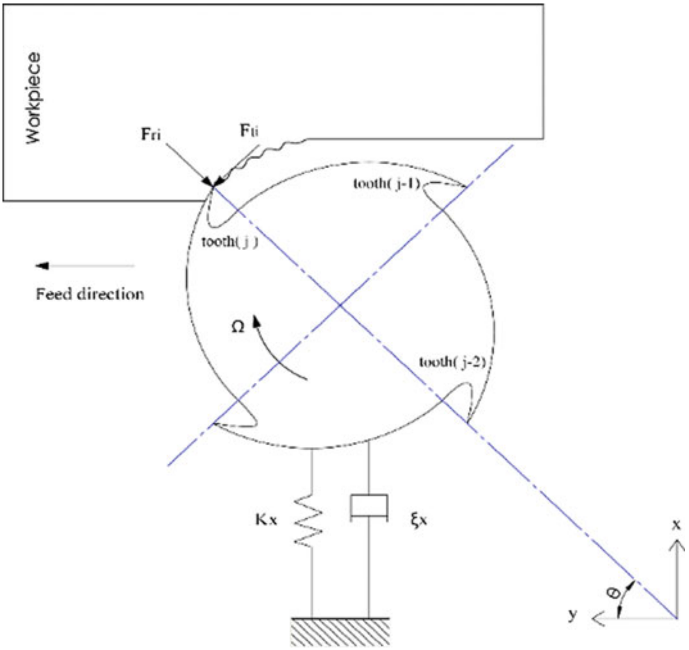


Fig. 1 Dynamic model of the thin-walled workpiece–tool system

$$M\ddot{x}(t) + Kx(t) = 0 \tag{2}$$

where M and K are the system mass, and stiffness matrices of size ($n \times n$), respectively, and x is the n-dimensional column vector of generalised coordinates. Equation (1) for a single degree-of-freedom (SDOF) system can be written as Eq. (3).

$$m\ddot{x}(t) + kx(t) = 0 \tag{3}$$

If $x(t) = x_0 \sin(\omega t)$, where $\omega = 2\pi f$ is the rotational frequency, then Eq. (3) becomes $(-\omega^2 m + k)\, x_0 = 0$. The solution of $(-\omega^2 m + k) = 0$ gives the natural frequency of the SDOF systems (f_n), as shown Eq. (4).

$$f_n = \frac{\omega_n}{2\pi} = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{4}$$

Similarly, Eq. (2) can also be written as

$$\left(-\omega^2 M + K\right)x_0 = 0 \tag{5}$$

Or could be written as

$$(K - \lambda M) = 0 \tag{6}$$

Equation (6) represents the equation of the eigenvalues and eigenvectors, where $\lambda = \omega^2$ are a set of the eigenvalues, the $\lambda = [\lambda_1, \lambda_2, \ldots \lambda_n]$, and the corresponding eigenvector matrices are $\varphi = [\varphi_1, \varphi_2 \ldots \varphi_n]$ or called normal mode.

To identify the frequency content of milling force signals, Fourier transform is commonly used to transform from the time domain to the frequency domain. Since the signals from sensors are discrete, discrete Fourier transform (DFT) usually is used. DFT is given by [14, 25, 26].

$$F(k) = \sum_{n=0}^{N-1} F(n) \exp\left[\left(\frac{-j2\pi}{N}\right) kn\right], 0 \le k \le N - 1 \tag{7}$$

Based on the periodicity, symmetry, reducibility, and orthogonal of the exponential part of Eq. (7), FFT reduces the computational complexity of an N-point DFT to about $N \log_2 N$ arithmetic operations.

$$SF = \frac{n}{60} = \frac{1000v}{60\pi D} \tag{8}$$

[[[[The frequency spectrum is discrete to periodic signals; the amplitude spectrum appears at its variation frequency and harmonics. In milling process, the signal of cutting force is periodic, and its variation frequency is tooth passing frequency (TPF), so the amplitude spectrum of the cutting force shows peaks at TPF and its harmonics. However, the peak value of milling force will usually appear at spindle frequency (SF) and its harmonics for the mill run out. SF and TPF are defined as

$$\mathrm{TPF} = N.\mathrm{SF} = \frac{1000Nv}{60\pi D} \tag{9}$$

where n and v are the spindle speed (in revolutions per minute) and linear speed (in metres per minute), respectively, and D is the diameter of the mill. On TPF, the appearance of peaks at additional frequencies indicates the chatter. This well-known property of milling dynamics is often exploited for the detection of the chatter.]]]

2 Experimental Work

The cutting test was carried out on a high-speed milling centre MAHO DMC 835 V CNC 3-axis VMC, with an 18,000 maximum rpm spindle. Experiment set-up is shown in Fig. 2. The end mill tools used AlCrN-coated solid carbide with four cutting edges, the diameter of 10 mm and overhang length of tools is 30 mm.

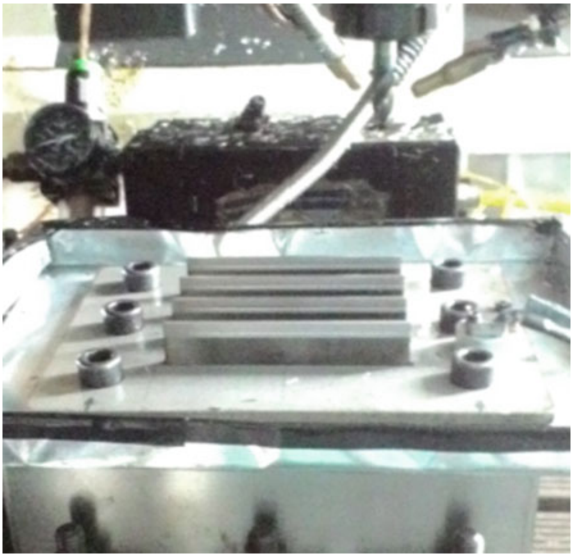


Fig. 2 Experimental set-up

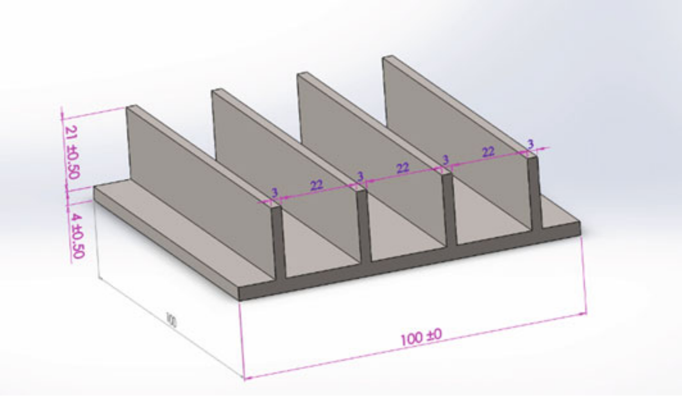


Fig. 3 Geometry and dimension (mm) of the workpiece thin-walled Ti6Al4V

The workpiece material was thin-wall titanium alloy Ti6Al4V (grade-5). Figure 3 shows the geometry and dimension of the thin-walled Ti6Al4V workpiece. The machining was done under MQL-cutting condition using coconut oils as the cutting fluids. The vibration of the workpiece was measured in the three directions of the tool feed (*x*-axis), perpendicular to the machined surface (*y*-axis) and the axial direction of the tool (*z*-axis). The workpiece vibration signal was monitored using accelerometer mounted on 35 mm in near the workpiece. The sampling rate in this experiment was set 20,000 s. The vibration signals magnified using a Daqcard

Table 1 Cutting process parameters

Trial numbers	Cutting speed (m/min)	Feed/tooth (mm/tooth)	Spindle frequency (Hz)	Radial DOC (mm)	Axial DOC (mm)
1.	64	0.063	135.76	0.32	7.07
2.	156.25	0.063	31.44	0.32	7.07
3.	100	0.025	212.12	0.32	7.07
4.	100	0.158	212.12	0.32	7.07
5.	100	0.063	212.12	0.32	7.07
6.	100	0.063	212.12	0.32	7.07
7.	100	0.063	212.12	0.32	7.07
8.	100	0.063	212.12	0.32	7.07
9.	100	0.063	212.12	0.32	7.07
10.	100	0.063	212.12	0.32	7.07

direct amplifier, and the analogue device was a National Instrument MX and collected by a data collection of the Dewesoft 7.0.6 software. The signals were analysed by MATLAB R2012a® software. To capture the surface quality, the Olympus STM6-LM was used. The thin wall was down milled with cutting process parameters are listed in Table 1.

3 Results and Discussion

3.1 Computation of Thin-Wall Natural Frequency and Vibration Analysis

The computation of thin-wall natural frequency is based on free vibrations with neglecting the damping. Natural frequency values are to compare with tooth passing frequency values of spindle speed in cutting parameters; it is done to avoid resonance or chatter in the machining process. The distribution of natural frequencies and mode shapes for SDOF is shown in Fig. 4. Based on Fig. 4 and Table 1, the frequencies of cutting parameters do not coincide with the natural frequency.

The mean values of workpiece acceleration at different cutting processes are shown in Fig. 5, in which x, y, and z represent the mean acceleration of x-direction, y-direction, and z-direction. It is observed that the increase in cutting speed and feed rate tends to increase acceleration in all the three directions. The acceleration value in y-direction or perpendicular to the machined surface is higher than the other directions.

The frequency and surface topography will be used to analyse further vibration analysis on thin wall. Figure 6 section first (time domain vs. acceleration) is shown

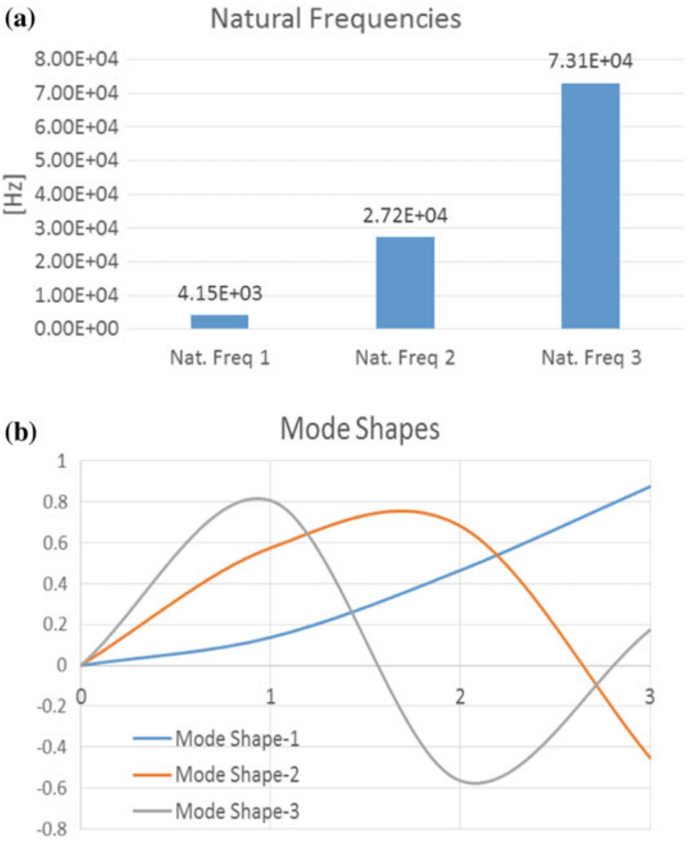
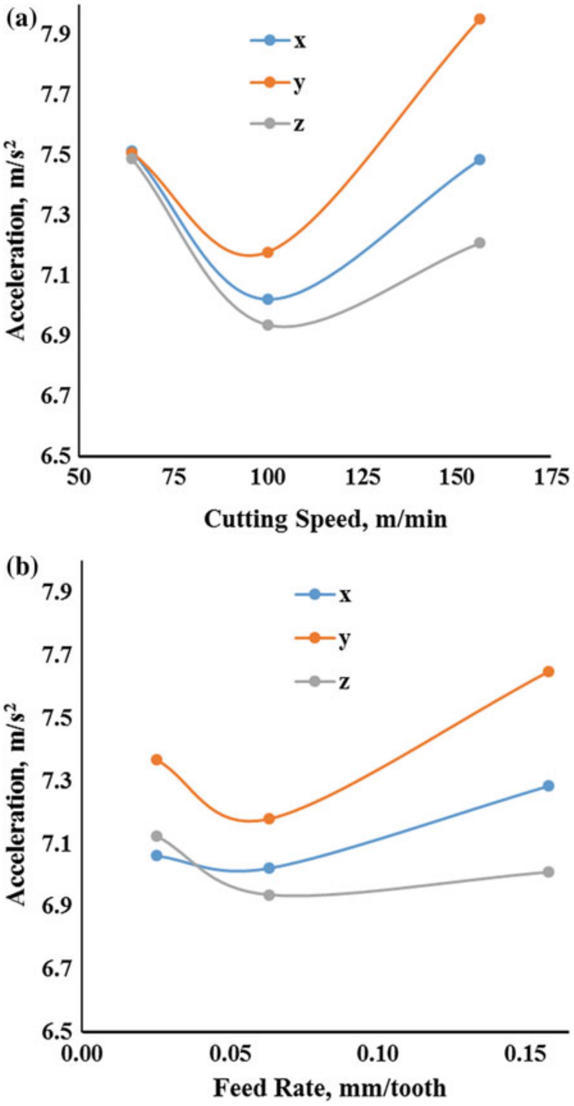


Fig. 4 **a** Natural frequency. **b** Mode shapes of the thin wall

the raw signals of the vibration. The cutting process is divided into three states—entry cutting, machining cutting, and exit cutting. The data during machining state is used to analyse the influences cutting process towards vibration. To verify the cutting process, whether unstable machining (chatters) occur, the vibration *y*-direction was analysed using FFT. The fast fourier transform spectrum is shown in Fig. 6.

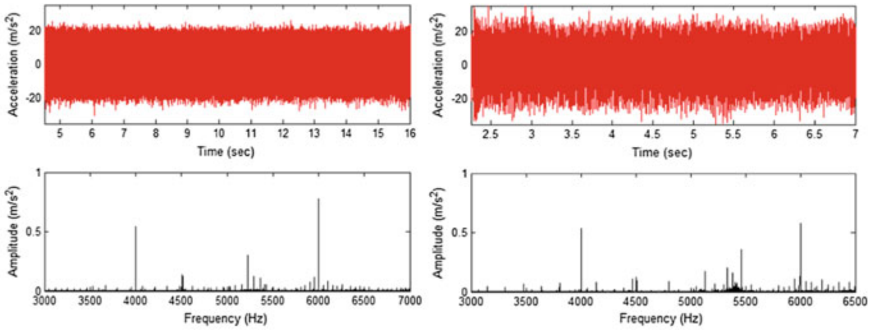
It is shown that the peak values of milling vibration are more significant when the cutting speeds are 156.25 m/min, feed rate 0.025 and 0.158 mm/tooth. When cutting speed is 100 m/min, its frequency spectra distribution is stable. In order to further analyse stability machining (chatter), no chatter appears on all machining. Dominant vibration or maximum point’s peak value occurs at 4000, 4503, 5333, and 6000 Hz, but it causes no chatter.

Fig. 5 Vibration acceleration on, **a** cutting speed, **b** feed rate variation

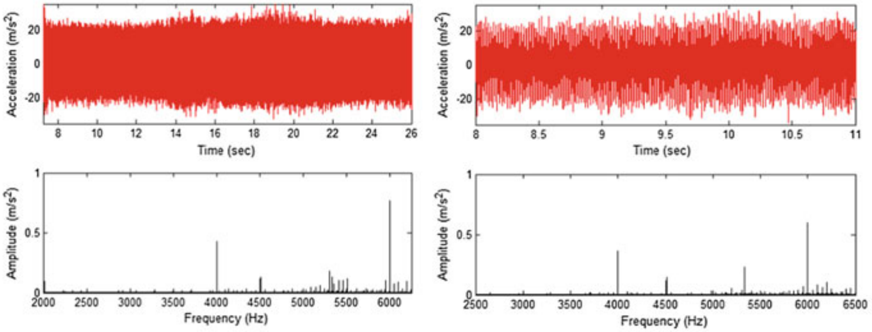


3.2 *Surface Quality*

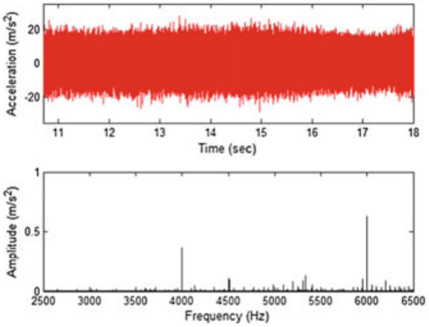
However, on the surface topography as shown in Fig. 7, the surface is poorer at a maximum cutting speed and maximum feed rate. Based on these results, it can be proven that the experiments were in good agreement and the maximum vibration appears far away from the natural frequency.



(a) Cutting speed 64 m/min (b) Cutting speed 156.25 m/min



(c) Feed rate 0.025 mm/tooth (d) Feed rate 0.158 mm/tooth



(e) Cutting speed 100 m/min and
feed rate 0.063 mm/tooth

Fig. 6 Time domain and FFT output during machining at cutting speed and feed rate variation

The surface topography has shown small influence due to vibration on the surface texture. This phenomenon can be proven when the surface roughness values were measured using surface roughness tester Accretech Handy-Surf type E35A/E. The influence of cutting speed and feed rate is shown in Fig. 8a, b.

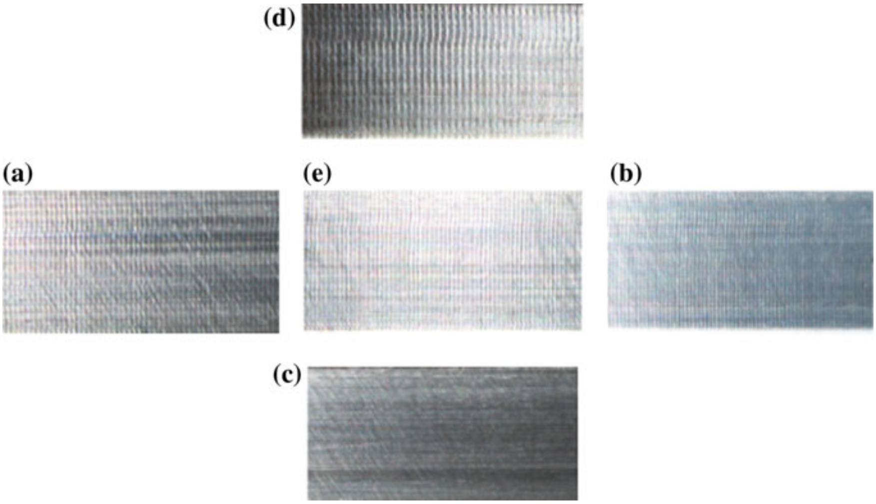


Fig. 7 Surface photographs of the workpiece at cutting speed and feed rate variation. **a** Vc = 64 m/min, **b** Vc =156.25 m/min, **c** fz = 0.025 mm/tooth, **d** fz = 0.158 mm/tooth, **e** Vc =100 m/min and fz = 0.063 mm/tooth

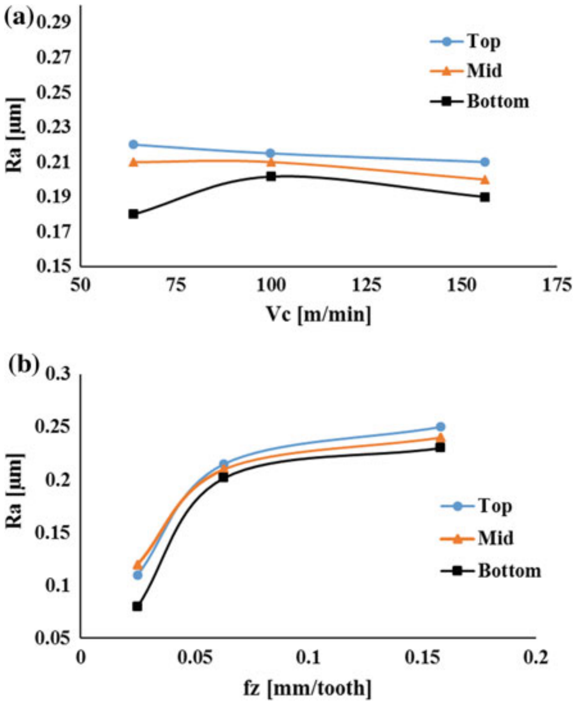


Fig. 8 Influence of cutting speed, **a** and feed rate, **b** on surface quality at several positions of thin-wall Ti6Al4V

From Fig. 8a, it is apparent that increasing cutting speed generally affected on decreasing surface roughness values, hence yield in better surface quality. On the other hand, increasing the feed rate yields in poorer surface quality as shown in Fig. 8b.

This phenomenon is agreeing with the basic theory propagation of surface roughness, which also proven in [27] during hard turning on AISI D2 steel. Solely at the bottom of the thin wall, the surface roughness is increased with the rise of cutting speed. From Fig. 8, it is also to recognise that the surface roughness values decrease from the top to the bottom of the thin wall. This could be caused by the deflection on the top of the thin wall is higher than the bottom. Thus, the surface deterioration is more influenced on the top of the thin wall.

4 Membrane Technology

4.1 Potential and Handling of Membrane Technology

It is known that conventional cutting fluid is hazardous, but reducing the amount of cutting fluid to control environmental hazard leads to compromising performance measures. In this case, operations with minimum quantity lubrication (MQL) is one of the strategies that can offer technological that associated environmental concerns and economic advantages over the traditional fluid application. Under MQL, microdroplets of sustainable lubricants are supplied in the machining zone. The prevailing trend of many researchers in machining processes, vegetable oil, has been selected as cutting fluid based on their ability to influence performance and characteristics such as biodegradability, oxidation stability, and storage stability.

Vegetable oils possess excellent lubrication properties, resistance to corrosion, and high flash and boiling points.

Storage and disposal of exhausted cutting fluid have always been challenging for the machining industry.

Removing the chips in the wasted cutting fluid is the first step to treat the waste cutting fluid [28]. In this study, oily water emulsion, similar as wasted cutting fluid, are the primary pollutants emitted into the water by manufacture operation and tend to have significant pollution problem because oilfield produced water has distinctive characteristics due to organic and inorganic matter. Fatty alcohols and synthetic hydrocarbons which include the waste cutting fluid are initiated hazardous materials. Some treatments of oily wastewater have been studied namely, chemical emulsification, pH, gravity settling, centrifugal settling, filter coalesce, heating treatment, electrostatic coalesce, and membrane filtration. The unit operations and processes used for the removal of significant constituents found in wastewater are tabulated in Table 2.

Table 2 Unit operations and processes used to removed constituents found in wastewater

Constituents	Appropriate treatment technologies
Suspended solids	Screening, grit removal, sedimentation, flotation, chemical precipitation, surface filtration
Biodegradable organics	Aerobic suspended growth variations, Aerobic attached growth variations, physical–chemical systems, chemical oxidation, advanced oxidation, membrane filtration
Refractory organics	Carbon adsorption, chemical oxidation, ion exchange, breakpoint chlorination, membrane filtration
Heavy metals	Membrane filtration, evaporation, electrodialysis, chemical precipitation, ion exchange
Fat, oil, and grease	Coagulation/flocculation/floatation, membrane ultrafiltration
Colloidal and dissolved solids	Membrane filtration, chemical treatment, carbon adsorption, ion exchange

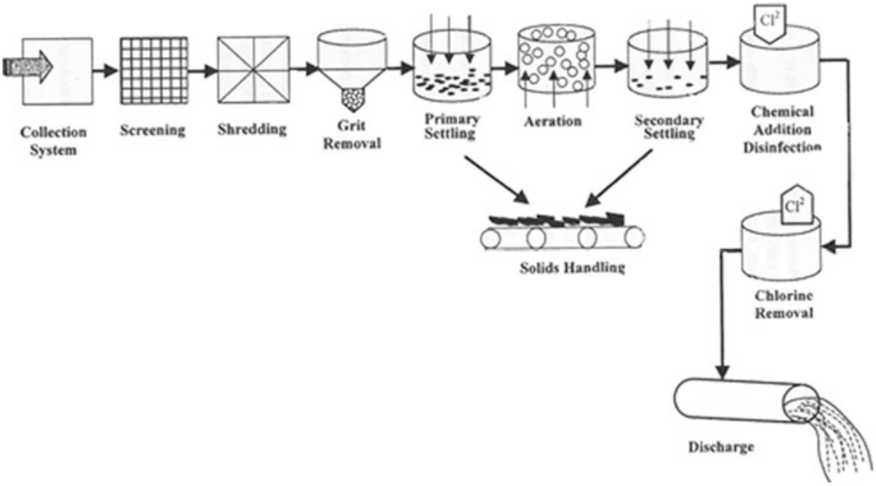


Fig. 9 Mechanism of wastewater treatment

The suspended solids and other constituents that are difficult to remove are being treated by improved and new technologies. The unit operation for wastewater treatment is shown in Fig. 9, while the terminology of wastewater constituent removal using a membrane is shown in Fig. 10.

The performance evaluation of various membrane materials was reported by [29]. They evaluated the suitable membrane materials for the coolant wastewater treatment and the effect of nanoparticles additives on the membrane morphology.

They concluded that the application of PVDF membrane in the metal industry for long-term performance could be an alternative solution regarding the purpose of nanoparticles in the membrane to minimise fouling and prolong the membrane

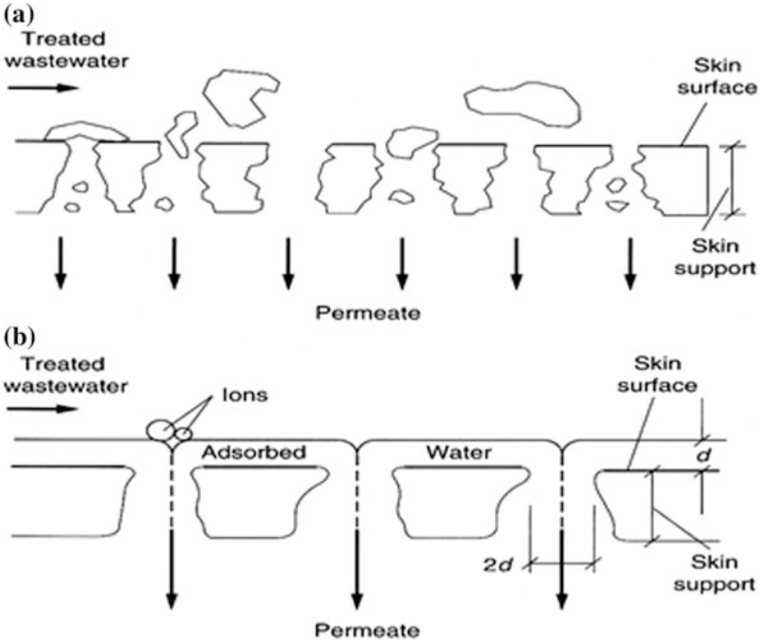


Fig. 10 Rejection of ions by adsorbed water layer in waste water treatment by membrane technology

lifetime that affects directly to the enhancement of the efficiency of the treatment process. Heterogeneity of coolant effluent has been reported by some researchers because it is made by nature and effect of fouling that was harder to control and forecast. The fouling phenomenon of the membrane is one of the drawbacks in membrane technology that cannot be prevented but can be minimised. Related to the fouling phenomenon, hydrophilicity characteristics plays also important role in oily wastewater filtration. Hydrophilicity contributes to the formation of a thin, protective water film on the membrane surface that increases the water removal from wastewater cutting fluid. On the otherhand, hydrophobicity tends to repel and not absorb water. It has been reported that hydrophilicity membranes have more advantages concerning fouling than hydrophobic membranes [29].

4.2 PVDF Membrane for Mitigation of Wasted Cutting Fluids

As known, membrane separations have been significantly developed over the last three decades and are becoming an essential place in wastewater treatment. The membrane technology has emerged as an alternative to the conventional physical–chemical treatment process and also decreased the environmental pollution significantly. Membrane filtration system involves the passage a wastewater through the thin membrane for removing particulate materials, organic matters, nutrients, and dissolved substances, which cannot be removed by conventional treatment processes. Membrane processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and electrodialysis (ED). The microfiltration and ultrafiltration membranes are used for filtrating the secondary effluent in depth and surface filtration. Meanwhile, nanofiltration, reverse osmosis, and electrodialysis systems are used for removing the dissolved solids. They also have high oil removal efficiency, low energy cost and compact design compared with traditional treatment. Many studies of membrane separation for oily wastewater treatment have been reported, particularly in microfiltration (MF) and ultrafiltration (UF). The performance of hydrophobic polyvinylidene fluoride for oily wastewater filtration can be characterised according to their permeability, rejection ability, and fouling resistance [30]. More specifically, such performance can be compromised due to pore clogging via oil particle, preferential adsorption of oil which can result in fouling as well as the formation of cake layers on the membrane surface.

Regarding the application of membrane in wasted cutting fluids treatment, PVDF membrane achieved the significant result to remove the contaminant and also remove the colour component. Part of colour pigment which affected by vaporisation could be remained by adsorption on suitable bleaching earth. The remaining colour components are the thermally degraded during deodorisation at high temperature (150 °C) for 100 min.

Part of the colour pigments are physically adsorbed by bleaching earth, and other components are chemically bound to bleaching clay via covalent or ionic bonds [31]. Decomposes peroxide in alkoxyl and alkyl radicals occur as first step in oxidation pathway. Second step, acid activation enhances the adsorptive power due to an increasing negative surface area of the membrane. Based on these results, it can be concluded that modified PVDF membrane with the negative charged surface is the better solution in order to treat the wasted cutting fluid.

4.3 Experimental Set-up of PVDF Membrane Technology

The coolant wastewater was produced while the milling of thin-wall Ti6Al4V using coconut oils as cutting fluids under MQL systems. After finished the experiment, the exhausted cutting fluid was collected in a bottle. For this experimental purpose, it is must to prepare a synthetic coolant wastewater according to a collected sample of MQL-exhausted cutting fluids, which was collected in the previous experiments. The prepared synthetic coolant wastewater is to be used as the feed solution in ultrafiltration experiments [32].

Table 3 Properties of PVDF membrane

Parameter of the membrane	Type/value
Membrane material	PVDF/SiO_2
Membrane configuration	Hollow fibre
Inner diameter (mm)	0.6
Outer diameter (mm)	1.2
Membrane area (dm^2)	10.48
Pore size (nm)	35.2

The submerged membrane separation system used in this experiment consists of a feed reservoir up to 14 l volume, hollow fibre bundles, a peristaltic pump, a permeate flow metre, and a permeate collector. The boundary conditions of the filtration experiments are as follows: vacuum on the permeate side 0.5 bar abs, room temperature.

The membrane was produced using a peristaltic pump (Master flex model 7553–79, Cole Palmer) with the water permeate being withdrawn from the open end of fibres. In order to let the water permeate from outside to the inside of the hollow fibre, the transmembrane pressure (TMP) was maintained at a constant pressure of 0.5 bar. The turbulent flow was created using the continuous aeration so that the cake layer thickness and the average particle size could be reduced.

The properties of the membrane used in this experiments are given in Table 3.

In these experiments, the hollow fibre membranes were immersed in the feed reservoir. The withdrawal of permeate through the fibre was generated using the employment of vacuum on the outlet of the fibre lumen [33–35].

To characterise the oily machining wastewater, several substances were taken into account as measured parameters, namely oil and grease, chemical oxygen demand (COD), total organic carbon (TOC), sulphide, and total suspended solids [36].

4.4 PVDF Membrane Experiments Results

The removal of organic wastes from oily wastewater has been proven successfully using developed PVDF membrane technology and its application in coolant wastewater filtration. In this device, hollow fibre membranes are directly immersed in the feed reservoir with the withdrawal of permeate through the fibres in vacuum pressure application on the fibre lumen outlet of the membrane. As known, coolant wastewater was characterised by the presence of chemical oxygen demand (COD), total organic carbon (TOC), and suspended solids (TSS). After coolant wastewater filtrating using PVDF hollow fibre membrane with factors such as mixed liquor suspended solids, the concentration of coolant wastewater, pH and hydraulic retention time, the results of the study were achieved in the value of COD 555 mg/L, TOC of 29.1 mg/L, and suspended solids of 20 mg/L. These values were achieved entirely using modified PVDF hollow fibre membrane with SiO_2 additives that affected as modifier area, highly miscible, fine suspend ability in aqueous solution and relatively environmentally inert. PVDF/SiO_2 has been found to be a promising modifier to improve the permeability and selectivity of PVDF membrane [32].

5 Conclusions and Future Directions

In this study, dynamic behaviour during end milling thin wall of Ti6Al4V is verified. The results found are as follows:

1. It was found that the natural frequencies occurred are 4154.5, 27,203, 73,089 Hz for the first, second, and the third, respectively.
2. The dominant vibration or maximum point's peak value occurs at 4000, 4503 and 5333, and 6000 Hz.
3. The vibration value in *y*-direction or perpendicular to the machined surface is higher than the *x*-direction and *z*-direction.
4. The value of acceleration in three directions increased significantly with the increase of cutting speed and feed rate.
5. The surface quality is better when the cutting speed increased. In contrary, the surface quality becomes worst when the feed rate rise.
6. The results of the study were achieved in the value of COD 555 mg/L, TOC of 29.1 mg/L, and suspended solids of 20 mg/L. These values were achieved entirely using modified PVDF hollow fibre membrane with SiO_2.
7. PVDF/SiO_2 has been found to be a promising modifier to improve the permeability and selectivity of PVDF membrane.

The proposed future work in this field is to observe the opportunity of combining vegetable oils in MQL, cryogenic, and air-cooled systems.

In order to mitigate the hazardous effect of the wasted cutting fluids, the PVDF membrane offers an excellent solution. Thus, the green machining through coconut oils as cutting fluids in MQL system has been proven the optimum cutting condition for the aerospace materials such as titanium alloy.

Through the optimum selection of a cutting condition, the occurred vibration in machining of Ti6Al4V can be controlled in the acceptable zone. Thus resulted in adequate surface quality.

The higher cutting speed should be investigated in the future to find higher optimum cutting condition, which suitable for the machining of titanium

In the handling of wasted cutting fluids, it is essential to explore the opportunity of other types of the membrane in filtering the wasted cutting fluids to foster the environmentally friendly machining process, especially for aerospace materials.

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Sustainability Assessment-Based Comparative Evaluation of Precision Miniature Gear Manufacturing Processes

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Abstract Nowadays, the adoption of sustainable manufacturing practices is a prime requirement in manufacturing sector to comply with strict environmental regulations and sustain in global competitiveness scenario. Sustainability requirements have accelerated the research and development endeavours to find the advanced and/or sustainable substitutes of conventional manufacturing processes. This article reports important aspects of manufacturing of miniature gears by abrasive water jet machining with an aim to find a viable alternate of the conventional manufacturing processes. It also presents a comparative evaluation of abrasive water jet machining, wire-EDM, and hobbing considering various processes and product performance-based sustainability aspects such as geometric accuracy, surface finish, manufacturing cost and time, wastage, resource and energy efficiency, health and safety, and noise for manufacturing of miniature brass gears. Miniature gears made by these processes are of the same material (i.e. brass) and specifications with 0.7 mm module, 8.4 mm pitch circle diameter, and 5 mm thickness. In this study, based on some sustainability indicators such as manufacturing cost and time, energy and resource consumption, noise, wear and tear, wastage, and health and safety, the abrasive water jet machining process has secured the highest value of total process sustainability index of 82.5%; hence, it is identified as the most sustainable process for manufacturing of miniature gears.

Keywords Abrasive water jet machining · Precision · Gear · Manufacturing
Noise · Sustainability

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1 Introduction

In general, ‘sustainability’ is the ability to continue a defined behaviour indefinitely. It is defined in terms of sustainable development in the United Nation’s ‘*Brundtland Report*-1987’. The escalating environment impact due to the higher demand of the resources caused by increasing work population is mainly responsible for the accelerated global trend of sustainable development [1, 2]. According to US Department of Commerce, sustainable manufacturing is ‘the creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound’. The sustainability associated with any product depends mainly on two factors, its manufacturing and performance. In other words, the sustainability aspects of any product can be determined by the impact of the activities or tasks performed during its manufacturing (related to the concerned processes) and product’s functional performance during its intended service life.

Gears and subsequently the gear manufacturing industry act as a backbone for other industrial segments as it fulfils the major requirements of keeping the machineries, equipment, and instruments operational. There has been a phase shift in manufacturing sector including gear industry from traditional to the advanced and sustainable production due to the increased emphasis on sustainability. Whether it is manufacturing of the giant gears or miniature gears, the sustainable manufacturing practices are being given considerable importance in order to attain high quality at low environmental footprints [1].

Miniature gears are the key components of various miniature devices such as miniature motors and pumps, scientific instrument, business machines, robots, speed reducers, and appliances. They fulfil the motion and/or torque transmission requirements. Although there is no international classification system exists to categorize the miniature components based on the size or dimensions; yet based on the consistency and ease, the miniature gears can be micro-gears (outside diameter less than 1 mm) or miniature gears (outside diameter 1–10 mm) [3].

Profile, pitch, and run out are the important micro-geometry parameters that determine functional performance characteristics such as noise behaviour, accuracy in transmission, and load-carrying ability of these gears [3]. On the other hand, tribology aspects, wear behaviour, and service life depend on the surface roughness parameters that include average roughness, maximum roughness, mean roughness depth, skewness, kurtosis, and bearing area characteristics [3]. Miniature gears are conventionally manufactured by hobbing, die-casting, powder metallurgy, stamping, and extrusion. Out of these conventional processes, hobbing is the most extensively used for miniature gear manufacturing [3].

Advanced machining processes such as wire-EDM, abrasive water jet machining, and laser beam machining are being explored as an alternate to the conventional processes for manufacturing of miniature gears [4–6].

Recently, a detailed experimental investigation conducted on manufacturing of miniature gears by wire spark erosion machining reveals the suitability of non-traditional or advanced machining processes to become a superior substitute of conventional or traditional processes for manufacturing of quality miniature gears [5]. A comparative study between wire-EDM and hobbing based on various aspects of process and functional performance of gear reveals the superiority of wire-EDM to manufacture quality miniature gears [3].

1.1 Motivation

Conventional processes of manufacturing of miniature gears suffer from certain individual inherent limitations, and in common, they all are not capable to produce high-quality gears. Gears manufactured by these conventional processes possess quality in the range of DIN 9-12 [3, 5]. DIN is an acronym of German standards Deutsches Institut für Normung, and DIN 3962 are referred to assign quality numbers to gears based on the tolerance attained. It ranges from 1 (tightest tolerance) to 12 (loosest tolerance). Furthermore, these processes necessitate the assistance of secondary finishing operations such as grinding, honing, lapping to attain high-quality requirements. As regards sustainability, the use of secondary finishing operations implies long process chain of gear manufacture that results in:

- High consumption of energy and resources;
- High wastage with an increased burden of handling, recycling, and disposal;
- High risk of health and safety.

There are number of limitations reported by Gupta and Jain particularly of hobbing process [3].

The literature review reveals that wire-EDM as investigated by Gupta and Jain a superior alternate of conventional processes also suffers from some limitations such as low productivity, long gear manufacturing time, and low surface finish of gears [3, 5].

These factors all result in high overall manufacturing cost and environmental footprints.

This compels to explore and develop a sustainable alternate to these techniques for environmentally friendly and cost-efficient manufacturing of quality gears.

Abrasive water jet machining (AWJM) has the potential to be such a process. In AWJM, abrasive particles mixed in high-velocity water jet with high erosive effect are used to remove workpiece material for cutting required shape of the part [7]. Based on its previous track record to machine precision engineered parts such as microelectronic components [8], micro-pillars [9], micro- and nanostructures [10], precision drilling and cutting [11], and its sustainability aspects such as reduced wastage, no heat-affected zone, low environmental contamination, and no cutting fluid requirement [12–14], abrasive water jet machining (AWJM) has been explored for sustainable manufacturing of precision miniature gears in this research work. The literature review also reveals that except few attempts on machining of miniature gears by AWJM, there is no work systematically describes the process mechanism, effect of parameters on gear surface quality, and sustainability assessment of AWJM process.

This research work fulfils that gap. The main objective is to cut down the length of long process chain of gear manufacture by minimizing the requirement of secondary operations; to produce near-net-shaped miniature gears at significantly low cost and with less environmental footprints; and to identify the most sustainable process among AWJM, wire-EDM, and hobbing for manufacturing of precision miniature gears.

2 Materials and Methods

Omax 5-axis water jet machine has been used to fabricate miniature gears of brass having specifications as same as of the gears manufactured by Gupta and Jain [15, 16] using wire-EDM and hobbing and given in Table 1. Garnet abrasives of mesh size 80 were selected to machine miniature gears. The least traverse speed, i.e. speed of the jet head (66 mm/min) that corresponds to generate the highest quality level in AWJM, was selected to be fixed.

The experimental study on manufacturing of miniature brass gears by AWJM has been conducted in three stages. At first, some pilot experiments were conducted to bracket the range of AWJM parameters to confirm the feasibility of machining miniature gears of brass. Thereafter, analysis of the effect of AWJM parameters (namely abrasive mass flow rate, water jet pressure, and stand-off or nozzle distance) on miniature gear surface quality was done conducting main experiments

Table 1 Details of experimental parameters, gear specifications, and material composition

AWJM parameter details		**Gear specification**
Abrasive type and mesh size	Garnet 80	Material: brass; type: external spur gear; pressure angle: 20°; module: 0.7 mm; outside diameter: 9.8 mm; number of teeth: 12; pitch circle diameter: 8.4 mm; face width: 5 mm
Abrasive mass flow rate (g/min)	300	
Water jet pressure (MPa)	350	
Nozzle dia (mm)	0.75	
Orifice dia (mm)	0.35	
Stand-off distance (mm)	1.0	
Traverse speed (mm/min)	66	
Composition of gear material Cu: 64–66%; Sn: 0–0.10%; Pb: 0–0.05%; Fe: 0–0.05%; Al: 0–0.02%; Ni: 0–0.2%; Zn: 35% [Brass ASTM B36 C26800]		

designed on Taguchi's L_9 orthogonal array. Main experiments were then followed by confirmation experiments conducted to verify the predictions of desirability technique-based optimization that was done to secure the best gear quality at a single set of AWJM parameters. Table 1 presents the details of optimum AWJM parameters used to machine the best quality miniature gear whose characteristics are compared with that of other miniature gears manufactured by Gupta and Jain [15, 16] using wire-EDM and hobbing. The sequence of manufacturing of miniature gears by AWJM is shown in Fig. 1.

It is worth mentioning that in order to achieve high surface quality, machining at optimum parameters is required to be done to minimize the *jet lag* which is the difference between the theoretical and actual position of the abrasive laden water jet comes out from the nozzle and occurs due to the fluctuations in pressure; kinetic energy, type, amount, size and cutting ability of the abrasive particles; feed rate; and the nozzle position [17, 18]. Water jet pressure was found to be the most influential factor affecting surface quality of gears. High values of water jet pressure and abrasive mass flow rate associated with low magnitude of jet lag and increased penetration and cutting ability of jet were found to be desirable for the best surface quality, i.e. high geometric accuracy and fine finish of miniature gears, while a trade-off has been recognized for the stand-off distance that led to optimization.

As given in Table 1, the optimum values of AWJM parameters at which the best surface quality for miniature gears has been obtained are water jet pressure 350 MPa, abrasive mass flow rate 300 g/min, and stand-off distance 1 mm.

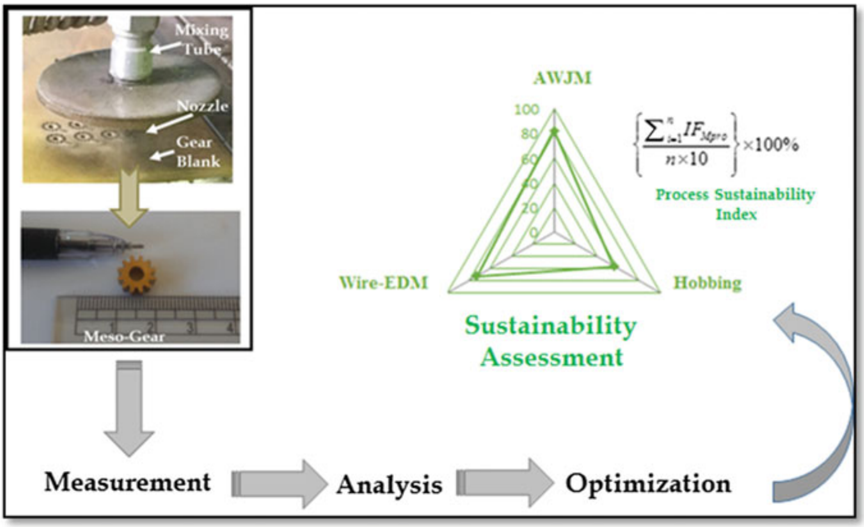

Fig. 1 Sequence of tasks performed during manufacturing of miniature gears by AWJM

Stylus profile metre was used to measure the roughness parameters on tooth flank surface across the direction of jet head, i.e. along root to tip. The evaluation and cut-off lengths were 0.75 and 0.25 mm, respectively. Three measurements at a different location on per single tooth of a gear were taken, and their average value is considered. Profile error was measured using CNC gear tester on the flank surface of gear teeth along and across the direction of jet head.

The wire-EDMed miniature gear referred in this comparative evaluation was manufactured at optimum parameters with 10 V voltage, 0.6 μs pulse-on time, 170 μs pulse-off time, and 13 m/min wire feed rate, while the hobbed miniature gear was manufactured at optimum values of hobbing parameters using micro-hobbing machine by Gupta and Jain [15, 16].

3 Results and Discussions

3.1 Sustainability Assessment

As regards the assessment of sustainability of miniature gear manufacturing, a comparative evaluation between AWJM, wire-EDM, and gear hobbing processes has been done for miniature gears of the same specification. For this purpose, firstly the process sustainability index (PSI) was calculated by considering the process and functional performance (of gears)-based sustainability aspects such as geometric accuracy, surface finish, manufacturing cost and time, wastage, resource and energy efficiency, health and safety, and noise. The details of sustainability-based comparative evaluation are prescribed in the subsequent sections.

The responses measured for the sustainability assessment are:

- Quality of the machined product through surface integrity that includes geometric accuracy in terms of profile error and surface finish;
- Manufacturing cost and time;
- Resources and energy consumption;
- Wastage;
- Health and safety performance;
- Noise;
- Wear and tear.

Table 2 presents the details of the aforementioned parameters in case of AWJM, hobbing, and wire-EDM. The data and values of these parameters for hobbing and wire-EDM are as reported by Gupta and Jain [15, 16]. Process and product performance values for wire-EDM are obtained by machining best quality miniature gear at optimum wire-EDM parameters, while for hobbing these are the best values obtained for the hobbed gear.

3.2 Calculations of Process Sustainability Index (PSI)

In order to calculate the process sustainability index, the sustainability model as proposed by Kadam and Pawade [19] has been used. The first step of PSI is to allocate the scores of affecting parameter as per the regime from worst to best. Then, the PSI of process and product performance components is calculated using Eqs. 1 and 2 as given below. In the end, the overall total process sustainability index is calculated using Eq. 3. The scoring criteria for the influencing factors of the respective sustainability components are discussed in the next subsequent section. Table 3 shows the calculations of sustainability assessment.

$$\mathrm{PSI}_{\mathrm{Menv}} = \left\{ \frac{\sum_{i=1}^{n} \mathrm{IF}_{\mathrm{Menv}}}{n \times 10} \right\} \times 100\% \tag{1}$$

$$\mathrm{PSI}_{\mathrm{Mpro}} = \left\{ \frac{\sum_{i=1}^{n} \mathrm{IF}_{\mathrm{Mpro}}}{n \times 10} \right\} \times 100\% \tag{2}$$

$$\mathrm{PSI}_{\mathrm{T}} = \left| \frac{\mathrm{PSI}_{\mathrm{Menv}} + \mathrm{PSI}_{\mathrm{Mpro}}}{2} \right| \tag{3}$$

Table 2 Comparison between AWJM, hobbing, and wire-EDM based on various performance measures for manufacturing miniature gears of the same specifications

Performance measures	AWJM	Hobbing	Wire-EDM
Profile error/quality	14.15 µm/ DIN 8	30.2 µm/DIN 10	11.9 µm/ DIN 7
Average roughness	1.03 µm	0.2 µm	1.26 µm
Maximum roughness	6.25 µm	1 µm	6.67 µm
Mean roughness depth	4.6 µm	0.78 µm	5.8 µm
Skewness	−0.242	−0.360	−0.165
Kurtosis	2.99	2.635	2.455
Bearing area characteristics	Almost similar		
Wastage	Low	High	Low
Comparison based on to attain quality > DIN 9			
Manufacturing cost	≈1 Euro	>10 Euro (combined cost of teeth cutting and finishing)	>2 Euro
Overall manufacturing time (per gear)	3 min	Very long (gear is subjected to secondary finishing operation)	12 min
Energy and resource consumption	Lowest	High	Low

Table 3 A comprehensive sustainability assessment of miniature gear manufacturing processes

Process	Performance measures in terms of quality, cost and time				$PSI_{(Menv)}$	Performance measures in terms of ecological aspects				PSI $_{(Mpro)}$	PSI_T
	Geometric accuracy	Surface finish	Manufacturing cost	Overall manufacturing time		Noise	Wear and tear	Resource and energy consumption	Wastage, health and safety		
AWJM	8	6	9	9	80	8	8	9	9	85	82.5
Hobbing	4	9	5	5	57.5	5	9	5	3	55	56.25
Wire-EDM	9	4	7	6	65	9	7	7	9	80	72.5

where PSI_{Menv} and PSI_{Mpro} = PSI for machining environment component and machined product component,

PSI_T = overall total process sustainability index,

IF_{Menv} and IF_{Mpro} = influencing factor rated on a scale of 0–9 for the process performance and product performance components, and

n = number of influencing factors considered.

3.3 Process Performance/Machining Environment Sustainability Components

Geometric accuracy: As mentioned in the forgoing sections, profile error is a significant contributor to ascertain the geometric accuracy of a gear which determines its functional performance, basically noise. Low value of profile error implies high geometric accuracy. As shown in Table 2, the geometric accuracy for AWJMed gear (profile error 14.15 μm) is much better than hobbed gear (profile error 30.2 μm) and slightly lower than gear manufactured by wire-EDM (profile error 11.9 μm). This allocates a maximum score of 9 to wire-EDM, score ‘8’ to AWJM, and 4 to hobbing.

Surface finish: The hobbed gear is found to have superfine surface finish with average and maximum roughness values of 0.2 and 1 μm, respectively, and mean roughness depth 0.78 μm. The values of these parameters for AWJMed gear and wire-EDMed gear are 1.03-6.25-4.6, and 1.27-6.67-5.8 μm, respectively, that are acceptable for miniaturized applications. Based on that, hobbing is given maximum score of ‘9’, AWJM is given ‘6’, and wire-EDM is ‘4’. It is worth mentioning that there is a marginal difference in other roughness parameters (skewness, kurtosis, and bearing area) for gears manufactured by hobbing, AWJM, and wire-EDM.

Manufacturing cost: The cost implies to manufacture a gear of quality DIN 8 by hobbing is significantly higher due to addition of the cost components associated with secondary finishing operations. On the other hand, the same quality gear can be obtained in an expenditure of approximately one euro by AWJM and two–three Euros by wire-EDM. Hence, a maximum score of 9 is allocated to AWJM, 7 to wire-EDM, and 5 to hobbing.

Overall manufacturing time: The quality of gears obtained by AWJM and wire-EDM is DIN 8 and 7, respectively, which is better than the quality of gear machined by hobbing. When the hobbed gear is exposed to finishing operations for correction of profile error to meet quality standard DIN 8, it prolongs the gear manufacturing time to a great extent and much higher than the time taken by AWJM (3 min) and wire-EDM (12 min). Based on that, AWJM is given maximum score of ‘9’, wire-EDM is ‘6’, and hobbing is ‘5’.

Consumption of energy and resources: The gear quality produced by AWJM, i.e. DIN 8, is equal to the quality of gears finished by grinding, honing, lapping, and shaving-type finishing operations for precision applications [3]. No requirement of finishing operations implies short process chain of gear manufacturing in AWJM. This significantly reduces the consumption of cutting fluid and tools, and saves energy and resources, whereas gear manufacturing by hobbing requires high consumption of cutting fluid, tools, energy, and resources. It significantly increases when hobbed gears are required to be finished in order to produce quality better than DIN 9. The assistance of secondary finishing prolongs the manufacturing time, yields extra cost, and increases the consumption of energy and resources with high environmental footprints. In case of wire-EDM, also there is no requirement of finishing as the process itself is capable to manufacture high-quality gears, but the consumption of energy and resources is more as the gear manufacturing time is longer than AWJM (refer Table 2). Hence, the maximum score of ‘9’ is given to AWJM process and low score of ‘5’ and ‘7’ is given to the hobbing and wire-EDM process, respectively.

Wastage, health and safety: The amount of wastage including those to be exposed to recycling has become a significant factor for assessing the ecological aspects. The minimum amount of material is removed from the blank while machining gears by AWJM and wire-EDM, whereas gear hobbing results in high amount of wetted chips difficult to recycle. High amount of worn-out tools, exhausted coolants and lubricants, and wetted chips extensively contributes towards the generation of wastages in gear hobbing. Use of environmentally unfriendly lubricants and toxic fumes generated in gear hobbing makes this process unhealthy and unsafe. Due to short process chain-based resource-efficient manufacturing of gears, AWJM and wire-EDM both produce less wastage as compared to gear hobbing, therefore allocated to a maximum score of ‘9’ compared to ‘3’ of gear hobbing.

3.4 Product Performance Sustainability Components

Noise: Noise, as an important component of environmental pollution, became in recent years a global problem due to its presence in all the issues of modern life. It is harmful as well as the origin of many diseases, dysfunctions, and premature deaths [20–22]. A high noise level can lead, not only to hearing deficiency, but also to reduced concentration, with direct effect on lowering productivity and increasing the risk of accidents. Therefore, the decrease of noise has lately become a demand for minimizing environmental pollution and increasing life standard.

Along with growth and development, noise has become a significant factor based on which the quality of life is assessed. This compels to control the noise levels in many areas of society specially the working places where people spend a significant amount of their time.

Gears are extensively used in mechanical systems to transmit motion and/or power. Operation of gears is a complex process that involves noise emissions. A significant research has been done to reduce noise generated by gears. Micro-geometry errors, most importantly, profile errors, are the major cause of gear noise. A low value of profile errors leads to high geometric accuracy and therefore low noise. Low profile errors imply high manufacturing quality.

The gear fabricated by AWJM process possesses quality DIN 8 for a profile error value of 14.15 μm. It is better than the quality of hobbed gear whose characteristics are reported by Gupta and Jain [15, 16]. The AWJMed gear is smooth and silent, and therefore will produce low noise pollution compared to hobbed gear. The quality of wire-EDMed gear is DIN 7 with profile error value of 11.9 μm, marginally better than AWJMed gear and much better than hobbed gear. Hence, a score of ‘8’ is given to AWJM process, a low score of ‘5’ is given to gear hobbing, and ‘9’ is given to wire-EDM process.

Wear and tear: Wear and tear is an important aspect that affects functional performance and service life of gears [23]; Gupta and Jain, [15, 16]. High wear and tear has negative impacts on environment because it requires extensive repair and maintenance, lubrication, and increases wastages. In extreme cases, it causes premature gear failures before its intended service life and making gear a scrap. The surface conditions in terms of finish, most importantly the parameter skewness, kurtosis, and bearing area characteristics that govern the gear tribology, wear resistance and control, determine the associated wear and tear prospects of a gear [24, 15, 16, 25, 26]. As shown in Table 2, the average and maximum roughness values of the hobbed gear are much better than the AWJMed and wire-EDMed gears, but as regards the other roughness parameters which mainly account for wear and tear, there is a marginal difference in the gears machined by all the processes considered. Therefore, a score of ‘9’ is given to hobbing, ‘8’ to AWJM, and ‘7’ to wire-EDM.

Table 3 depicts the allocated scores to AWJM, hobbing, and wire-EDM for various performance measures and the calculated values of process sustainability indexes. From the model as shown in Fig. 2, the highest total process sustainability index (PSI_T) of **82.5%** is found in case of AWJM process. Hence, within the

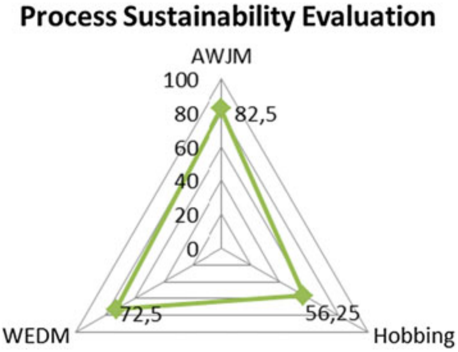

Fig. 2 Total process sustainability index (PSI_T) for different gear manufacturing processes

explored zone, it is suggested that the manufacturing of miniature gears by AWJM is expected to be the most sustainable.

Based on the results obtained in the present work and the sustainability assessment as conducted in the forgoing section, AWJM is claimed to be recognized as a ‘green’ or sustainable process.

4 Conclusions

This article presents sustainability assessment-based comparative evaluation of three important manufacturing processes, i.e. abrasive water jet machining, wire-EDM, and hobbing for environmentally friendly manufacturing of precision miniature gears. Process and product (i.e. miniature gear) performance-based aspects such as geometric accuracy, surface finish, manufacturing cost and time, wastage, resource and energy efficiency, health and safety, and noise have been considered for sustainability assessment. Following conclusions can be drawn from this comparative evaluation:

- The manufacturing quality of miniature gear machined at optimum AWJM parameters is DIN 8 for a profile error value of 14.15 μm. The quality obtained is much better than that produced by other conventional processes including hobbing and more importantly without the assistance of any secondary finishing operation that ensures short process chain of gear manufacture.
- Manufacturing time and cost for miniature gear manufacturing by AWJM are significantly lower than wire-EDM and hobbing.
- The short process chain of gear manufacture and manufacturing time in AWJM ensures further low consumption in energy and resources.
- The highest value (82.5%) of total sustainability index identifies AWJM as the most sustainable process of miniature gear manufacturing among wire-EDM and hobbing.
- The benefits such as low noise and wastage, energy and resource efficiency, low manufacturing cost and time, and short process time associated with AWJM identify this process as a sustainable (clean, safe, and efficient) alternate to the conventional processes of miniature gear manufacturing.

This research facilitates engineers and specialists working in the field of gear manufacturing by providing an optimal combination of abrasive water jet machining parameters for eco-efficient and cost-efficient manufacturing of quality miniature gears. It also encourages researchers to make R&D efforts in the area to further improve gear quality and sustainability aspects.

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