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ORIGINAL ARTICLE

Potential of alternative lubrication strategies for metal cutting processes: a review

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Abstract In the last many decades, the usage of cutting fluid is a common technique for improving the machinability of metals. The application of cutting fluid during the machining phase significantly influences the environmental burden of the process. The disposal of these cutting fluids imposes threat to the environment due to their high noxiousness and non-biodegradable. Several researchers in the metal cutting sector have focused their work to improve the economic and ecological conditions of the machining process by reducing the consumption of the cutting fluids. There is a need to explore different green and innovative techniques to facilitate cooling and lubrication during the machining phase. The conventional cutting fluids not only have environmental and health restrictions, but also they are costly due to the strict regulations for disposal. In this paper, sustainable nature of different cutting fluids has been investigated. The paper also provides a detailed review of the cooling strategies with respect to their environmental impact on human's health and developments in eradicating the usage of conventional cutting fluids has also been reviewed. Furthermore, different environment friendly cooling strategies, mainly minimum quantity of lubrication (MQL), and cryogenic arrangement have been reviewed in the literature, and it is found that there is a giant scope of further research work to optimize these cooling strategies in order to make them functionally applicable.

Keywords Cooling strategies · Minimum quantity lubrication · MQL · Cryogenic cooling · Engineering alloys · Sustainability

1 Introduction

Machining some highly developed engineering materials is generally associated not only with high machining cost but also less production of materials because of extreme heat emulsion at the cutting zone [1]. Such elevated at the cutting zone can cause change in dimensions and early collapse of the cutting tools. It also ruins the product's surface reliability with induced tensile residual stresses and micro-cracks along with speedy rusting and corrosion [2, 3]. The application of cooling strategies serves a vital part in machining operations. Most of the operations are not able to work out effectively without them. When a coolant is applied during a machining phase, it can enhance cutting tool's life and dimensional accuracy. It also decreases the cutting temperatures and surface roughness, so the power consumption becomes less, making more production [4, 5].

Various conventional cutting fluids (oil based) are used to cut down the cutting temperature of the machining metals. Basically, the cutting fluids are applied while cutting metals to cut down the heat generated at the tool chip interface and workpiece friction [6]. The magnitude of the crater wear and the integrity of the cutting edge are commonly influenced by chip formation and curl, so when a coolant is applied during machining it affects the chip formation and curl. In general, when temperature is reduced, it not only cuts down the wear

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results but also enhances tool life. On the other hand, by reducing the workpiece temperature, the shear stress gets increased. This point towards the increase in cutting force and reduced life of the tool [7]. Seah et al. [8] conducted turning experiments on AISI 4340 steel using uncoated tungsten carbide tools with water-soluble lubrication. The study was focused on tool wear measurements. The study observed hardly any considerable difference among the coolant used and dry cutting technique cases. The study proved to bother flank and crater wear in a few cutting circumstances. The study also examined that in comparison to dry cutting the usual cooling action can worsen the surface roughness [9].

Simon et al. [10] performed experiments when machining Titanium at low speed with demineralized water and used auger analysis to examine the cutting effect on a chlorinated fluid. It was observed that chlorine film is made on the surface of workpiece. It was also concluded that machining Titanium with chlorinated cutting fluid cannot be sustained. Also, some very serious health and environment-related hazards are observed in the industry while applying these usual cutting fluids [11]. A cutting fluid is used in machining processes for tool and the workpiece lubrication. It also carries away the excessive heat created. These fluids can enhance the life of the tool and its surface integrity. Moreover; during drilling (a machining operation) particularly, cutting fluids remove chips from the drilled hole which otherwise can result in drill breakage [12, 13]. All these fluids produce contamination in nature, water and soil. The reason is the chemical breaking down of the fluids at high temperature and when they are disposed of. Moreover, they cause genetic and skin problems to the worker's health. Those hazards come as fumes, smoke, odours and physical contact with bacteria. It also requires additional floor space and extra systems to pump, store, filter, chill and recycle [14]. To some firms, the costs associated with cutting fluids epitomize a big expanse of the total machining costs. A number of investigators observed that the prices linked to these cutting fluids are comparatively more than to the cutting tools [15]. They recorded a large amount of cutting fluid consumptions in countries like the USA: 100 million gallons/year and 75,491 tons in Germany. It is estimated that almost 16 % of total industrial expenses are related to cutting fluid cost, and during machining hard materials, they can reach up to 20–30 % [16]. Different environmentally cooling techniques have been reported in the literature in order to make machining processes sustainable, biodegradable, non-toxic and to mitigate heating effect at the cutting zone.

These days, dry machining has gained remarkable attention in order to promote green manufacturing in the industry. The improvement in tool coating technology eliminates the usage of cutting fluids completely in some machining processes. Out of all these limitations, these fluids are still needed in many processes because of their capability to overcome friction, bonding tendency between work and tool materials, difficulty of chip and the heat removal [17, 18]. However, in dry cutting, the removal of chip and dust particle is a difficult process. Further research work is required in this technique. Therefore, a middle way is needed to achieve machining processes in order to promote improved tool life and better surface integrity. While dry machining is not applicable in some processes and is not economical, another method can be applied that is named as minimum quantity of lubricant (MQL). It is applied to minimize the amount of cutting fluid for machining processes. Lugscheider et al. [19] implemented this technique very effectively. Therefore, a most favourable way out to lubricate conditions can be found between dry cutting and conventional flood cooling in some applications. In consideration of this, minimum quantity lubrication (MQL) is a practical way out to compensate the demerits of dry and flood cooling machining processes. The efficacy of MQL process can be well seen in turning [20], milling [21] and drilling [22]. In MQL technique, a little amount of cutting oil is applied as misty particles to the cutting zone. The well-directed penetration of oil particles reduces friction at the cutting interface and results in reducing the temperature, surface roughness and the cost [23]. When machining Ti6Al4V, the MQCL (minimum quantity lubrication + cool air) cooling technique performed better than dry cutting condition and study found that cutting temperature in MQCL approach was decreased by 26.6, 17.9 and 17.5 % for 90, 120 and 150 m/ min cutting speeds, respectively [24].

Davim et al. [25] have performed an experimental study under dry, minimum quantity lubricant and flood-lubricated conditions on aluminium (AA 1050) drilling. The research utilized orthogonal arrays of different feeds, cutting speeds and varied forms of lubrications. In order to confirm the validity of the proposed parameters, how much they contribute an analysis of variance (ANOVA) was performed. The test proved that by selecting properly the range of cutting parameters, it is not impossible to achieve same results as to flood lubricated conditions by using MQL. Rahim and Sasahara [26] performed MQL-assisted experiments and used vegetable oil and synthetic ester. The experiment showed that the arrangements based on palm oil MQL executed better results than synthetic ester. Zeilmann and Weingaertner [27] used MQL assisted machining experiments on *Titanium alloy* *(Ti_6Al_4V)* by consuming uncoated carbide and *TiALN, CrCN* and *TiCN*-based coated drills. The study reported that the performance of internal MQL system is superior to MQL (external) system. Wang et al. [28] performed machining tests using titanium alloy under dry, flood and MQL arrangements. It has been observed that, at higher cutting speeds, MQL performed comparatively superior to conventional flood strategy that can be linked to improved lubrication capability, but results were found more encouraging for interrupted cutting setup. Cia et al. [29] also conducted MQL-assisted machining experiments using end milling operation. The study incorporated different oil flow rates ranging from 2 to 14 ml/h. The study observed relatively higher diffusion wear rate for lower oil flow rates when compared with higher oil flow rate. Klocke et al. [30] machined high performance titanium alloys using high pressurized coolant stream. The research work revealed that temperature at the cutting tool was reduced up to 25 and 50 % tool wear improvement has been achieved. Yasir et al. [31] investigated the machining performance of Ti6Al4V using coated cutting tools under MQL arrangements with coolant flow rates ranging from 50 to 100 ml/h. The study was conducted using three cutting speed levels of 120, 135 and 150 m/ min. At higher flow rates, improved tool life was observed for cutting speed of 135 m/min.

Solid materials (nano-sized) are themselves lubricants or an additive for lubricant. They used Molybdenum disulphide (MoS_2), graphite, boron nitride and polytetrafluoroethylene (PTFE) as dry powders or coating materials for solid lubricants [32–33]. Generally, these lubricants cut down the cutting forces and roughness on the surface during the machining test [34–36]. These solid lubricants can be combined with oil-based lubricants as well. During grinding processes, MQL lubricant with MoS_2 nano-sized particles was introduced [37]. There MoS_2 grinding lubricant revealed exceptional results on cutting forces despite its low dissociation temperature at 350 °C, in rusting environments. Park et al. [38] have developed a potential MQL lubricant with exfoliated nanographene particles. They used vegetable oil mixed with exfoliated nanographene particles in a high-speed mixer. The resulting nano-enhanced MQL-based cutting lubricant was assessed for its tribological and cutting behaviours. The frictional performance of the proposed approach was examined carefully under different speeds and lubricants. The study also conducted ball milling cutting experiments with MQL-based nanographene upgraded lubricant to illustrate an extraordinary betterment by reducing tool wear rate along with edge chipping at the cutting edge of tool.

Su et al. [39] conducted cutting tests on titanium alloys under milling operation. The study analysed different cooling and lubrication methodologies by monitoring tool wear. The experiment exposed that compressed cold nitrogen gas with oil mist (CCNGOM) method have excellent results and resulting extended tool life. Yildiz et al. [40] reported that cryogenic coolants could control cutting temperature at cutting zone very effectively by providing improved tool life. Sun et al. [41] employed cryogenic-assisted compressed air to machine titanium alloys and reported that tool wear reduce significantly by using this strategy. Bermingham et al. [42] developed and utilized a cooling methodology based on cryogenic arrangements and reported that heat generation was efficiently controlled. Sharma et al. [43] reported that LN_2 technique produced excess cooling on the workpiece surface; this may result in the embrittlement of workpiece material. Shane et al. [44] numerically estimated cutting temperatures with respect to cutting speeds using finite element modeling approach. The results clearly pointed out at the efficient control of the cutting temperature in case of liquid nitrogen when compared with conventional emulsion-based cooling.

The literature review proposes that minimum quantity lubrication offers effective solution to make machining process workable. The paper investigates the environment-friendly cooling strategies, mainly minimum quantity of lubrication system (MQL) as a potential replacement of conventional fluid cooling strategy. It is found in the literature that there is a giant scope of further research work to optimize these cooling strategies in order to make them functionally applicable for machining high performance alloys.

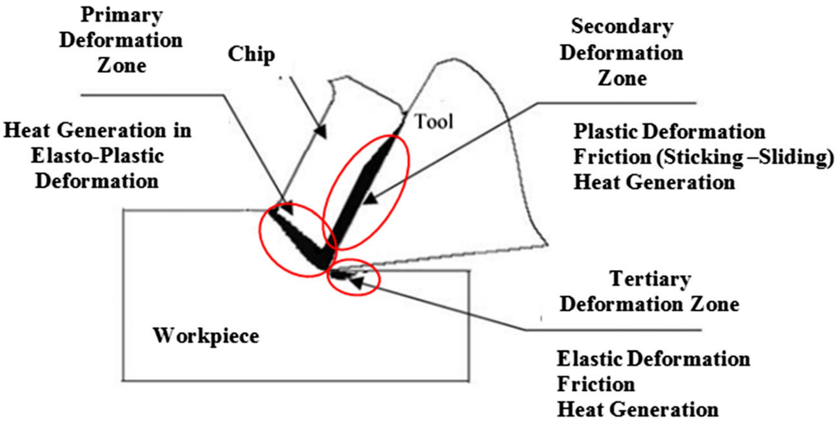
2 Lubrication/ cooling requirements in machining processes

2.1 Heat generation in machining process

Heat is produced in the metal cutting operation because of the material's plastic deformation in primary shear zone and to overcome friction at the tool–chip interface in the secondary deformation zone. During machining, heat can be dissipated by the conduction into the cutting tool, workpiece and chip formed and by the convection through cutting fluid application. The large amount of the heat flows through the chip, and an amount is directed into the work material. That part is superior for low rates of metal removal and small shear zone angles, but less significant for high rates of metal removal [45]. Abukhshim et al. [46] reported that the physical and chemical properties of the workpiece and cutting tool materials have a controlling influence on the heat generation in the primary and secondary deformation zones. They also found that temperature gradient depends more on cutting conditions, tool geometry and cutting fluid. During the machining phase, major zones of heat generation are shown in Fig. 1.

Heat generation has a controlling influence on the machining performance of a cutting operation. Tool wear rate and tool life are directly related to the temperature in the cutting zone. Due to the complex nature of the mechanics involved in machining, cutting temperature distribution is difficult to measure and predict. Another issue is that material properties of workpiece and cutting tool vary with changing temperature in the cutting zone. The cutting process is tightly coupled together thermally and mechanically making the problem to be solved with multi-physics approach. Several researchers have focused their work to investigate cutting temperature either experimentally or numerically. A finite element-based computational model was developed by Majumdar et al. [47] in order to verify the temperature circulation in a metal cutting process. Their model showed similar temperature distribution, and they

Fig. 1 Heat production zones in orthogonal cutting (adopted from Abukhshim et al. 2006 [46])



proved that the maximum temperature generation occurred at the tool–chip interface.

NG et al. [48] performed turning experiments on hardened die steel and AISI H13 by employing PCBN cutting tool. The study used infrared pyrometer and finite element formulation to measure the cutting temperature at the cutting zone. A good agreement was found between experimental and numerical data, and the modeling approach revealed the point of highest temperature on the cutting tool. Groover et al. [49] found increase in the cutting temperature by increasing cutting speed and feed rate when machining engineering steel with cemented carbide tool. Hong and Broomer [50] used cryogenic chip cooling method to machine AISI 1008 steel. The study reported that maximum temperature was reduced by 26 %. Silva et al. [45] have performed an experiment of orthogonal cutting of aluminium and found that the contact length of the cutting interface is affected by the cutting tool temperature. O'Sullivan and Cottrell [51] performed turning experiments on Al 6082-T6 alloy using carbide tools. They calculated machined surface temperature by using thermocouples. The results showed that, by increasing the cutting speed, there can be a decrease in machined surface temperature. This cut down was credited to the elevated material removal rate. This rate resulted in the dissipation of more heat by the chip and thus resulting less heat generation on the workpiece.

Kitagawa et al. [52] performed machining test in high speed turning of Inconel 718 and milling of titanium alloys. The study employed embedded thermocouple technique to measure the cutting temperature. This technique involved insertion of thermocouples in the tool or workpiece by drilling holes. It was observed that ceramic Inconel tool material pair at speed of 150 m/min showed 1200 °C temperature. Similarly, carbide Ti-6Al-6V-2 Sn tool material pair at speed of 500 m/min revealed 1100 °C temperature. Chen and Tsao [53] employed inverse heat conduction method (IHCM) to calculate the heat flowing into the rake face of the cutting tool. This technique used thermocouple to measure the interior temperature variations. The study showed that this technique has drawbacks of inserting thermocouple in hole and low response time. Abukhshim et al. [46] used thermal imaging camera to measure the cutting temperature in high speed cutting of super alloys. They observed heat production, heat partition and temperature mapping in metal cutting process. The temperature calculation in metal cutting was projected by analytical and numerical models. It was reported that extrapolation of cutting temperatures is a challenging task in machining. This was due to abundant practical difficulties in the cutting process, so there is a need to explore and develop advanced numerical models to envisage the contact geometry with modified penetrating and sliding regions.

2.2 Temperature distribution at tool chip interface

Komanduri et al. [54] studied the temperature circulation in metal cutting on the joint effect of tool chip edge of the frictional heat source and the heat source of shear plane in the primary shear zone. The researchers used numerical values of model developed for normal machines made of steel embedded with a carbide tool and aluminium which had diamond of a single crystal. They found that maximum temperature rise was from the tool tip in the steel machine and in the aluminium machine close to the tool tip. This example was credited because of the dissimilarities in the heat properties of the workpiece and tool. The model is validated by matching the results in the analytical form with the results of experimental one, as shown in Fig. 2.

H. Ay. et al. [55] performed an experimental study of machines comprising of copper and 6061 aluminium and AISI 1045 steel, as workpiece material. The investigators utilized some uncoated carbide inserts as a cutting tool. They monitored variations in the tool and workpiece temperature in orthogonal cutting. They used both thermocouples and infrared thermo-vision. The combining outcomes are depicted from the infrared and thermocouple tests for cutting 1045 steel alloys, as shown in Fig. 3. It is observed that the tool showed extreme temperature at rake face.

Silva et al. [45] reported that a change in the tool hardness and the extreme temperature at the tool rake face is distant

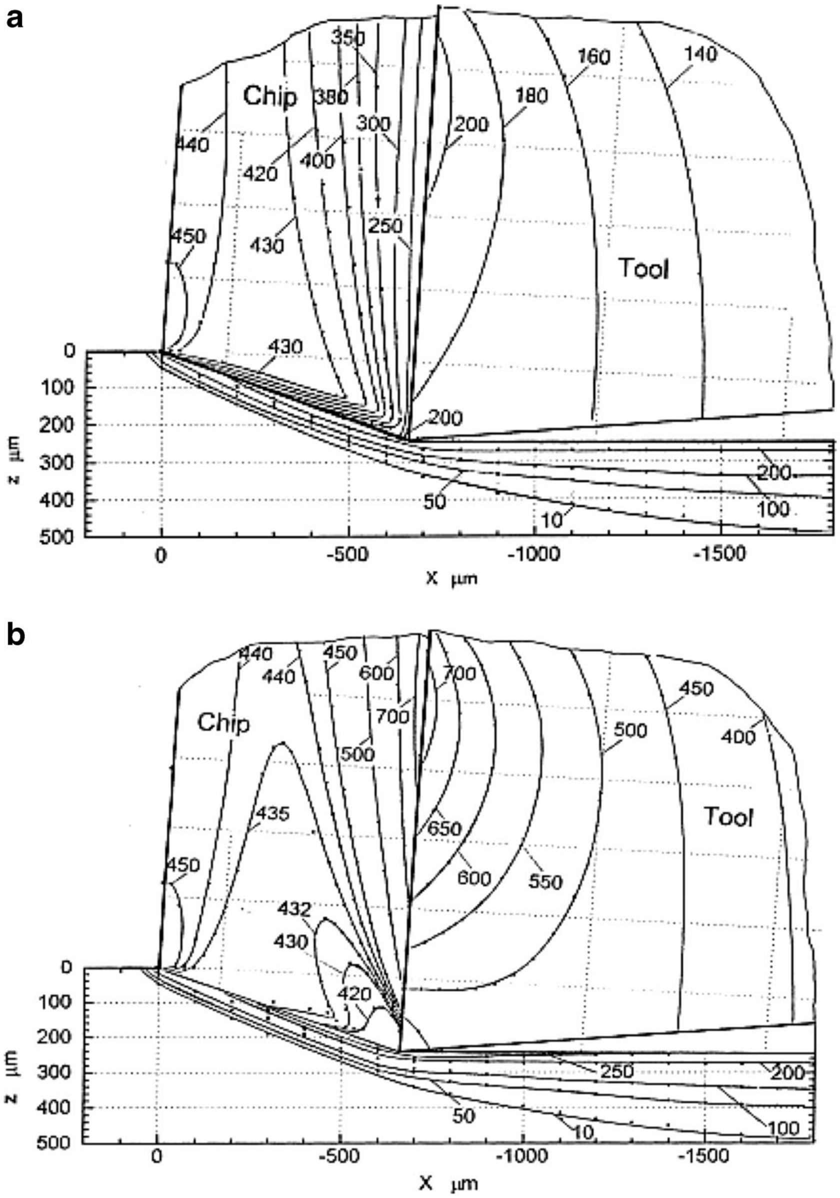


Fig. 2 The temperature rise in the tool chip and workpiece: **a** steel machine with carbide tool (conventional), **b** single-crystal diamond tool (aluminium) [54]

from the cutting geometry. This metallographic change occurs in various materials cutting conditions and due to ductility of the material, but it is different for different materials, as shown in Fig. 4.

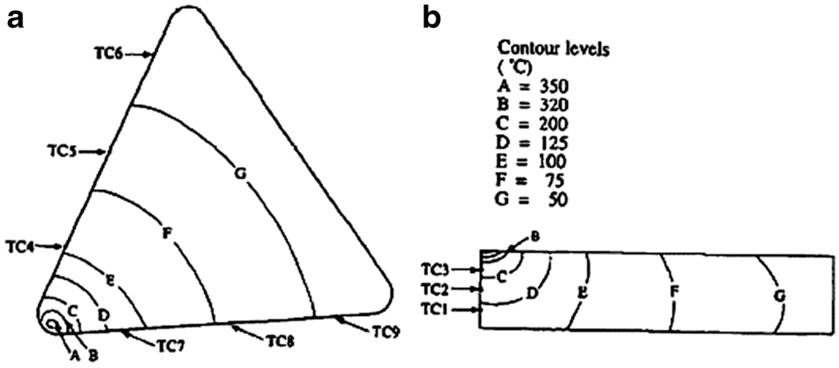


Fig. 3 Temperature distribution in VC7 TENA 332 insert when machining AISI 1045 Steel: **a** rake face, **b** flank face [55]

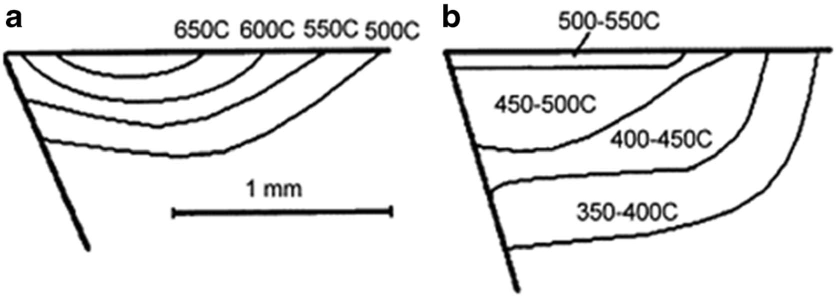


Fig. 4 **a** Temperature contours on the rake face of a tool. **b** Temperature contours for machining copper [45]

Chou et al. [56] and Groover et al. [57] reported that tool failures happen mostly around the tool's principal zone. It includes the areas of tool cutting edge, flank wear, crater wear and BUE formation. The above studies proved that the extreme production of heat takes place, in a machining route, tool face and chip edge. Minton et al. [58] developed a methodology to provide a mechanism of cooling the inner area to the cutting insert while machining titanium. The study measured swarf and coolant temperature by using tools which were coated and uncoated with diamond for machining grade 2 CP titanium. Figure 5 shows the experimental setup utilized in the study and change in coolant temperature observed during the machining.

Liu et al. [59] observed that, due to high temperatures, there is creation of crater wear on the tools rake face at high-speed face grinding of hardened steel which utilizes an Alumina-based ceramic and cemented carbide tool. Casto et al. [60] found the same results when the 1040 steel alloy was turned through ceramic tools. Thus, a proficient coolant application which intends to have a cooling effect on tool–chip edge nearby the rake face of the tool can be capable to alleviate the heat production at cutting zone. Liao et al. [61] have performed an experiment on end milling of titanium alloys with different cutting speeds by cemented carbide tools. They observed that the rise of cutting temperature and strain hardening were due to the low cutting speed. It was studied that, during milling of Inconel 718 at low cutting force with increased speed, the tool life improved. At medium cutting speed, the material becomes soften because of thermal stability property of γ' precipitation of titanium alloys. It was observed that if the cutting speed is enhanced, a majority of the chips were soldered on either sides of the slot and inhibited the chip flow. This apart, the nickel alloy's toughness will increase with an increase in the temperature at 650 °C, as shown in Fig. 6.

It was found during the high speed machining of titanium alloys, there were two main causes like the high cutting temperature and dumping of chip. Furthermore, it was observed that machining of titanium alloys (Inconel 718) with cemented carbide tools proved better. Besides, in milling operations, feed does not have a noteworthy effect on temperature. Pittalà et al. [62] performed an experiment on milling of titanium alloys and measured workpiece temperature by utilizing infrared camera. They noticed that the values of cutting speed and feed rate were altered during experiment. By using the experimental data, an FEM model was developed. Later, the model was calibrated using different milling tests. The experimental values were promising with FEM model. It was concluded that the methodology can be beneficial to tool designer engineer to develop the tool enactment.

Pervaiz et al. [24] performed an experiment of machining Ti6Al4V alloys and recorded cutting temperatures using infrared camera under dry, minimum quantity cooled air lubrication (MQLCA) and flood environment. Flood cooling technique was the most effective way of heat removal at cutting edge of the workpiece and tool. By utilizing the MQLCA strategy at cutting speed of 90 m/min, the temperature reduced by 25 % as compared to dry machining same like the temperature reduced 17 °C at speed of 110 m/min. The machining temperature measurement of Titanium alloys under dry environment at different speeds is shown in Fig. 7.

2.3 Influence of lubrication/cooling on tool wear and life

During metal cutting machining operation, cutting tool gets deformed and loses tool material. The more the machining time, the more heat is produced at tool–chip interface [63, 64]. With the progress of cutting operation, two general modes of wear, namely flank wear and crater wear, grow on the flank and rake faces, respectively [63]. It is reported in the literature that flank wear directly controls the machining performance by affecting geometric accuracy and surface integrity, whereas crater wear can destroy the integrity of the cutting edge that facilitates fracture. In the metal cutting industry, tool life is generally evaluated by monitoring flank wear as guided by ISO standard (3685: 1993 -E) [65]. Shaw [64] describes that heat generation at the cutting interface controls the overall machining performance of the cutting operation. In order to improve machinability, cutting fluids have been applied extensively in the cutting processes. These cutting fluids either facilitate the heat dissipation from the cutting zone or lubricate the cutting interface between rake face, chips and machined surface [66].

Astakhov [67] developed the first law of metal cutting. He reported the existence of a critical value of temperature called

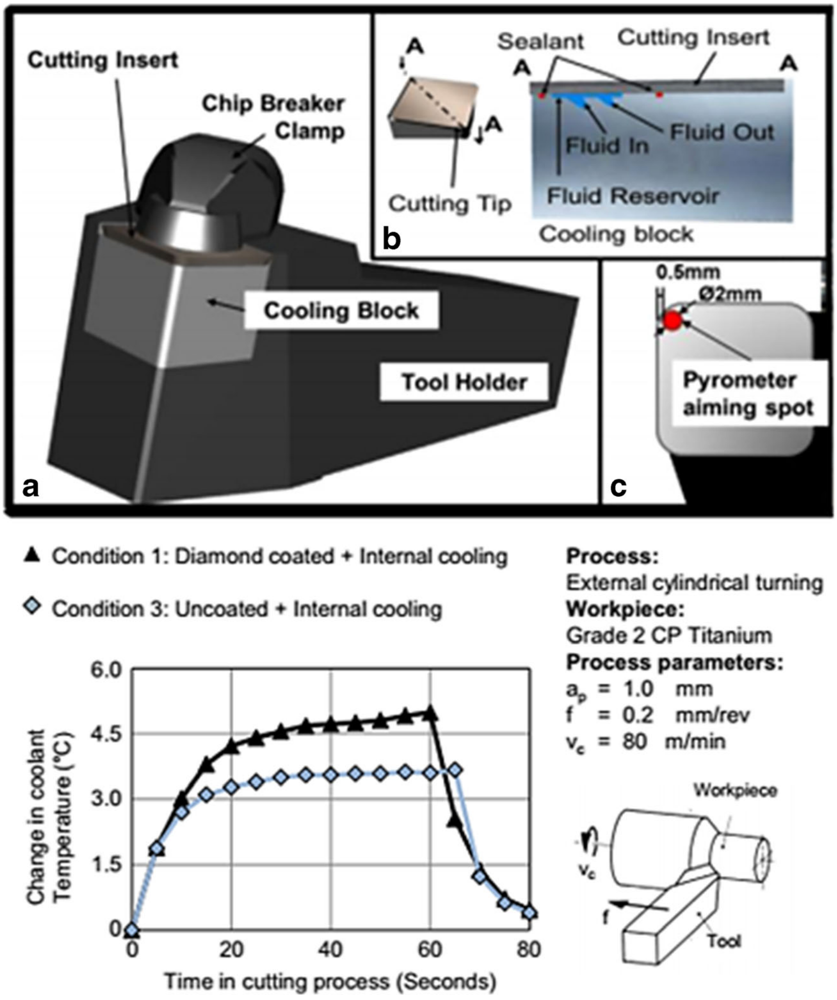


Fig. 5 Diagram of experimental setup. **a** Tool with a cooling block. **b** Cross-section of cooling block. **c** Pyrometer for temperature measurement. **d** Change in coolant temperature difference [58]

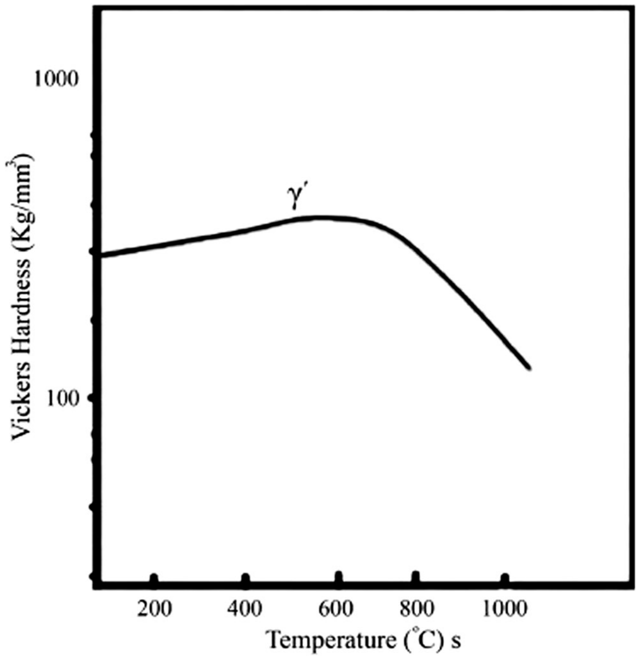


Fig. 6 Temperature relationship with Vickers hardness of Inconel® 718 [61]

as optimal cutting temperature (θopt) that results in maximum machinability. The study revealed that θ_{opt} is strongly linked with the cutting tool and workpiece material's properties. Generally, cutting fluids are applied to maintain the cutting temperature at lower level to enhance cutting tool's performance. However, the other methods such as pre-heating, plasma and ion-beam heating are engaged to facilitate the cutting temperature near the optimal cutting temperature value. The application of cutting fluid helps the cutting edge to maintain its integrity by lowering the thermally induced wear mechanisms such as diffusion and adhesion. The reduction in friction at the tool chip interface results in lower abrasion wear [68]. El Baradie et al. [68] reported that by decreasing the temperature of the workpiece can increase hardness of the material. Consequently, it increases the cutting forces and power consumption, thus reducing the tool life [11, 68]. However, coolants provide more encouraging results for high speed machining. Literature [69] reports low cutting forces and elevated cutting temperatures under high speed machining arrangements. It is also reported that, in machining, the substances used for cooling and/or lubrication are termed as

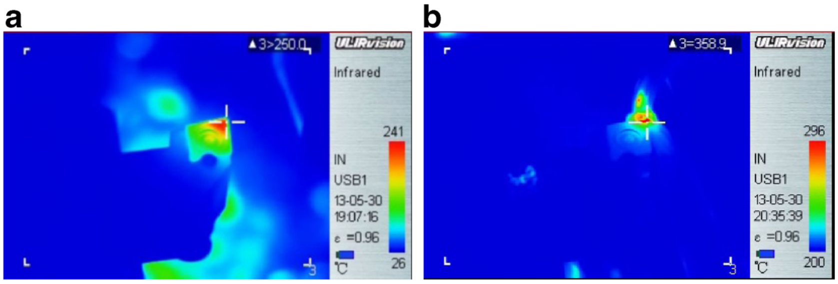


Fig. 7 Cutting temperature of titanium alloys in dry cutting. **a** Cutting speed = 150 m/min and feed = 0.15 mm/rev, **b** cutting speed = 150 m/min and feed = 0.25 mm/rev [24]

cutting fluids, gas-based coolants/lubricants and solid-based lubricants [70]. Abukhshim et al. [46] performed cutting tests on high strength alloys and monitored cutting temperature and flank wear. The study pointed out at higher cutting temperature in dry cutting. William and Tabor [71] inspected the function of cutting fluids in machining operation. They observed the friction mechanism at the cutting interface between tool and chip. The study suggested a design of interconnecting capillaries to reduce friction at the interface.

It is reported that Titanium alloys possess low thermal conductivity due to which heat stays close to the cutting edge. To maintain the integrity of the cutting edge, different cooling approaches can play a vibrant role. Pervaiz et al. [5] performed an experiment on machining of Titanium alloy Ti6Al4V under dry mist and flooded conditions and observed the flank wear using a tool maker microscope at different cutting speed, as shown in Fig. 8. They used coated and uncoated tools for this experiment. Hence, under all cutting environments, Flank wear rate was found for greater feed rate. To reduce the coefficient of friction, tool coatings are found very useful between chip and tool. When the coefficient of friction is reduced, the production of heat during metal cutting operation also cuts down. It will not only increase the tool performance but also the tool life [5]. In comparison to the dry cutting, mist and flood cooling approaches facilitate heat transfer and result in improved machining performance, as shown in Figs. 8 and 9 [5].

Ecological condition plays a vital role towards flank wear transmission. They also reported that a rapid increase in flank wear is observed with increasing cutting speed when environment is dry. Nevertheless, the results for flank wear are equally good in misty and flood environments. They found, apart from misty environment, the flood environment showed better results when at low feed and cutting speed. It is seen that Minimum Quantity Lubrication (MQL) technique is more suitable as compared to flood or dry technique to cut down ecological pollution when applied at higher cutting speeds [5]. Jawaid et al. [72] investigated experimentally to assess the machinability of Ti-alloy under dry conditions. The experiment was conducted with four different levels of cutting speed at constant depth of cut. They used uncoated cemented carbide tools. The investigation showed that the performance of finer grain size tools was better than the coarser grain size tools. On flank face, some abrasion wear mechanism was perceived. Cordon et al. [73] studied the machining performance of titanium alloys using polycrystalline diamond, carbon boron nitride and TiB_2-coated tools. They found that polycrystalline diamond performance was best at cutting speed of 150 m/min. Carbon boron nitride tools were highly appropriate to finish cutting conditions, while the functioning of TiB_2-coated tool was found reasonable at the cutting speeds lower than 100 m/min. They also reported that the dominant wear mechanisms were adhesion and diffusion. Elmagrabi et al. [74] led an investigational study to evaluate dry slot milling of titanium alloys using coated and uncoated tools. The coated carbide tools were found to have improved tool life whereas feed rate and depth of cut have controlling influence on surface roughness.

Wang et al. [70] performed stress analyses of machining of RBSN ceramic tool with CBN insert and used a cryogenic coolant. They came to know that there is a decrease in temperature when cryogenic coolant is used, and it results in stress reduction at the flank face. Li et al. [75] showed that diffusion and adhesion of tool chip interface are reduced when machining under cryogenic cooling condition ferrous metals with natural diamond tools.

Hwang et al. [76] estimated machining performance of Al 6061 using different cooling and lubrication methods. The study was conducted using minimum quantity lubrication (MQL) system and water-soluble conventional flood cooling. Taguchi method was utilized in this study, and it was exposed that machining parameters have an important influence on the cutting forces. Kumar and Choudhury [77] performed an experiment on machining of stainless steel 200 in dry and cryogenic LN_2 coolant environment and investigated tool wear conditions. They reported that cryogenic machining provided 37.39 % improvement in the flank wear when compared with dry machining. Dhar et al. [20] studied LN_2 coolant behaviour in machining of AISI 304 stainless steel and reported that LN_2 cooling initiated cracks on the tool at all cutting speeds. This cooling strategy was endorsed to make the workpiece material harder. Dhar et al. [4] performed an experimental study on AISI-4340 steel using MQL system. The study was focused

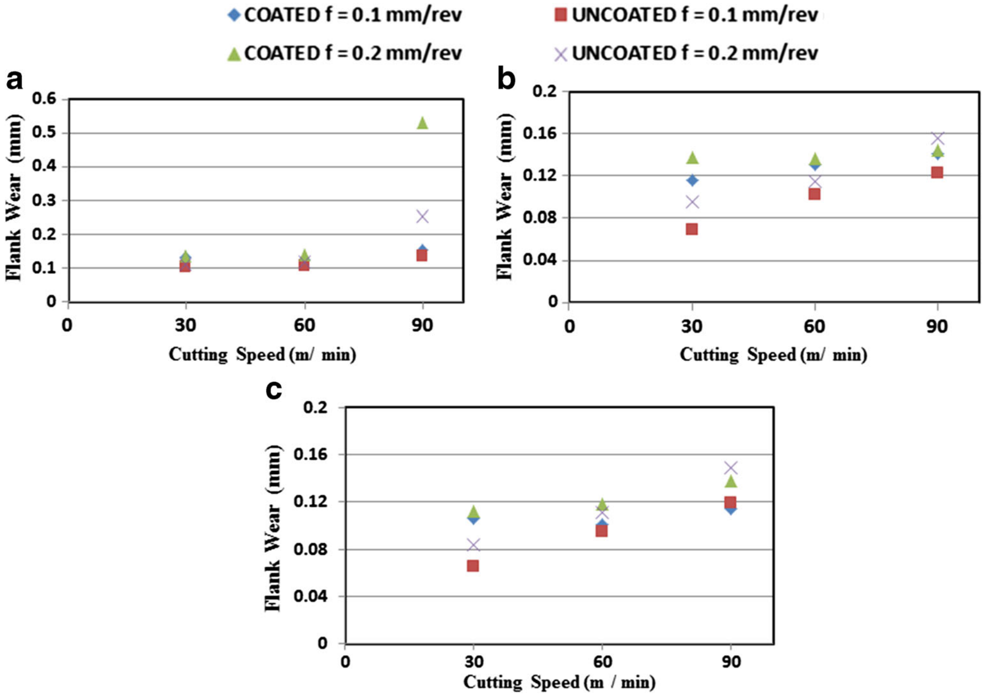


Fig. 8 Flank wear on coated and uncoated tool: **a** dry, **b** mist and **c** flood [5]

on the tool wear and surface roughness. They obtained promising results in dry, wet and MQL cooling strategy, as shown in Fig. 10.

The results in Fig. 10 shows ample reduction in tool wear rate and surface roughness by MQL technique. It is studied that MQL reduced the cutting zone temperature and favourable change in the chip tool and work tool interface.

2.4 Influence of lubrication/cooling on cutting forces and power

It is reported that climate change is due to carbon dioxide emissions and, consequently, based on energy demands and consumptions. Therefore, for sustainable manufacturing, it is important to decrease the usage of energy consumptions [78]. Pusavec et al. [16] have proposed various approaches to enhance sustainability in manufacturing. They reported that the carbon dioxide CO_2 emissions can be reduced by using energy-efficient protocols. In machining power, consumption is a major factor. The study showed that from, the total, only minor portion of energy is needed for a machining process [79]. While machining a product, if the power usage is reduced, it can save not only cost but also reduce the global warming. The greater the amount of energy is used in machining more the CO_2 emissions will be in the environment. Many researchers studied this area of machining in order to reduce power usage.

Gutowski et al. [80] studied the power distributions in machining process for different cutting speeds, as shown in

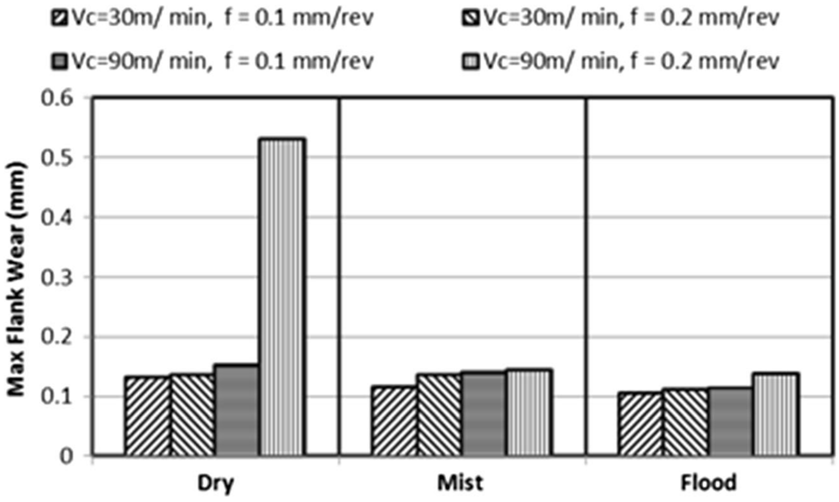


Fig. 9 Maximum flank wear measurement [5]

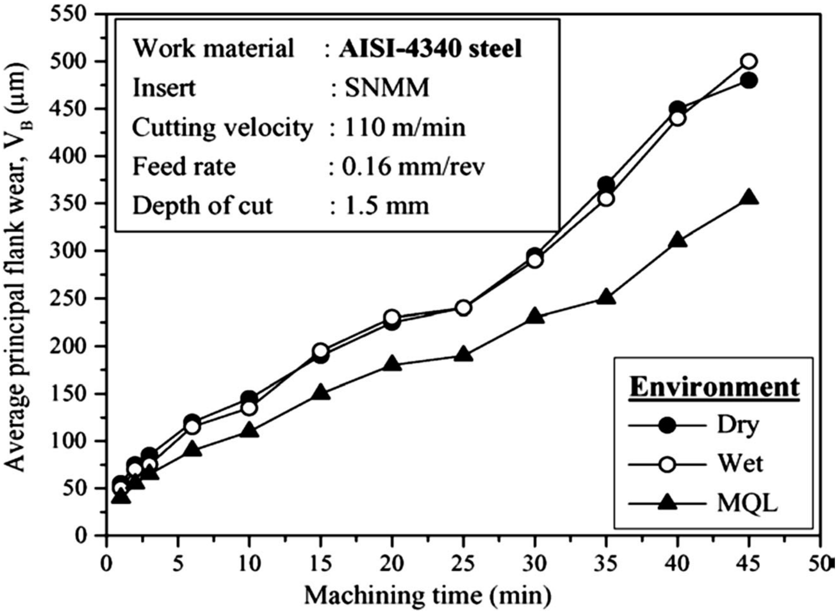


Fig. 10 Flank wear in dry, wet and MQL environments [4]

Fig. 11. In order to indicate the needed power for machine module, the machine should be turned on with the spindle turned off. It has observed that idle power represents the power required to run the components of the machine and spindle. The metal removal rate and workpiece material are highly influenced by the machining power. Figure 11 represents the use of power in non-cutting operations which is more as compared to cutting process. It is observed that, in actual practice, the power consumed in machining process was 31, 35 and 39 % at various cutting speed of 300, 400 and 500 m/min correspondingly [16]. Gutowski et al. [80] have concluded that the supply of power for machining ranges between 0 and 48 % and also depends on the cutting load. Therefore, it is important to select the machine which utilizes less power, consequently resulting in the less emission of carbon dioxide (CO_2) [16].

The consumption of power increased when the machining continued due to an increase in tool wear and by applying cutting fluids as their cooling action tended to increase the shear strength of the work material. Gutowski et al. [80] studied machining process with respect to its environmental impact and found that more energy is wasted in non-machining process. Munoz et al. [81] analysed the environmental impacts of machining operations. The study showed that power utilized by a machining process depends on workpiece complex geometry, material and the kind of coolant selected. Drake et al. [82] recommended a methodology to explain how power is consumed in machine tools. The proposed approach involved a six-step process to describe energy consumption. The study determined that out of total energy, only 35 % of it was used by spindle and the rest of energy was consumed in machine controller.

Kordonowy et al. [83] studied thoroughly different proportions of power consumption for a variety of machine tools. The study performed energy calculations using the energy consumption data for different phases of the machining operation. The study was based on injection moulding, manual milling, automated milling and automated lathe machine. Diaz et al. [84] analysed a machine tool to develop a more proficient strategy of energy consumption. The study established a methodology of using energy specifically as a functional process rate. The suggested method without actually measuring power demand provides perfect energy consumption. Diaz et al. [84] also presented some design and operational strategies to minimize energy consumption. They studied kinetic energy recovery system (KERS), process parameter selection strategy and web-based energy estimation tool. The study showed that by using KERS, 25 % of energy can be saved. Kara et al. [85] offered an experimental model to predict energy consumption against the process parameters as input. This model got verification when applying on different metal cutting processes. The suggested model calculates power consumption with 90 % perfection. Shan et al. [86] focused on energy involved in mechanical equipment and offered some strategies on energy-saving and emission reduction. Reddy et al. [87] performed an experiment on machining AISI 1045 steel with solid-coated carbide end mill cutters and used some solid lubricants. They successfully discovered that the use of solid lubricant can reduce cutting forces, specific energy and good surface finish. They also studied that friction at tool chip interface was greatly decreased in case of molybdenum

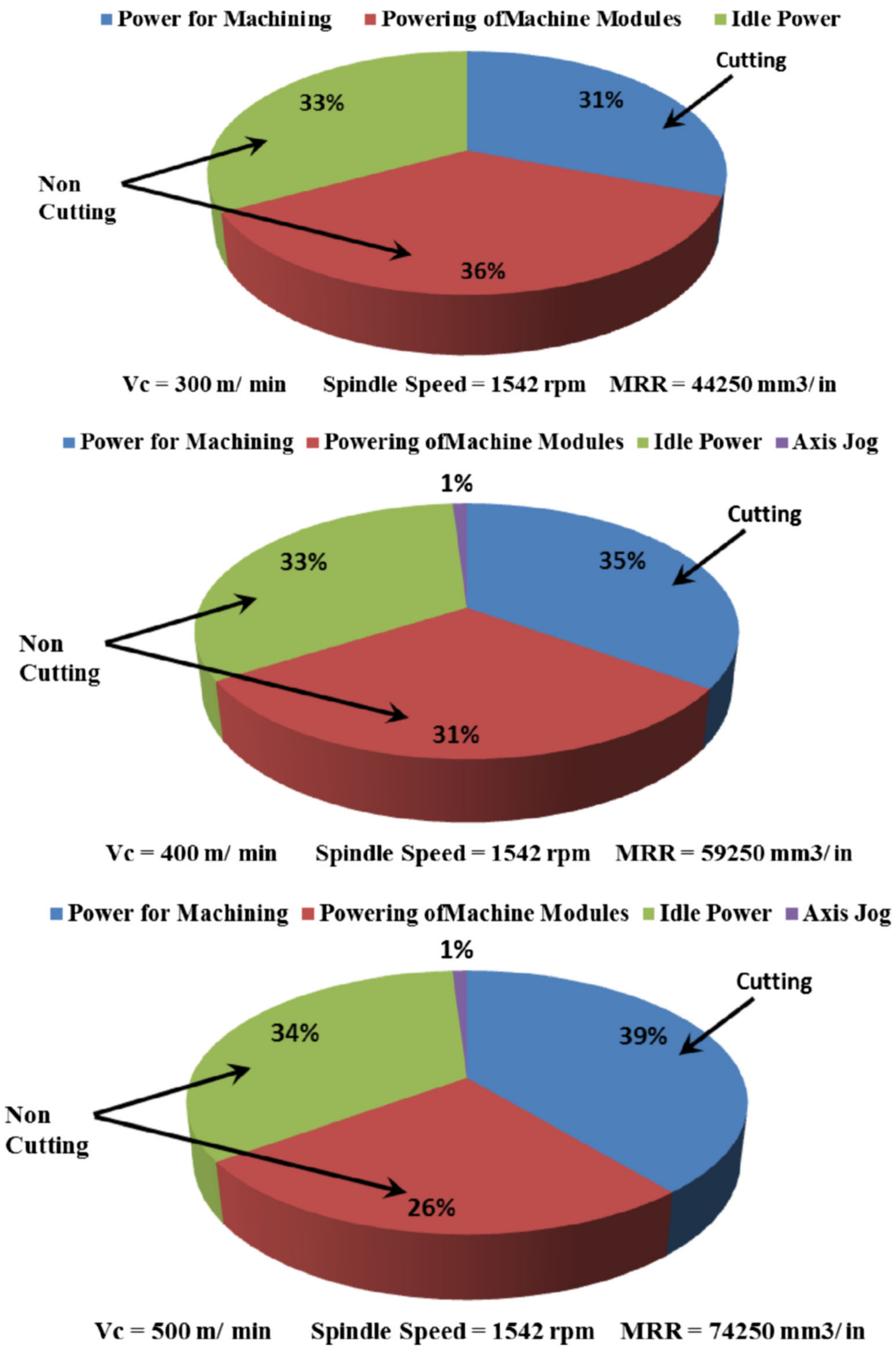


Fig. 11 Power partition for different cutting speeds (redrawn from [79])

disulphide when compared with graphite and flood machining [88].

Vieira et al. [79] operated face milling experiments to machine AISI8640 steel with coated carbide tools using dry, emulsion-based mineral oil, semi-synthetic cutting fluids and synthetic metal working fluids. The study monitored surface roughness, power consumption and cutting temperature. It was recorded that when machining with the semi-synthetic and synthetic cutting fluids, the power consumed is highest, as shown in Figs. 12 and 13. At high cutting speed of 110 m/

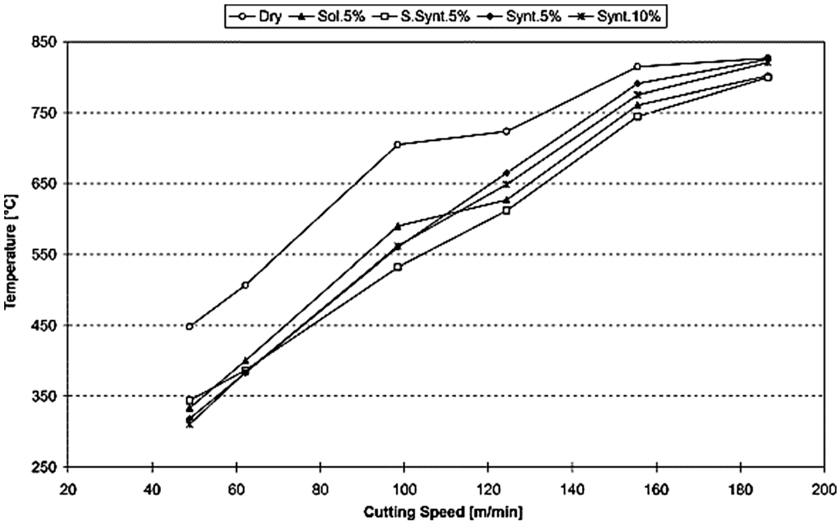


Fig. 12 Cutting temperature at different cutting speeds under different cooling environments [79, 70]

min, the semi-synthetic cutting fluid exhibited the best cooling strategy and it is followed by emulsion-based mineral oil, 5 % concentration and 10 % concentration of synthetic fluids.

Suresh et al. [36] performed an experiment on machining AISI 1045 by using solid lubricant with different cutting tools geometry. It was observed that performance of solid lubricant molybdenum disulphide revelled better results as compared of graphite and wet machining in terms of temperature, cutting forces, specific energy and surface finish. By using ANOVA techniques, they found the relative contributions results of speed, feed, rake angle on cutting forces, as shown in Fig. 14. It is studied that radial rake angle found to be the most important factor persuading the cutting force in all range of machining system. The study observed that the chip thickness was less in molybdenum disulphide as compared to wet and graphite machining.

Devim et al. [25] performed drilling experiments using aluminium (AA1050) by employing dry, flood-lubricated and MQL conditions. The behaviour of cutting forces and power consumed has been observed. More power was consumed at higher cutting speed. In Fig. 14, it can be seen that during dry machining process, the force of cutting somewhat increased when the feed augmented from 0.15 to 0.20 mm/rev. The graph trend exhibited an increased slope because of advanced order temperature established at greater speeds of cutting. This increased in temperature factor would affect the property of the tool and consequently increase the force of cutting, as shown in Fig. 15a. By using MQL strategy, it was observed that when speed of cutting at 90 m/min was used, there was an increase of the force of cutting at steady rate with feed range from 0.15 to 0.25 mm/rev, as shown in Fig. 15b. When the cutting speed at 60 and 75 m/min were used, there was negligible variation in cutting power and the tool has mitigated the heat generated to the lubricant. It was noted that cutting force was meager pertaining to all the speeds in flood lubricated environments, as shown in

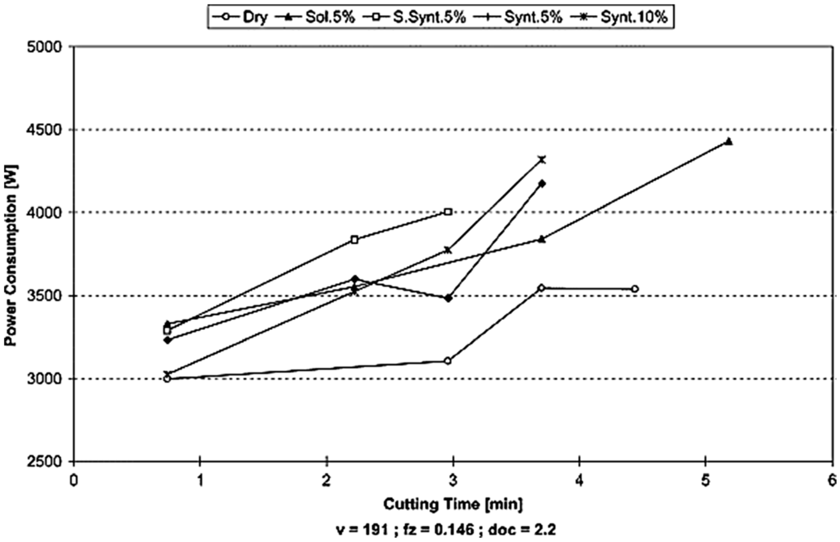


Fig. 13 Cutting power consumed during machining under various coolants and cutting speeds [79]

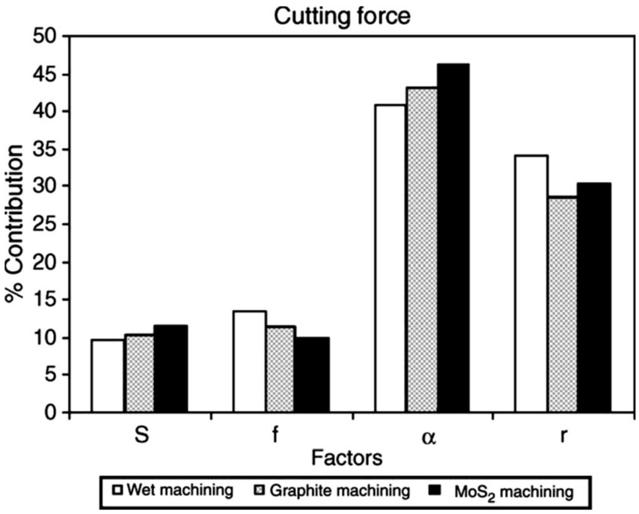


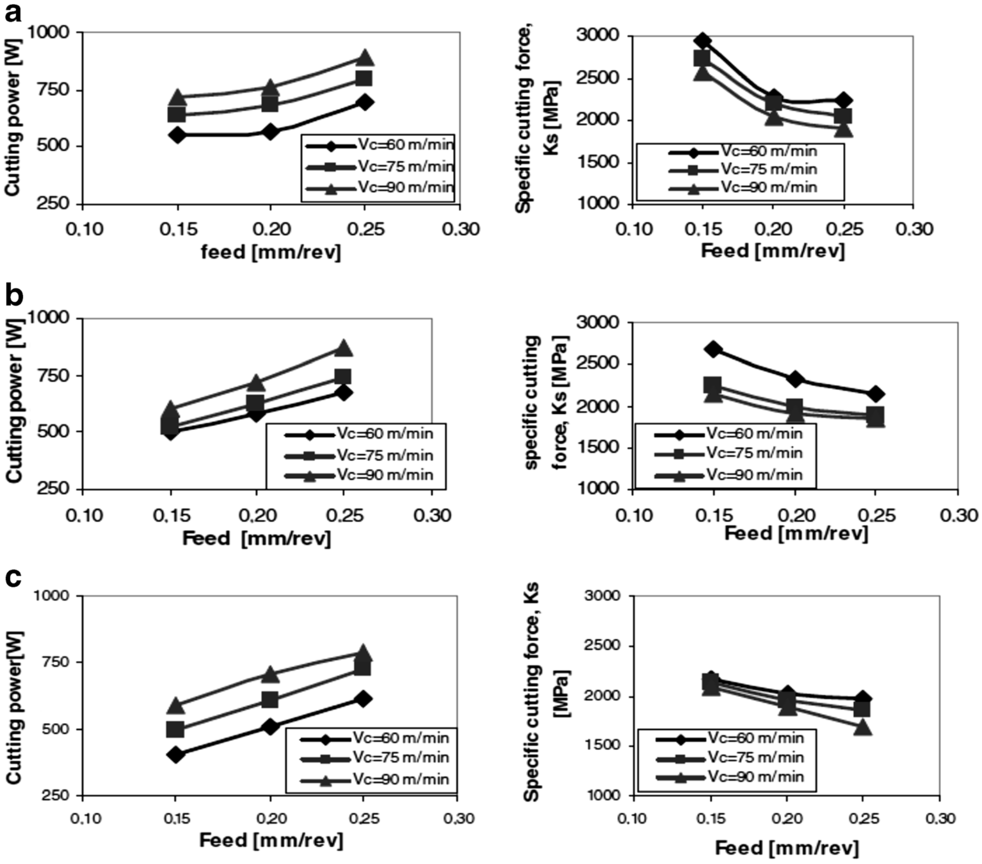
Fig. 14 Relative contribution of cutting parameters on cutting force (cutting speed '*S*', feed '*f*', radial rake angle 'α' and nose radius '*r*') [36]

Fig. 15c. Similarly, the cutting forces, power and energy were more for dry machining and reduced in MQL, flood lubricated conditions.

Pervaiz et al. [5] studied machinability of Ti6Al4V by monitoring power consumption and tool wear. They found that, if compared, the dry environment exhibited less energy consumption than mist and flood environments, but as a result, more heat is generated. The data related to energy consumption exhibited that energy utilization was less at lower cutting conditions (feed and cutting speed). Variation in energy utilization during each machining case can be linked to the variation in cutting forces and power requirement to pump coolant. For proper energy comparison in dry, mist and flood machining tests, particular energy utilization was calculated by keeping in view the material removal rate (mm^3/min), as shown in Fig. 16a–c. The results show that more energy was consumed at low feed and cutting speed. Machining will take more time with low feed rate if the movement of tool is slow.

The consumption of power for mist and flood was more because of higher cutting forces and higher pumping requirements for hydraulic pump. Least energy was consumed by dry cutting at the cutting speed of 60 m/min consumed least energy for both feed levels. At both feed levels, misty environment showed potential of improved heat dissipation at 90 m/min speeds of cutting. In most of the cases, flood environment consumed high energy which shows clearly that, under flood conditions, high cutting forces were produced. The coated tools at cutting speed of 30 m/min utilized additional power than their uncoated counterparts. On the other hand, energy consumed is very less for coated tools at higher levels of cutting speeds (60–90 m/min), as shown in Fig. 16a–c. Less energy will be consumed when the feed rate is high. Thus, it is

Fig. 15 Cutting power and specific cutting force behaviour using different machining parameters: **a** dry machining, **b** MQL (250 ml h^{-1}), **c** fully lubricated (120,000 ml h^{-1}) [25]



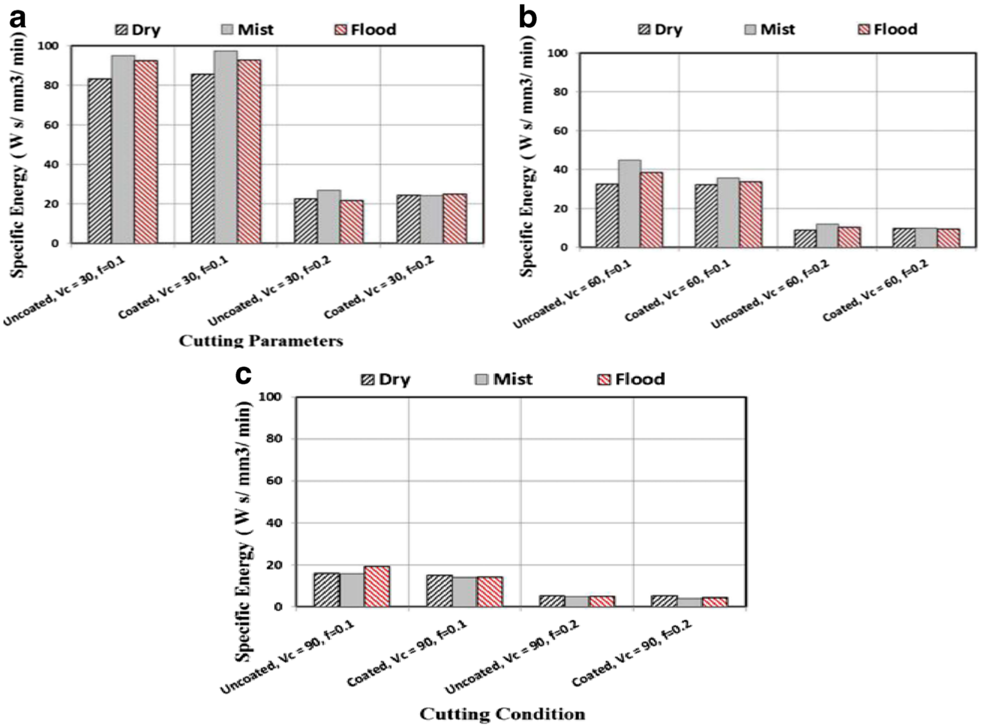


Fig. 16 Specific energy consumption: **a** 30 m/min dry, spray and flood environments; **b** 60 m/min dry, spray and flood environments; **c** 90 m/min under dry, mist and flood conditions [5]

concluded that when machining Ti6Al4V using PVD-TiAlN and uncoated carbide tools, the coefficient of friction can be reduced with the help of TiAlN coating. TiAlN-coated tools especially at elevated cutting speeds showed comparatively less energy consumption.

3 Utilization of conventional cutting fluids

It is not wrong to say that, in machining processes, cutting fluid is taken as an essential add-on which is regularly applied to enhance production rate, improve surface quality, reduce costs and increase profit [67]. Cutting fluids provide cooling action and lubrication effect at the cutting interface to dissipate heat generation and lower friction at the tool chip contact, resulting in improved machinability [69]. Cutting fluid helps to maintain the temperature close to the optimum cutting temperature ($_{\mathrm{opt}}$). Optimal cutting temperature ($_{\mathrm{opt}}$) is the temperature at which highest ratio of cutting tool material hardness over the workpiece material hardness is accomplished. Highest possible machinability is achieved when cutting temperature is maintained close to optimum cutting temperature ($_{\mathrm{opt}}$) [67]. Cutting fluid also performs other important functions of chip disposal and avoids corrosion on workpiece and tool materials. Amount of cutting fluid being applied during the machining operations also depends on the nature and type of the machining process. Some machining operations such as grinding, broaching and deep hole drilling require more amount of cutting fluids than other conventional machining process such as turning, milling and drilling operations [89]. Generous amount of cutting fluids in grinding operation facilitates heat dissipation, grinding wheel cleaning and chip evacuation.

Taylor [90] in 1907 was the first who reported the use of coolants in machining and achieved an increase of 40 % in cutting speed when machining steel with high speed steel tools. He used water as a coolant. In spite of water’s outstanding cooling ability, it lacks the lubricating property, and literature [17] also reports corrosion-related issues at machine tool structure and workpiece. Since that time, all new approaches are designed in a way that their good lubricating and/or cooling properties are very good. Cutting fluids can be classified as oil or water based [91, 92]. Mainly to assist lubrication and cooling during machining, water-based fluids are used. They can be further divided into emulsions and solutions. To achieve a good lubricating property, an oil base or pure oil is mainly used. The water-based fluids consist of water combined with oil particles suspended in it. The solutions comprised of basic fluid with many additives. Semi-synthetic fluids comprise of 5–50 % of mineral oil and synthetic components also known as additives which form emulsions in water. The lubricating and wetting properties of synthetic and semi-synthetic fluids are very good. They combine low corrosion rate and low vulnerability to bacteria growth, and thus, there is less irritation to the skin and very less odour.

Machado et al. [92] studied a variety of cutting fluids when turning AISI 8640 steel with triple-coated cemented carbide tools. He showed that by using synthetic and semi-synthetic fluids, tool life could become longer than emulsions of mineral oils. The synthetic fluid performed well as compared to the semi-synthetic fluid when machining at lower cutting speeds (up to 250 m/min). On the other hand, the semi-synthetic fluid gave at high cutting speed longer tool life. In order to improve tool life, cutting temperature should be maintained lower than the thermal softening temperature of the tool material. The cutting fluid facilitates cooling effect and tool wear mechanisms such as diffusion and adhesion gets decreased. The abrasion on the rake face could be reduced by the lubrication [88]. On the contrary, by decreasing the workpiece temperature in certain conditions, material hardness could be increased, thus cutting forces and power consumption got increased and the tool life would be reduced [68]. Flushing of chips away and avoiding the machined surface and cutting tool from corrosion are other major responsibilities of cutting fluids [93]. It is very important to select cutting fluids properly because the tool life, cutting forces, power consumption, machining accuracy, surface integrity, etc. could be affected. Generally, cutting fluids with higher lubrication capacity are encouraged for severe machining processes such as for low speed machining and machining difficult-to-cut alloys. Cutting fluids with higher cooling action are recommended in high speed machining where high cutting temperatures are reached [93].

Mendes et al. [94] performed experiments on aluminium alloy (AA 1050-O) under drilling operation by applying mist. The study also incorporated turning experiments on AA 6262-T6 by employing cutting fluids under conventional flood. The cutting fluid was contained additives like chlorine, sulphur and phosphor. It was found that drilling operation (AA 1050-O aluminium) with mist condition, the feed forces decreased but torque and power consumption increased. It was studied that surface finish was not considerably affected by the cutting fluid flow rate. On the other side, in the turning operation of AA 6162-T6 aluminium, the best results were observed when applying 10 % fluid concentration. At higher speeds, cutting fluid with chlorine as an additive provided less surface roughness and lower cutting forces at low feed/depth of cut. In spite of all the significant effects of cutting fluids, the nature and arrangement of delivery system are chosen on the recommendations of cutting fluid manufacturers and machine tool makers [67]. Cutting fluids can be categorized as cutting fluids, gas-based coolants/lubricants, solid lubricants, etc. [69]. Many approaches are used to categorize the cutting fluids due to their varying nature and characteristics. However, miscibility in water is one of the broadly established characteristics of the cutting fluids. Thus, it is generally used to classify the cutting fluids, i.e. water-soluble (water-miscible) cutting fluids and non-water-soluble (oil-based cutting fluids) [11].Also, gas-based and solid coolants are used in a variety of machining processes, which are discussed in next section.

3.1 Water miscible cutting fluids

As quoted earlier, the benefits of cutting fluids are to eliminate the heat which is produced due to conduction at the cutting zone. Hence, it is imperative that for the cooling action to take effect, cutting fluid must have a high degree of thermal conductivity [11]. Progress in the development of water-miscible cutting fluids was carried out with the development of carbide cutting tools. Water is the main ingredient in these types of the cutting fluids, where 1–20 % cutting fluid is concentrated in water. The quality of water is an important aspect of the cutting fluid. The hardness of water and its corrosive nature have controlling influence in the cooling applications [95]. Particularly, the most favourable coolant fluid is water which is also very economical in cost, but water has corrosive effect to ferrous materials particularly when used in some expensive machine tools. The low lubricating effect of water has a negative impact on the surfaces of the lubricant and consequently results in the wear of machine. Thus, in order to rectify the difficulties and improve the lubricating characters of water-based cutting fluids, many composite additives were mixed with water [93].

The water-miscible cutting fluids are categorized into three groups, i.e. synthetic fluids, semi-synthetic fluids and soluble oil. It is noted that soluble oil includes a mineral oil which is complemented by emulsifiers to permit the oil to get spread in the water [96]. It not only has a cooling effect but also is a remedy against corrosion. The organic and inorganic properties of synthetic fluids are free from mineral oil, thereby preventing corrosion and surface tension [1]. Synthetic cooling lubricants possess lubricants which are water-soluble, high pressure additives, corrosion resistance and defoamer. They are water-based and are used for low cutting force operations. These are the major demerits of these coolants and that is why its use is restricted in industries [67, 68]. On the other hand, both mineral oils and chemical additive properties contain semi-synthetic cutting fluids, which make it more considerable and favourable lubricant as compared to synthetic fluid. They have anti-rust property and are cleaner than soluble oils. The main problem of the water-miscible fluids is the bacterial and fungal growth which can cause serious health issues. To overcome these shortcomings of the cutting fluids, some extracts like humectants, germicide and bactericide are recommended [68]. Water-miscible cutting fluids are utilized in the metal cutting industry as one of the major shareholders for the cooling/lubrication-related applications. In one of the reflections, the annual sales of water-miscible cutting fluids have been reported to be 140,000 t/a for the EU [97].

3.2 Oil-based or neat-oil cutting fluids

There are other alternative coolants which are oil-based and are broadly used in majority of the machining processes. They are generally mineral oils containing some additives comprising lubricants and amalgams with high pressure to improve their usage [96]. The cutting fluid of such kind is normally utilized in lubrication of the interface of the tool-chip. It also helps in overcoming the friction at cutting zone. This reduced friction results in minor cutting forces and less crater wear at tool face. It also helps to minimize the friction between the machine moving parts [68]. There are two categories of oil-based cutting fluids which are paraffinic mineral oils and naphthenic mineral oils. By adding fatty lubricants, the characteristics of these mineral oils can be enriched. These high pressure additives contain chlorine, sulphates and phosphates. It also possesses viscosity index modifier, thickness modifier, odorants and polar additives [67].

These types of oils have the ability to lubricate, anti-lock property and resistance of corrosion, but they cannot maintain their properties at higher temperatures and load. Due to this drawback, these types of oils are not suitable for aluminium, magnesium and low carbon steel. The composite mineral oils are favourable at high machining temperatures and pressures. It is also suitable for low speed substantial machining operations like tapping, threading and broaching [67, 93]. It is observed that these types of lubricants make film between the sliding surfaces, resulting in less friction. It is also important that there should be no chemical reaction with machining surface. For example, in machining titanium alloys, chlorine is used as an additive which could develop chemical reaction on the machined surface [98]. Oil-based cutting fluids dominate in the metal cutting industry for cooling/lubrication-based applications. As reported in one of the reflections, their annual sales volume was approximately 220,000 t/a [97].

3.3 Gas-based coolant–lubricants

These coolants are usually referred to the substances which are in the gas form at room temperature, but in machining processes, they are applied either in the shape of pressured fluids and gas. The major constitutes of gases coolants are nitrogen, argon, helium or carbon dioxide. The gas coolants are also utilized in combination with conventional cutting fluids in the form of spray [1]. The common application of these types of coolants is used in dry cutting process. The main function of the air is to cool the tool and workpiece and remove the chips from cutting surfaces [68]. Therefore, the thermal conductivity of gases is very poor, and also they have low cooling capacity. Various approaches are in vogue to improve the efficiency of gas coolants like compressing and liquefying at low temperatures. Compressed gas coolants are suitable for heavy duty machining process where the conventional cooling techniques fail [68].

Brandao et al. [99] in their study tried to find out the effect of three gas-based cooling techniques. These techniques comprised of dry, chilled and compressed air. They observed that by using compressed chilled air, the heat dissipating efficiency increased as compared to dry cutting. The minimum dimensional variation on machine surface can be achieved by using compressed air coolant. Chilled air is applied as cutting coolant in machining medium density fibreboard (MDF). It improves the service life of tool without altering the power consumption and cutting forces [100].

Hong et al. [101] studied the machining of Ti–6Al–4 V titanium alloy under turning experiments and reported the effects of different cooling methods in which liquid nitrogen (LN_2) is used as a cutting fluid. They observed that by the application of LN_2 on flank face of the uncoated carbide tool increased the life up to 3.3 times. In another investigation, the effect of LN_2 on the friction coefficient was studied through the disc-pin sliding test. The observation showed that LN_2 coefficient of friction can be reduced when the frictional behaviour of the material is changed due to ultra-low temperatures. Moreover, LN_2 is a good lubricant by itself and has the ability to minimize the coefficient of friction between sliding parts of machine [102]. By the addition of a small amount of lubricant, there could be a reduction in the cutting temp and forces. It is reported that the tool wear reduced up to 44 % by spraying micro-drops of oil in air when machining low carbon steel [103]. Gaseous coolants like nitrogen and helium can prevent the oxidation on machine surface at high temperatures [103]. Yildiz and Nalbant [40] conducted a literature review on the utilization of cryogenic cooling-based approaches for metal cutting sector. The study assessed different types of cryogenic cooling setups, namely cryogenic pre-cooling of workpiece, cryogenic spraying or jet cooling, cryogenic treatment and indirect cryogenic cooling. The study reported the outcome of previously cryogenic temperature techniques on low carbon steels, high carbon steel, stainless steel and titanium alloys, as shown in Table 1.

3.4 Economical, environmental and health issues associated with coolants and lubricants

In the USA, the annual consumption of cutting fluids is approximately 100 million gallons. In Japan, this consumption is equal to 71 billion Japanese Yen where 42 billion Yen is the disposal cost only [104]. In 1994, the consumption of cutting

Table 1 Cryogenic features of different materials [40]

Mechanical properties of material	Toughness	Elongation	Reduction in area	Hardness	Tensile and yield strength	Impact strength
Titanium alloys	No change	Decrease	Increase	Increase	Increase	Decrease
Aluminium 390	–	No change	Decrease	Increase	Increase	Decrease
Carbon Steel AISI-1008	Decrease	Decrease	Decrease	Increase	Increase	Decrease
Carbon Steel AISI-1010	Decrease	Decrease	Decrease	Increase	Increase	Decrease
Carbon Steel AISI- 1070	Decrease	Decrease	Decrease	Increase	Increase	Decrease
Chromium Steel AISI- 52,100	Decrease	Decrease	Decrease	Increase	Increase	Decrease
Nickel Chromium AISI- 304	Decrease	Decrease	Decrease	Increase	Increase	Decrease

fluids in manufacturing industries in Germany was estimated 75,491 ton; it includes 28,415 ton of water-miscible cutting fluids [105]. The estimated cost related to the cutting fluids is around 16 % of the total costs [15], and with regard to machining difficult to machine material, it is about 20–30 % [14]. This cost exceeds the tooling cost by about 2–4 % of the total cost of manufacturing [105]. The cost of these fluids includes the buying, preparation, maintenance and their disposal. The costs of their disposal can rise up to 2–4 times their buying costs in countries like America and Europe respectively [106]. The main reason as why there is escalation in their cost is that the cutting fluids need affluent treatments since they are not naturally bio-degradable before they get disposed [106].

There are many environmental control authorities like (COSHH) UK based, (TRGS) German based which impose regulations to control the cutting fluid waste and hazardous [107]. It has been reported that, only in the USA, around 155 million gallons of cutting fluids are discharged and exposed to the environment annually [107]. To maintain their optimum characteristics, a regular maintenance is required. The cutting fluids offer a rich environment for bacterial and fungal growth. It is studied that bacteria germs could change the PH level of cutting fluid and increase corrosion which can be risk for the machine operator [107]. To minimize the growth of bacteria in cutting fluids, some anti-bactericide constitutes are used. It is reported that some bacteria are still alive even above the pH level 10 in the cutting fluids [108]. It is seen that few bactericides like *Pseudomonas* could last even in the existence of anti-bacterial [109]. The existence of the bacteria is not only restricted to the cutting fluids but also in the work place. This needs attention to monitor the bacterial growth at work place. There are many bacterial infections released due to cutting fluids, and that is the reason why the local government authorities restricted not to dispose the waste fluid without treatment [107]. The study revealed that to maintain the functionality of cutting fluids, antimicrobials and biocides can be used. It is reported by International Agency for Research on Cancer (IARC) USA that the cutting fluid (mineral oil) contains carcinogenic substances which could cause skin cancer [110].

The study revealed that non-formaldehydes are injurious to health [107]. Apart from biocides, there are additional chemicals in the cutting fluids are also risky to the environment. Some constitutes in chlorine and sulphur present in cutting fluid has chemical reaction with cutting materials. They are thought as poisonous materials for the health of the workers and the surroundings [101]. In extreme pressure, cutting fluids chlorinated paraffin changed its properties in the presence of heat and pressure. The disposal of waste chlorine processing cost increases up to 7 % due to imposed environmental controls [104]. The vaporization and atomization of cutting fluids in machining operations can cause different kinds of diseases like respiratory, asthma and cancers. It has been further reported that flood cutting process releases 12–80 times more air pollution than dry cutting [111]. Furthermore, these small air particles present in the environment can easily be inhaled by the workers which can cause serious health issues.

It is reported during year 1993 that around 16 % of industrial diseases in Finland were due to vapours of cutting fluids. These diseases are musculoskeletal, hearing loss and related to skin [112]. On the other hand, the study shows that gas cooling lubricants are much safer to the environment, but they are more costly than the cutting fluids. The cost of the gas cooling lubricant is high because they require additional equipment [113]. Moreover, gas-based coolants cannot circulate in machine since they are not reusable [114, 101]. The disposable cost of the gas-based coolant is less as compared to flooded coolant [42]. For the use of gas-based coolant, appropriate ventilation system is required in order to dispose of the CO_2 [101]. Hence, it is concluded that gas-based coolants strategy is environment friendly as compared to conventional cooling strategy, but it is expensive [106].

4 Environmentally sustainable machining

To access sustainability of a product, whole life cycle starting from extraction until disposal has to be considered and examined. To obtain meaningful results in advanced models, measures for sustainability assessment and optimization procedures are required to address the product, process and system levels [61]. It is reported that there is no universally accepted definition for sustainable machining process. A recent study defines it as a process that leads better environmental conditions, operational safety and personnel health. This process also reduces cost and power consumption and products' waste, as shown in Fig. 17 [115].

Wanigarathne et al. [116] reported that sustainability rating system composed on the components as shown in Fig. 18. It indicated that rating 0–2 is worse and 8–10 best.

In recent years, dry machining is considered environmentally safe and friendly. In some of the machining processes, due to drastic improvement in tool coating technology, the cutting fluid methodology has been completely eliminated. However, still in most of processes, the cutting fluids are still essential to cater heat generation resulting from high friction and plastic deformation. The heat removal from the cutting zone also helps to reduce adhesion between work and tool materials [17]. The conventional flood cooling technique has environmental issues as discussed earlier like toxicity and non-biodegradability and also it is not economical. To make machining process workable in nature, a reduction in the amount of toxicity is required with an increase in biodegradability. In order to evade the risky effects of cutting fluid on the environment, the dry cutting is a better way out. However, the unnecessary heat was generated during dry cutting machining which bounds the material removal rate and provides poor tool life and higher surface roughness. To implement near dry machining, minimum quantity lubrication (MQL) arrangements are used. It is reported that MQL strategy seems to be a promising solution as it minimizes friction, but it offers low cooling capability due to the missing coolant. As per environmental concerns, usage of vegetable oil is healthier than mineral oil. MQL techniques utilize very less amount of lubricant to minimize friction in the cutting zone. However, the generation of fumes due to the evaporation of oil particles is a demerit. It is studied in the literature that, in MQL strategy, more experimental work has been performed than the numerical modals. More dedicated research studies are needed to explore the operating characteristics including optimization of air–oil moisture ratio, cutting zone temperature, coolant pressure and numerical modeling of MQL systems.

Cryogenic machining is also an emerging sustainable solution for metal cutting sector, but studies shows inconsistent machinability findings. The results are highly sensitive to the properties of workpiece and cutting tool materials. Change in tool and workpiece properties is the main cause of inconsistency. There should be further investigation on different pairs of tools and workpiece materials. It is studied that small amount of liquid nitrogen (LN_2) applied to cutting Ti-6Al-4V showed excellent results as compared to emulsion cutting. However, this cooling technique has high setup cost as the freezing effect at the nozzle hinders the flow of coolant and overcools the workpiece. Some of common environmentally conscious strategies are shown in Fig. 19.

There is a potential to work further on this environmental friendly technique. In the next segment, there are some reviews on different issues and achievements to cut down or

Fig. 17 Components of sustainable machining [115]

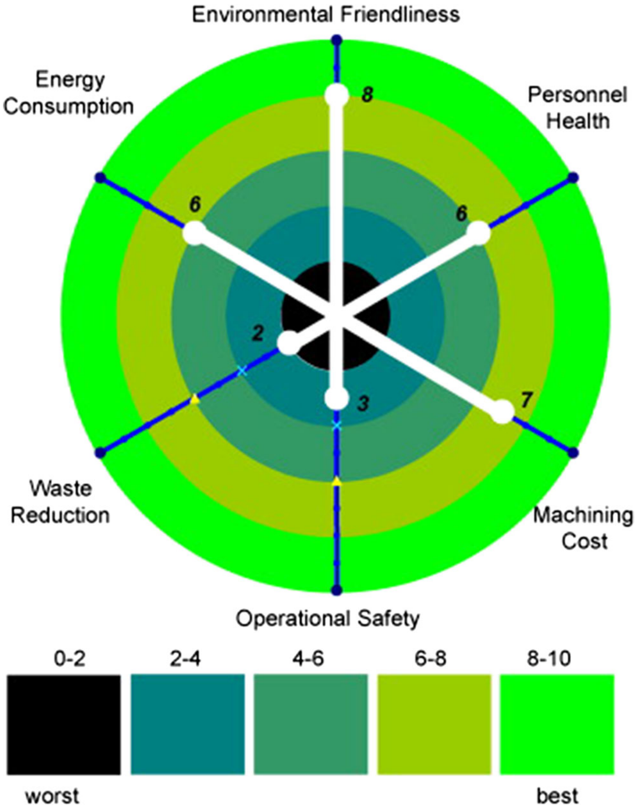


Fig. 18 Demonstration of the sustainability rating system [116]

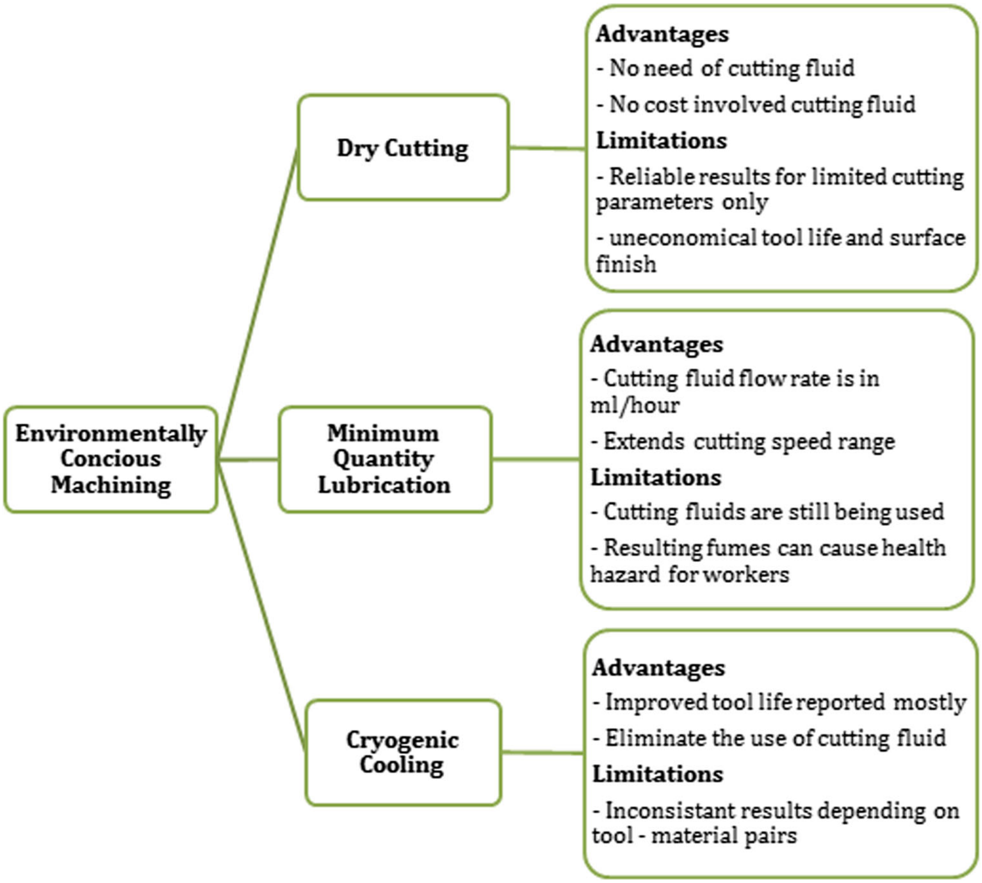


Fig. 19 Classification of different environmentally conscious machining techniques [1]

lesson the consumption of cutting fluids in machining by using different methods.

4.1 Approaches to enhance sustainability with conventional MWF

In this section, different approaches will be discussed to enhance the environmental performance of the conventional metal working fluids (MWF). Generally, the chemistry of MWF is changing throughout the service life of the fluid. By increasing the service life of conventional MWF, overall environmental performance of the metal cutting operation can be significantly improved [117]. When oil-based MWF is exposed to atmosphere here are chances of oxidation to take place. Similarly, temperature changes during the operation can initiate polymerization-based reaction. Both oxidation and polymerization reactions can drastically change the viscosity and flow-dependant properties of the MWFs. During the machining operations such as grinding operation, workpiece material chips and particles from the grinding wheel adds in the MWFs during operation and significantly change the chemistry [118]. Another important issue with the MWF is linked with the microbial growth during service life. Microbial growth results in biofilms that has harmful effects on the lubrication equipment such as storage tanks and filters [119].

It has been observed that the proper management, monitoring and maintenance of the MWFs resulted in improved overall environmental performance. Appropriate maintenance of the MWFs results in extended service life, and it provides economical benefits of saving purchasing and disposal costs [120]. Proper lubrication system management results in improved machining performance and reliable production. Here, it is also worthy to point out that poor MWF management can cause failure of machine tool and results in machinery-related downtime as reported by Rakic and Rakic [121]. Occupational health concerns of the human worker are also improved by implementing the practices related to the MWF management. Regular monitoring of concentrations of additives in the MWFs results in limiting bacteria and fungi growth [122].

Another important aspect of MWF application is to replace the mineral oil-based MWFs with renewable MWFs. This replacement supports sustainable development in the metal working sector as these renewable MWFs have low toxicity, small evaporation, less emissions and speedy biodegradability [123]. Several researchers have investigated the machining performance of such renewable MWFs. Winter et al. [124] evaluated the performance of oil of *Jatropha curcas* seeds for machining processes. *J. curcas* seed oil is inedible for human and reflects the suitable fatty acid pattern. The LCA-based analysis shows that oil of *J. curcas* seeds has environmental advantage over the conventional MWFs. The performance of oil of *J. curcas* seeds was found suitable for precision turning applications.

Lea, in another study [125], revealed that extraction and utilization of lubricants from harvestable resources were gaining popularity in the European market. The European market study revealed the growth of 16 % from 2000 to 2006 time period. The study projected that by strict environmental rules and regulations, this 16 % can further be increased to 35 % approximately. Herrman et al. [126] conducted a life cycle analysis (LCA)-based study to compare the properties of mineral oil and plant seed-based esters. The LCA was focused to draw conclusions regarding the economical, technological and ecological perspectives. The grinding operation was conducted under the mentioned MWFs. The study revealed that when market price and environmental performance were considered together, then animal fat and used cooking esters provided the best ratio. The global warming potential (GWP) associated with different conventional and renewable MWFs has been reported in Fig. 20 [126, 127]. Lawal et al. [128] provided a detailed review about the usage and application of vegetable oil-based MWFs for the machining of ferrous metals. The study concluded that vegetable oil-based MWFs have enormous potential to replace the mineral oil-based MWFs for machining ferrous metals.

To facilitate sustainability in the metal cutting industry, another important aspect is related to the energy consumed for the pumping and handling of conventional MWFs. In case of machining where generous amount of cutting fluids are employed, higher amount of energy is also utilized to pump the higher flow rates. Oda et al. [129] investigated the energy consumption in the machine tools. The study revealed that 54 % of the overall energy was consumed in the coolant-related equipment. The study investigated the energy consumed in different types of pumps to explore the potential of energy-efficient pumping. Shimoda [130] pointed out that reducing the MWF consumption results in the opportunities to reduce energy consumption as well. Such cooling strategies that deal with the reduced amount of MWF consumption (MQL, MQCL, etc.) require significant design changes in the machine tool accessories for coolant pumping system [116]. Denkena et al. [131] also point out at the huge potential of energy saving by optimizing the performance of high pressure pumps. The study was focused to reduce and control the flow rate of cutting fluid to explore the energy-saving potential. The outcome of study revealed the potential of saving up to 37 % of energy, and feed rate was found to be the most dominant factor for energy optimization.

4.2 Dry cutting

Dry cutting is one of the adoptable approaches to diminish the utilization of cutting fluids in cutting processes and thus helps in cutting down the machining costs and environmental issues [105]. Weinert et al. [116] reported the merits of implementing dry cutting which are shown in Fig. 21.

To employ cutting fluids can help in improving tool life, preventing built up edges (BUE) and reducing the cutting forces and surface roughness. Higher friction and cutting temperatures were found in dry machining than that of in flood machining. The presence of high temperature during cutting can results in lower tool life, poor surface quality and geometrical deviations in the machined surface. Another important issue associated with dry cutting is the production of metallic dust during the metal cutting process. However, this does not happen for all materials. Some positive effects are noted in machining operations under dry cutting like lesser thermal shock and improved tool life in some circumstances [17]. Different techniques have also been employed to avoid the use of cutting fluids in machining. These techniques involved indirect heat dissipation, improving cutting tools properties and coatings or tool geometries. This introduced the need to explore advanced tooling materials like as different multi-layer-coated tools, Cubic Boron Nitride (CBN), Polycrystalline Cubic Boron Nitride (PCBN), Polycrystalline Diamond (PCD), cermet and ceramics.

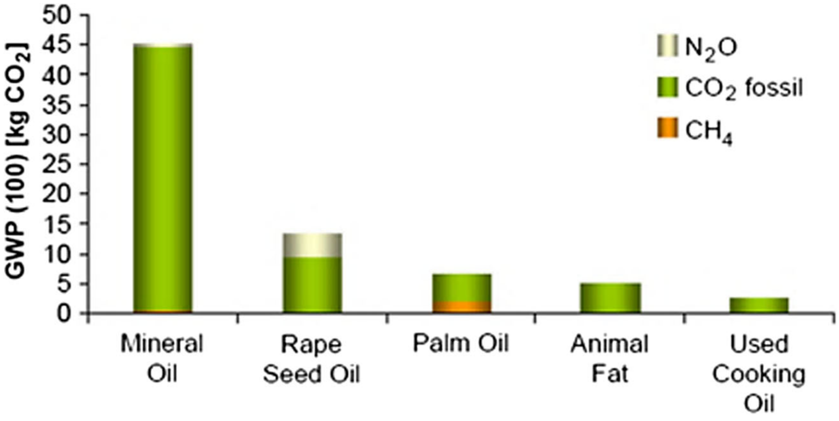


Fig. 20 Global warming potential (GWP) associated with different MWFs [127]

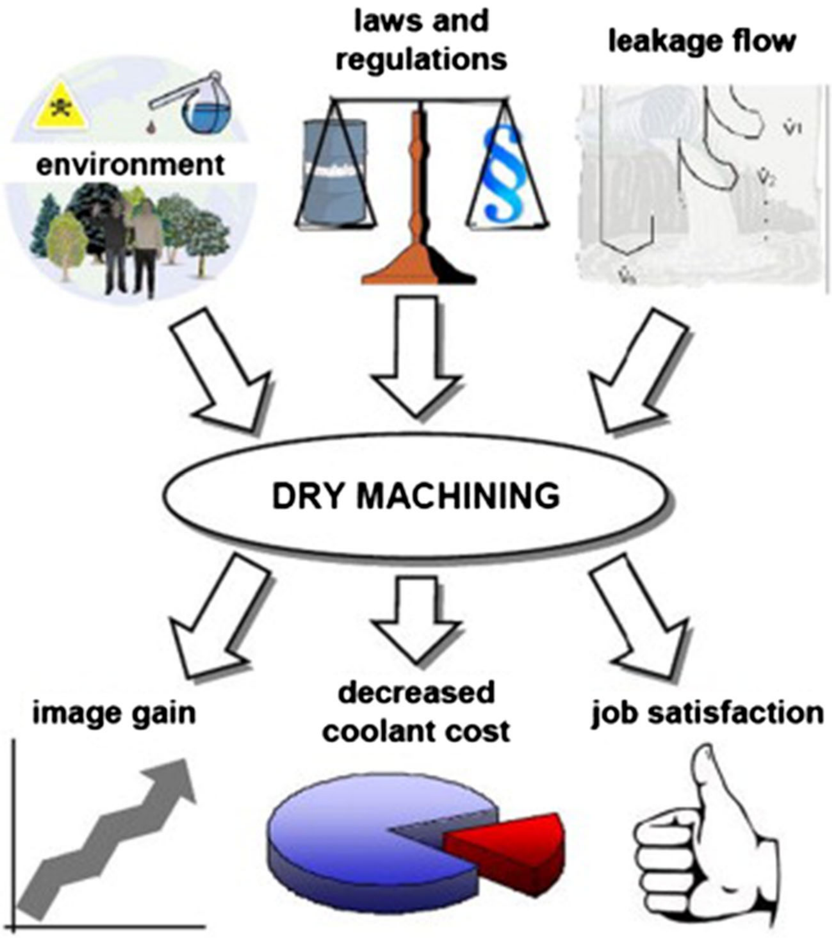


Fig. 21 Benefits of adopting dry machining [116]

Nouari and Ginting [132] performed dry end milling of Titanium alloys using uncoated tungsten carbide (WC) inserts with cobalt binders alloyed with 20.7 wt.% of (Ti/Ta/Nb)C. These findings were focused on chip formations, tool wear, cutting temperature and surface finish of the machined surface. The study also observed wear mechanisms on worn tools using scanning electron microscopy (SEM). The study observed that the leading tool failure mode is due to localized flank wear, and the other reason of failure is the brittle fracture of the cutting edge. Dearnley et al. [133] investigated that a tool did not suffer from unnecessary crater wear as reported by Nouari [132]. This could be further elaborated by the fact that continuous machining (turning) results in higher cutting temperature than that of in intermittent cutting (milling) operation. The presence of high cutting temperature aids the chip material to get adhered at the rake face and results in built up edge (BUE) formation. The BUE material is later removed by the flow of the chips. Also, high cutting temperatures assist the cutting tool material to diffuse into the chips at the cutting interface. Nouari et al. [132] studied that in turning process due to high cutting temperature, abrasion and diffusion are accountable for crater wear on the rake face of the cutting tool. Nouari et al. [132] made the conclusions that uncoated alloyed carbide tools are suitable for dry end milling of titanium alloys with cutting speed >150 m/min, feed rate = 0.15 mm/tooth, 2 mm of axial depth of cut and 8.8 mm radial depth of cut. All these machining parameters showed clearly that the tool life was 11.3 min with 0.61 μm surface roughness. Also, these investigations which are based on experiments revealed that FEA model can successfully predict the results when simulated for dry end milling operations.

Krain et al. [134] observed the dry machining process of Inconel® 718 nickel-based alloy to get increased productivity with optimized material removal rate. They noted that because of high cutting pressure at tool tip and chemical reactivity between tool and workpiece materials, adhesion and attrition were found to be the dominant tool wear mechanisms. Inconel® 718 low thermal conductivity helps to attain high localized cutting temperature at the cutting interface and thus assists the wear mechanisms. The workpiece material is adhered to the tool while cutting at high temperature and forms a BUE on the flank face.

It has been stated that nanostructured tools material is used in many researches for dry cutting. Kustas et al. [114]

observed that nanostructured materials can increase the characteristics of the cutting tool like increased hardness, increased strength, increased Young's modulus and increased wear resistance, increased fracture toughness, increased chemical stability and less frictional behaviour. They also investigated that coated tools can give better performance than uncoated cutting inserts under dry cutting as this coating can increase the tool hardness and prevent the tool material from exposing and reduce the friction coefficient. They also experimented on the influence of multi-layer solid lubricant (MoS_2/Mo)-coated high speed steel (HSS) drills and made a comparison in the results with an uncoated drill when drilling Ti64 workpiece material. The reduction of 33 % in the cutting torque was observed when coated drill is used. Nabhani et al. [135] observed that the performance of PCD (SYNDITE[1]) tools is better than PCBN (AMBORITE[2]) carbide tools in the dry turning of titanium alloy. These carbide tools chemically reacted with titanium, thus forming a TiC layer. The cutting tool is protected by this TiC layer from abrasion, thus reducing the diffusion rate. Consequently, that chemical reaction between tool and workpiece materials could make tool life better by forming a protective layer.

Liu et al. [136] studied what happens to the machinability with CBN tools when aluminium is added to pearlite cast iron. They observed that by adding aluminium to pearlite cast iron, there is a creation of a shielding layer of aluminium oxide on the tool surface. This layer gives protection to the cutting tool from abrasive wear and enhances the cutting speed up to 4500 m/min. Liu et al. [59] reported while machining titanium alloys, the main tool wear mechanisms were adhesion and diffusion at the rake and flank faces. They also reported that the other feature related to the machining of titanium alloys is the generation of narrow crater wear that is formed closer to the cutting edge due to a small contact area between tool and chip. Nouari et al. [137] performed an experiment of dry drilling of aluminium alloys with WC-Co cemented carbide tool. In this experiment, the enhanced tool geometry and cutting conditions were observed without lubricant. The studies revealed that combination of the optimized tool geometry and the cutting conditions caused a high surface quality, a good dimensional accuracy of the machined material and confirmed long tool life. It was observed that use of diamond layer as coating material generated less heat and increased tool life.

In machining operations, most of the energy used gets transformed into heat. When there are no cutting fluids in dry cutting, then the heat produced should be transferred by means of conduction mode through the chips, workpiece and cutting tool. Noor-ul-Haq et al. [138] reported an alternate solution to enhance the heat conduction to cool indirectly of the cutting tool or workpiece using heat pipes. Jen et al. [139] performed an experiment and used coolant fluid through the heat pipe for HSS drills. FE analysis and experimental examinations clearly showed that, by using this method, the cutting temperature can be reduced up to 50 %. However, there is a limitation of geometrical restrictions of cutting tools and manufacturing difficulties in applying this method. Noor-ul-Haq et al. [138] obtained 25 °C reduction in cutting temperature by using a modified tool holder integrated with brass heat pipe when turning engine crank pins using CBN tool. The study provided 5 % reduction in the cutting temperature at the cutting zone and leads to 9 % reduction in the tool flank wear. Dry cutting can reduce environmental pollution, health risk for Machine's operator and thermal shock in interrupted cutting, but lack of cutting fluids can limit cutting speed and high cutting temperature, rapid tool wear and degradation of workpiece surface integrity may occur as reported in the literature.

4.3 Minimum quantity lubricant

Minimum Quantity Lubricant (MQL) or near dry machining (NDM) is another substitute to conventional flood coolant. In MQL technique, a few drops of cutting oil is applied in the form of mist particles in the cutting zone. The well-directed penetration of oil particles reduces friction at the cutting interface, thus resulting in the reduction of the temperature, surface roughness and the cost [20]. The demerit of this method includes health hazard as a result of the production of mist. Vegetable oils are a better replacement of mineral oils related to cost, health, safety and environment. The work quality can be enhanced by the use of chip evacuating system. There is a need of some new researches which includes optimization of air–oil moisture ratio and coolant pressure. MQL system can be applied where dry machining operation is difficult [20]. Klocke et al. [30, 105] have reported the comparison between MQL and dry machining processes of different materials, as shown in Table 2.

Various companies have attempted to produce advanced MQL systems for machining operations. UNIST Inc. designed its first MQL system called uni-MIST® which was patented in 1957 at the Grand Rapids, Michigan [140]. A complete

Table 2 Application areas of dry and M.Q.L techniques for various materials [30]

Material	Machining processes			
	Drilling	Deep hole drilling	Turning	Milling
Aluminium	M.Q.L	M.Q.L	M.Q.L /Dry	M.Q.L /Dry
Steel	M.Q.L	M.Q.L	M.Q.L /Dry	M.Q.L
Cast iron	M.Q.L	M.Q.L	M.Q.L /Dry	M.Q.L /Dry
Titanium Alloys	M.Q.L	M.Q.C.L	M.Q.L /Dry	M.Q.C.L

commercial MQL system consists of five main parts, namely air compressor, CL container, tubing, flow control system and spray nozzle. The controlled coolant and pressured air after mixing are provided through the tubing and nozzle into the cutting point. The nozzle offer both arrangements either external or internal through-the-tool. Kamata et al. [141] developed a usual MQL system for turning process, as shown in the Fig. 22.

Sales et al. [142] developed a MQL system for face milling and the fluid is passing through the tool cooling, as shown in Fig. 23.

Rahim and Sasahara [26] performed experiments and used MQL setup with palm oil and synthetic ester. The experiment showed that palm oil arrangement performed better than synthetic ester. Kamata and Obikawa [141] utilized MQL arrangement to machine Inconel® 718 using TiCN/Al_2O_3/TiN and TiN/AlN-coated carbide tools. The study revealed that TiCN/Al_2O_3/TiN-coated tool provided the highest tool life, but TiN/AlN-coated tool provided the lowest surface roughness. Zeilmann and Weingaertner [27] studied MQL setup to machine titanium alloy. The study employed uncoated and coated drills and reported that internal MQL system showed better performance than external MQL system. Pervaiz et al. [24] did an experiment on machining of Ti6Al4V by using MQCL (minimum quantity lubrication + cool air) system. It is reported that MQCL cooling technique performed better than dry cutting condition and found that average cutting temperature decreased by 26.6, 17.9 and 17.5 % than the temperature attained in dry environment with cutting speed levels of 90, 120 and 150 m/min, respectively. The MQL's technique is also suitable for ductile materials. It is reported that MQL performed well when machining steel and aluminium alloys.

Davim et al. [25] performed an experiment on aluminium (AA1050) drilling. The experiments were performed under dry, minimum quantity of lubricant (MQL) and flood conditions. The experiments were intended on orthogonal arrays, made with machining conditions and various cooling strategies. The ANOVA technique was implemented to validate the proposed machining conditions. The test results showed that by selecting the range of cutting parameters properly, similar performances can be obtained to flood lubricated conditions by using MQL system. Dhar et al. [4] have performed experimental investigations on the influence of MQL system when machining AISI-4340 steel using uncoated carbides. The results showed good temperature control at cutting zone and less tool wear and surface roughness occurred. Park et al. [38] extended the study to investigate the operational aspects of MQL. They have established a potential additive to MQL lubricant. The study combined exfoliated nanographene particles in the vegetable oil to use it under MQL arrangement. The study also computed coefficients of friction for this newly developed cutting fluid under different cutting parameters. The same MQL-based system was then employed in the ball milling cutting experiments. The study shows an extraordinary improvement in controlling the tool wear and edge chipping. However, the generation of fumes due to the evaporation of oil particles is a demerit. This less efficient cooling ability limits the effectiveness of MQL arrangements especially when machining difficult-to-cut materials like titanium and nickel-based alloys where the major difficulty is excessive heat generation. It is studied in the literature that MQL strategy is explored experimentally and is rare to find the numerical modal for MQL system. More dedicated research studies are needed to explore the operating characteristics including optimization of air–oil moisture ratio, cutting zone temperature, coolant pressure and numerical modelling of MQL systems.

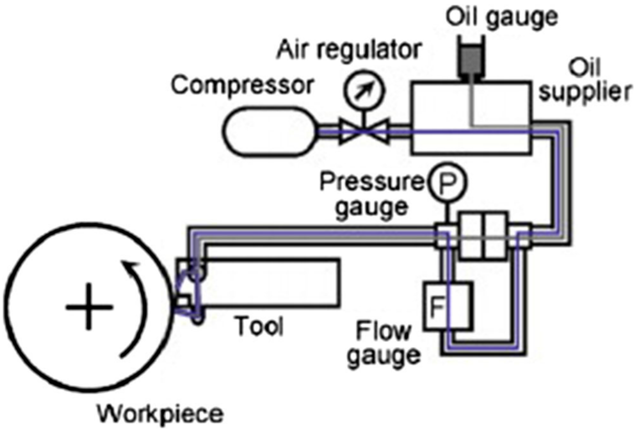


Fig. 22 Schematic representation of MQL system [141]

4.4 Cryogenic machining

Over the last six decades, there have been many studies on the Cryogenic cooling technique, but it is only during the last 10 years that there was substantial work in this technique which produced tremendous results. It has been noticed that Cryogenic cooling technique is still important in machining processes [40]. Cryogenic method guides cutting fluid (liquid nitrogen) under pressure and low temperature on the cutting edge. The liquid nitrogen is a well-secured, clean, non-toxic and easy to disposal coolant. It is lighter than air and has a share of 78 % in the atmosphere. This technique improves tool life, increase production and do not harm the environment [143]. Cryogenic machining process is performed at lower temperatures usually at 120 K [144]. Cryogenic technique proved to be an efficient method to keep the cutting temperature lower than the softening temperature of the tool material [145].

On the other side, CO_2 is considered as an air pollutant. However, it has been recommended [146] that CO_2 is made from the power plants' exhaust gases. Thus, it is not contaminating the atmosphere. It is to be noted that carbon dioxide is heavier than air which can deplete air and can cause serious

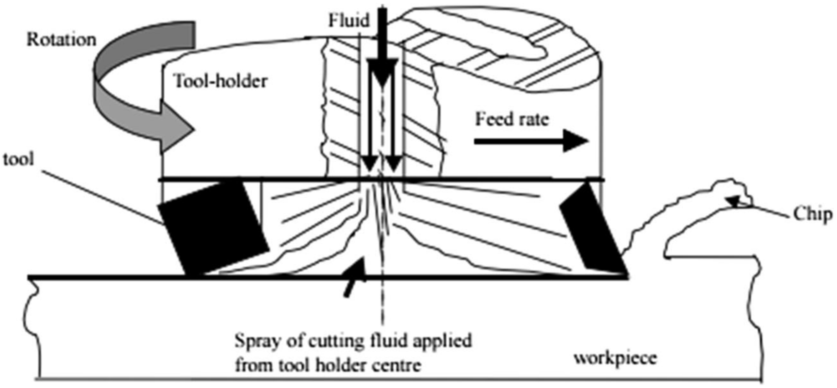


Fig. 23 Schematic view of face milling with through-the-tool MQL system [142]

problems at work place [106]. In cryogenic technique, the workpiece temperature is decreased which is followed by the changes in the workpiece properties as well as the tool materials. It is noted that, due to low temperatures, there is an increase in strength and the hardness of the material which produces brittleness in the material. This technique is suitable at room temperature [147]. Moreover, due to this cooling effect, the hardness of the tool increases and thereby enhances its life [106].

Many studies have revealed that a chemical reaction occurs in machining of ferrous alloys with diamond tools and graphitisation is observed. To overcome this problem, liquid Nitrogen below −196 °C as a coolant is used to avoid tool wear both chemically and thermally [148]. S. Hong [92, 99] reported that LN_2 is not only a good coolant but also good lubricant. It is studied that liquid nitrogen can easily enter between the tool and chip interface and consequently reduce the friction and temperature at cutting edge. It is also reported that this cooling technique has marvellous results while cutting titanium and nickel alloys. The commonly used cryogenic coolants are the air, liquid nitrogen, liquid carbon dioxide, solid carbon dioxide and liquid helium.

The adhesion and diffusion wear of the tool and chip interface can be reduced by spraying cryogenic coolant at the cutting zone which increases tool life [42, 106]. There are less chances of tool face built up edge and more surface finish by this cooling technique [44]. Venugopal et al. [149] concluded that by the application of liquid nitrogen, 77 % less tool wear was observed as compared to dry machining while cutting titanium alloys, as shown in Fig. 24. Hong and Ding [44] performed an experiment on machining of titanium alloys using cryogenic cooling technique and observed results which were four time better than dry cutting as shown in Fig. 25.

Su et al. [150] performed an experiment of machining of Inconel 718 base super alloy. The study examined cooling/lubrication approaches of dry, minimal quantity lubrication (MQL) and cooling air with minimal quantity lubricant (CAMQL). They performed a machining process of Inconel 718 alloys and studied the workpiece surface finish and tool wear mechanism. The study revealed that, in the use of cool air with MQL, the tool life improved to 124 % at cutting speed of 76 m/min when related to the dry cutting. It is observed that the tool life increased by the application of chilled air as a coolant. They concluded that by using this chilled air technique, the workpiece surface finish is extremely reliant on the cutting forces. Consequently, lower surface roughness was observed in air cooling as compared to dry machining. There are few limitations of using chilled air and gases. They are more expensive as compared to cutting fluid and required additional equipment to deliver air to the tool workpiece interface. It is reported that gases cannot be reusable as they are vaporized after the application.

They also reported cutting temperatures conditions of machining RBSN with CBN tools in dry cutting, cryogenic tool back cooling, emulsion cooling, pre-cooling the workpiece, cryogenic flank cooling, cryogenic rake cooling and simultaneous rake and flank cooling strategy, as shown in Fig. 25. Their analysis by FEA showed there was a temperature decrease of 1153 °C in dry cutting to 829 °C in the method of indirect cryogenic cooling. Wang et al. [70], by utilizing an indirect cryogenic technique in hybrid machining of titanium alloys, found that the tool life increased up to 156 %. In one of the investigations, it was found that indirect cryogenic tool cooling was 13 times less tool wear as compared to cryogenic

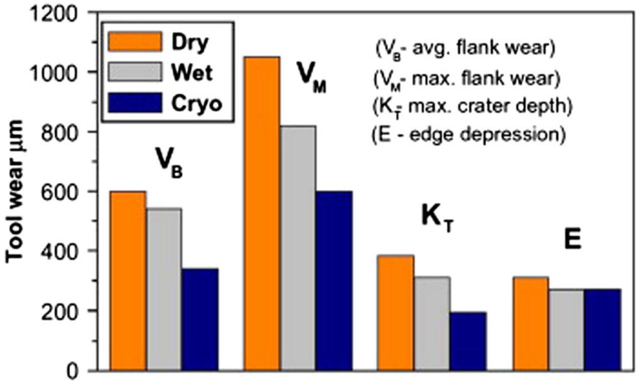


Fig. 24 Comparison of tool wear in machining titanium alloys [149]

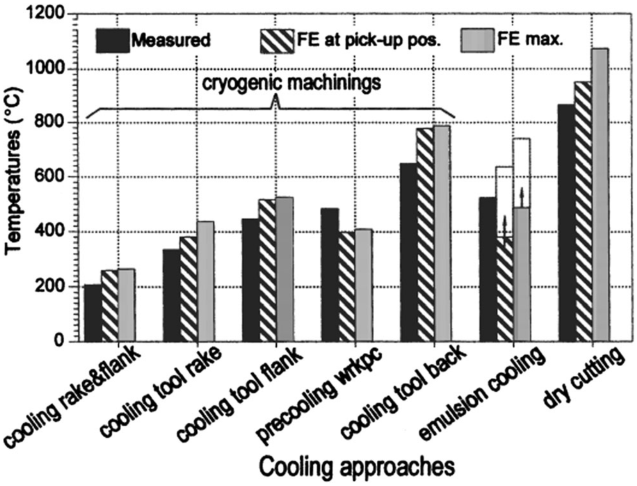


Fig. 25 The observed and expected tool temperatures, Hong and Ding [44]

chip cooling [151]. It is studied that small amount of liquid nitrogen (LN_2) applied to cutting Ti-6Al-4V showed excellent results as compared to emulsion cutting. However, this cooling technique has high set up cost, overcooling the workpiece and produces freezing effect at the nozzle. There is a potential to work further on this environmental friendly technique to reduce the cooling effect on the workpiece.

Hong et al. [106] investigated that the tool flank wear results are used to determine the tool life when using indirectly cryogenic cooling in machining of steel alloys and found that the tool life increased up to four times [152]. Similarly, in another study with the same indirect cooling technique, the Al_2O_3 ceramic inserts were used and found better results as compared to dry PCBN operations [153]. Hong et al. [44, 50, 106, 154] compared the results of machining low carbon steel by dry cutting, pre-cryogenic cooling of workpiece and chip, as shown in Fig. 26. The abovementioned techniques showed better performance as compared to dry cutting [154].

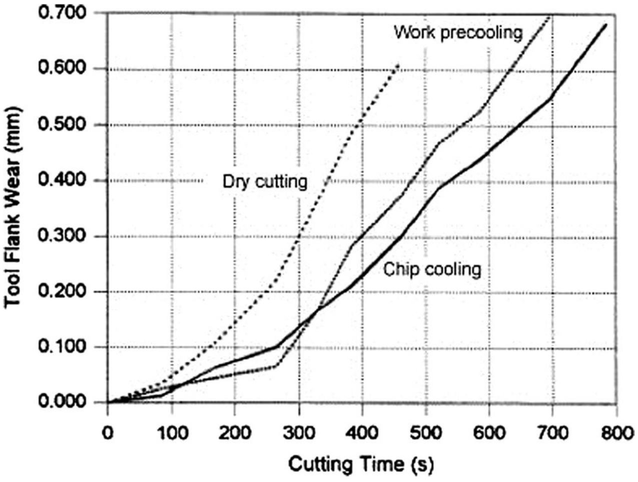


Fig. 26 The tool wears by various cooling methods [154]

Shaw et al. [64] reported that consumption of energy is directly proportional to cutting and friction forces. Bhattacharyya et al. [151] have performed machining experiment on Kevlar composite material by cryogenic and flood coolant techniques. They observed that the cutting forces were 50 % higher in cryogenic cooling as compared to flood cooling. The shearing force F_s was calculated for comparison of cryogenic chip cooling and workpiece pre-cooling. Figure 27 depicts the measured force components F_c, F_t and F_f. The results showed that cryogenic chip and workpiece pre-cooling formed an increase in shear force as compared to dry machining. It was observed that at a cutting speed of 6 m/s, the shear force increased up to 8 % in chip cooling, while in case of workpiece pre-cooling it increased more than 37 %. Therefore, it is concluded that in cryogenic cooling technique the cutting forces will increase [77].

Similarly, Kumar and Choudhury [77] have performed an experiment of machining of stainless steel 202 and that 14.83 % cutting temperature decreased by using cryogenic LN_2 as compared to dry cutting. Considering all these drawbacks, the cryogenic cooling technique is still attractive and widely used by industry [155]. There are two leading like companies Air Products Inc. and MAG IAS LLC which are manufacturing cryogenic cooling equipment. ICEFLY is the first company which made commercial cryogenic equipment. The MAG cryogenic cooling system distributes liquid nitrogen by CNC machine to the tool's face. Presently, it is used in the production of the Lockheed Martin's F-35 stealth fighter plane [156]. Pereira et al. [157] performed milling experiments on Inconel 718 with a novel combination of MQL mixed with CO_2 cryogenic-based cooling. The main objective of combining both strategies was to get the benefits of both being green and economy feasible in nature. Two nozzle adopters were developed and fixed on MQL nozzle, as shown in Fig. 28a. The study also incorporated computational fluid dynamic (CFD) simulations to optimize adopter nozzles. Tool life was observed for dry, wet

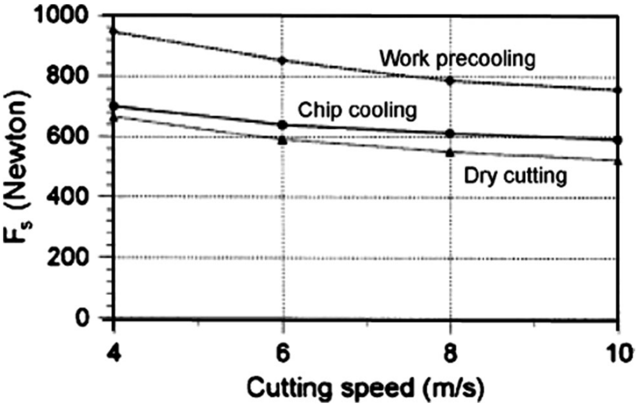


Fig. 27 Shear forces at various cooling techniques [154]

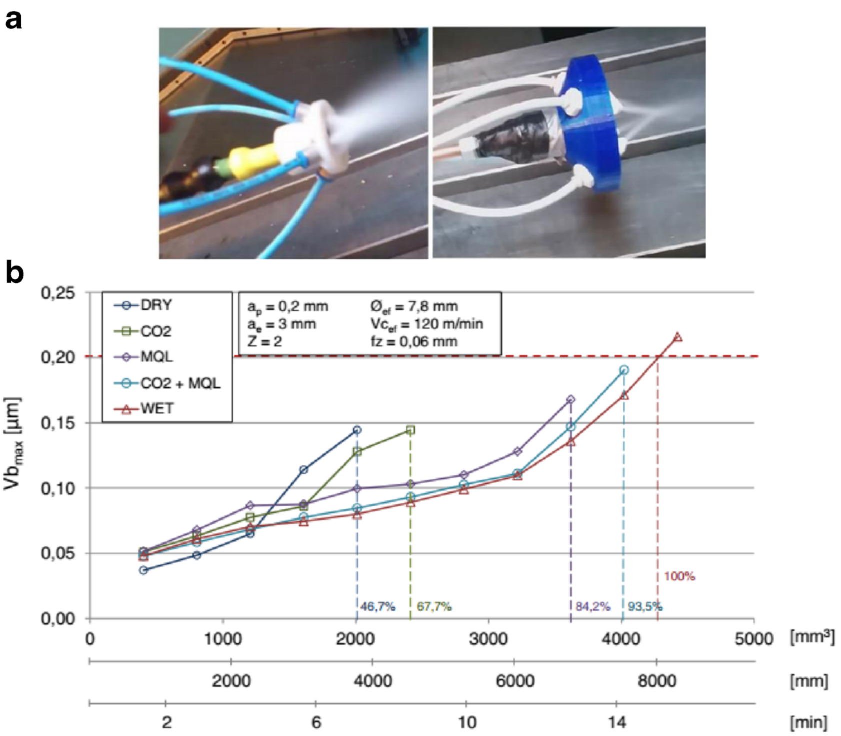


Fig. 28 **a** MQL + CO2 adopter nozzles developed for this study. **b** Tool life observed during different cooling strategies [157]

stand-alone both MQL and CO_2 cryogenic settings and combination of MQL with CO_2 cryogenic, as shown in Fig. 28b. Tool life for MQL + CO_2 cryogenic was found second best after wet cutting. It has been revealed in several studies that CO_2 is easier to handle than liquid nitrogen in terms of storage [157, 158].

Pušavec et al. [159] assessed the scope of cryogenic machining as per sustainability ideas. The study considered 1 year period to perform life cycle assessment (LCA) and compared the cryogenic-assisted machining outcomes with conventional flood cooling method, as shown in Fig. 29. The study provided a holistic overview of the sustainability by considering the aspects such as acidification, greenhouse gas (GHG) emissions, solid waste generation, water consumption, land usage and energy utilization. The study revealed that flood cooling generates sustainability concerns related to the acidification, water usage, greenhouse gas emissions and solid waste. However, cryogenic cooling only involves high amount of energy consumption, as shown in Fig. 29.

In another study [16], the life cycle analysis (LCA)-based material production outcomes of conventional flood and cryogenic cooling were reported. The outcomes for both cooling strategies were broken down in sustainability components for further understanding. The huge difference in the amount of energy usage was reported in case of cryogenic cooling.

4.5 High pressure compressed air cooling

Researchers in the metal cutting sector observed that for higher cutting speeds, cutting fluids lose their effectiveness to penetrate in the cutting zone. In 1952, Piggott and Collwell [160] developed a high pressure (2.75 MPa) oil jet to enhance cooling for a metal cutting operation. The machining performance was observed outstanding as the tool life was increased to 7–8 times and surface integrity was also enhanced. The study also revealed that high pressure jet cooling discouraged the formation of built-up-edge (BUE). Ramainyengar et al. [161] also conducted turing experiments under internally assisted high pressure jet cooling method. The study revealed that cutting forces decreased by 60 %. Mazurkiewicz et al. [162] performed high pressure (280 MPa) cooling machining experiments on UNS 1020 steel. The study revealed that feed force was decreased significantly by 50 %. At the same time, surface finish improved and coefficient of friction reduced. Wertheim et al. [163] investigated the role of high pressure flushing at rake face in grooving operation. The study incorporated the flushing pressure up to 25 bars. The study also revealed that chip curling and removal can be improved by increasing coolant pressure and flow rate. The application of high pressure cooling also minimizes built up edge formation.

The new emerging technology, like chilled and compressed air tool cooling, is widely used in industry. Air as a cooling method is considered as a clean option. Gandarias et al. [164]

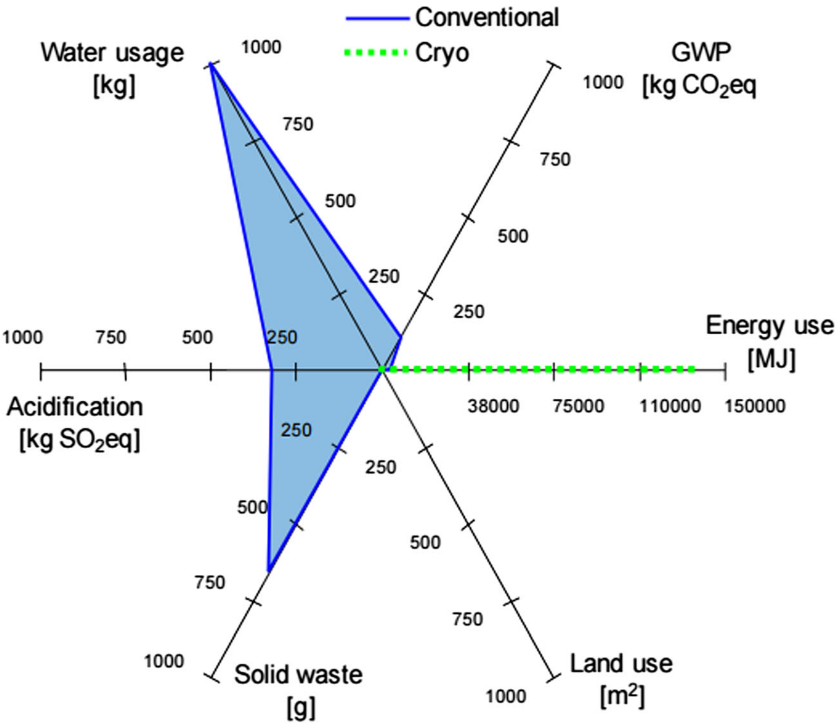


Fig. 29 Outcomes of life cycle analysis (LCA) for conventional flood and cryogenic cooling methods [159]

utilized high pressure cooling (HPC) and minimum quantity lubrication (MQL) methodologies to machine different grades of stainless steel under drilling and turning arrangements. HPC outperformed MQL in both drilling and turning arrangements. The study drilled more than 1600 holes using emulsion-based coolant with pressure of 60 bars, and machining performance was found much better than MQL method. Sun et al. [41] reported that chilled air coolant in machining process can consequently increase the tool life. Kumar et al. [77] reported that the consequences of chilled air on the surface of workpiece are dependent on machining characteristics. Kevinchou et al. [165] have studied turning the A390 aluminium with an uncoated WC tool and reported the properties of chilled air. The investigations revealed that tool flank wear decreased by 20 % at the cutting speed of 5 m/s and feed rate of 0.055 mm/rev by using chilled air. In addition, chilled air also reduces and there is less affinity of BUE at the tool face. This apart, they found that the tool life efficiency depends on the cutting conditions. It is reported that, in the machining of aluminium alloys, the leading tool wear occurs due to abrasion of silicon particles in the material structure.

Rahman et al. [166] studied the milling of steel alloys with uncoated WC tool at −30 °C and found lower surface roughness as compared to flood cooling. Kim et al. [167] reported that chilled air can increase the tool (TiAlN coated WC) life when machining hardened steel. Yalçın et al. [168] examined the machining performance of soft materials under different cooling strategies. They designed cool air cooling system to cool the tool, and the cool air was produced by a vortex tube. The annealed steel material AISI 1050 was used as the workpiece and HSS-Co8 DIN 844/BN as a cutting tool material. Prime cutting parameters were selected, and tool wear and surface quality were measured. The different cooling strategy effects were observed for 10–30 min of time duration. The air cooling strategy showed lower surface roughness values than dry cutting and more in flood cutting technique. The measured flank wear result values (Vb) for air cooling technique were nearby to flood cooling technique. On the other side, the flank wear results were showed high values at dry cutting due to material adhesion affinity.

Klocke et al. [30] exposed the potential of high pressurized cooling (up to 300 bars) for cutting titanium alloys. They mainly monitored the cutting temperature at the cutting interface; in addition, the study also observed tool wear, chip formation and cutting forces. The study provided that application high pressure cooling reduced tool wear by 50 % and cutting temperature by 25 %. Nandy et al. [169] studied the influence of flood cooling and high pressure cooling (HPC) with neat oil and water-soluble oil for machining Ti6Al4V. Experiments were operated using cutting speeds ranging from 90 to 111 m/min and supply pressure ranging from 70 to 140 bar. The results provided 250 % betterment in tool life with respect to the flood cooling. Sandvik [170] reported that by using compressed air, the results observed enhanced tool life for Ti6Al4V and Inconel

718. A typical high pressure air cooling system is shown in Fig. 30a. Similarly, other cutting tool manufacturers have developed solutions for high pressure cooling, as shown in Fig. 30b, c [171, 172]. ChipBlaster was the first manufacturer that developed high pressure cooling systems for the metal cutting industry and market. ChipBlaster was the first company that applied patent the use of cooling pipe as a nozzle for laminar flow [173, 174].

Sorby and Tonnessen [175] utilized high pressure cooling at rake and flank face arrangements to perform grooving in Ti6Al4V. Grooving operation was selected due to the difficult nature of cooling application required. The study revealed that tool life was increased by 200–300 and 50–100 % under 10–30 MPa pressure cooling at rake and flank faces, respectively. They also found that rake face flushing disturbed the surface finish of the workpiece due to the chip flow, whereas surface finish was found better under flank face flushing. Herranz et al. [176] provided an efficient way of process planning to cater static and dynamic problems (vibrations, deflections, etc.) of machining of thin wall structures. Yalcin et al. [168] reported that the tool life and surface finish decreased by dry machining of soft materials. It was suggested that chilled air is an environmentally friendly, less expensive as compared to flood cooling method. It is seen that the lower workpiece surface roughness is produced by high pressure air cooling as compared to dry cutting.

5 Conclusion

The conclusions drawn out of the current review have been mentioned as below:

- The most favourable method to reduce the use of cutting fluids in manufacturing processes is dry machining which consequently minimize the machining costs and environmental issues. However, dry cutting gets failed to produce required tool life and surface finish in some cases. Dry cutting also produces metallic dust that is also very harmful for the environment and the health of the worker. Dry cutting offers limited material removal rate in the machining process due to excessive amount of heat generation at cutting interface with increasing cutting speed. To understand more about dry machining advanced cutting tool materials, further research on the cutting parameters is required. However, development of advanced cutting tool technologies will be more expensive, resulting in higher machining costs.
- There is a need to develop novel hybrid lubrication/cooling methodologies by combining the existing lubrication/cooling techniques. For example, some studies revealed methodologies where minimum quantity lubrication (MQL) was mixed with cryogenic cooling such as low temperature air and CO_2. In stand-alone MQL technique, only lubrication has been provided and temperature is controlled by reducing friction at the tool chip interface

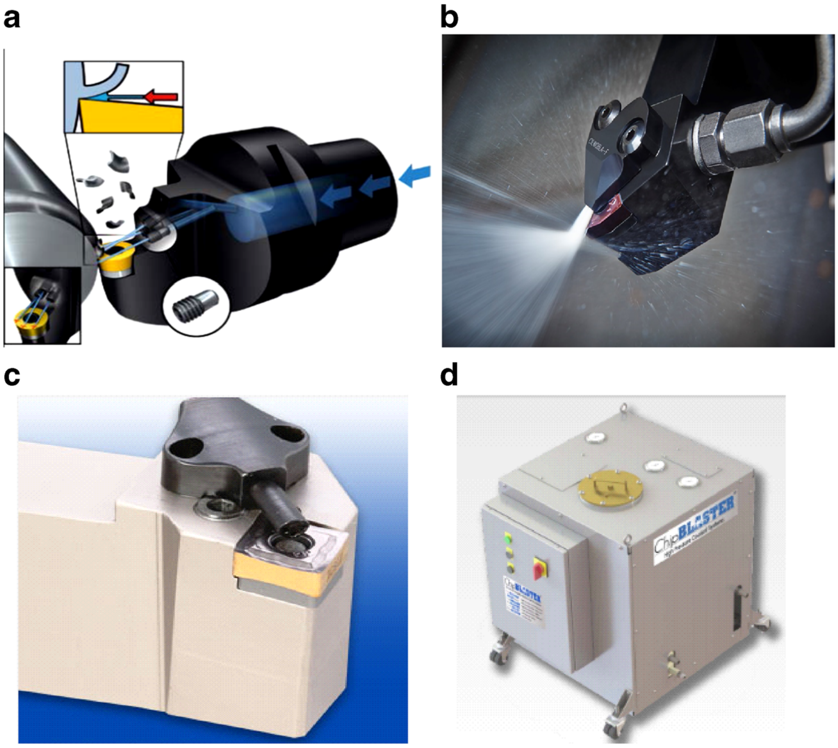


Fig. 30 **a** Tool holder by Sandvik Coromant AB to operate high pressure coolant internally [170], **b** Jet Stream tooling from SECO Tools [172], **c** JET HP–HELI TURN from ISCAR [171], **d** Fixed volume system for high pressure system (D 30–35), 8 gpm at 500 psi [174]

and evaporative mode of heat transfer. Mixing the cryogenic arrangement provides the missing cooling part. The concept was to reduce friction from MQL oil mist and achieve cooling action by the cryogenic arrangement such as low temperature air, liquid nitrogen and CO_2.

- Literature has highlighted that MQL/MQCL have potential to replace the conventional flood cooling method for the machining of several conventional and high performance alloys. However, MQL technique mixed with nano-particles is still a new research area that should be explored for better understanding.
- Another observation was that there is still a need to investigate the physics involved in the MQL methodology. The physics would be clearer if the fluidic behaviour of the cutting oil can also be investigated with respect to the cutting environment. For example, the fluid properties like viscosity, density, etc. of the oil play a critical role towards the lubrication capacity and penetration ability of the lubricant.
- The lubrication capacity has a strong link with the viscosity of the cutting oil. Theoretically speaking, more viscous cutting oils in the MQL system should perform better. However, more viscous cutting oils are difficult to penetrate in the cutting zone. It means that only the appropriate level of viscous behaviour is required to reach the cutting zone and lubricate at the same time.
- It has been observed that, in literature relevant to MQL strategy, only experimental methods have been explored in research, and it is rare to find the numerical modal for MQL system. More dedicated research studies are needed to explore the operating characteristics including optimization of air–oil moisture ratio, cutting zone temperature, coolant pressure and numerical modelling of MQL systems. Computational fluid dynamics (CFD)-based approaches can be developed to investigate the interaction of cooling environment with the cutting tool.
- For the efficient application of MQL/MQCL techniques in machining, cutting tools are made compatible to adopt the MQL/MQCL techniques. The general guideline for designing such cutting tools is based on rapid heat dissipation through chip evacuation and ability to with stand high temperatures through tool coatings. Lubricant supply can be optimized in MQL/MQCL systems through internal delivery passages in the cutting tools. Computational fluid dynamics (CFD)-based simulations can play vital role to reduce cost and facilitate the prototyping of such custom-made cutting tools.
- Solid materials (nano-sized) are developed as a lubricant itself, which are able to remove cutting fluids. Also, they can act as an additive for lubricant. For the solid lubricant materials, molybdenum disulphide (MoS_2), graphite, boron nitride and polytetrafluoroethylene (PTFE) have been used as dry powders or coating materials. These solid lubricants in the machining test can cut down the cutting forces and surface roughness.
- Using liquid gases, especially LN_2, is considered as a feasible alternative to get rid of the conventional cutting fluids in the machining operations despite the fact that there is improvement in the general machinability. The use of cryogenic LN_2 has been recognized as an efficient technique to increase the tool life. However, literature points out at the inconsistent performance of cryogenic machining that is highly influenced by the tool–workpiece material pairs. The type of cryogenic cooling method also controls the machining performance. There is a need to study and explore cryogenic machining with different combinations of workpiece–tool material pairs. The life cycle analysis (LCA) of LN_2 cryogenic cooling shows that the generation of LN_2 is very energy extensive as compared to other alternate approaches. At the same time, it has advantage that it has no other sustainability-related concerns such as acidification, solid waste, land usage and water utilization. To evaluate the overall sustainability for LN_2 systems, the energy mix (fossil fuels or renewable) of the geological location plays vital role.
- There is a potential to work further on this environmental friendly technique to mitigate the cooling effect on the workpiece. Thus, it is concluded that not a single of the abovementioned techniques could be considered as a wide-ranging method which can be utilized for all tool–piece material pair. In fact, at the present stage, each of these approaches has their own merits and demerits.

References

1. Shokrani A, Dhokia V, Newman ST (2012) Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids. Int J Mach Tools Manuf 57:83–101
2. Leskover P, Grum J (1986) The metallurgical aspect of machining. Ann CIRP 35(2):537–550
3. Tonshoff HK, Brinksmeier E (1986) Determination of the mechanical and thermal influences on machined surface by microhardness and residual stress analysis. Ann CIRP 29(2):519–532
4. Dhar NR, Kamruzzaman M, Ahmed M (2006) Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel. J Mater Process Technol 172(2):299–304
5. Pervaiz S, Deiab I, Darras B (2013) Power consumption and tool wear assessment when machining titanium alloy. Int J Precis Eng and Manufacturing 14(6):925–936
6. Adler DP, Hii WW-S, Michalek DJ, Sutherland JW (2006) Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns. Mach Sci Technol 10(1):23–58
7. Carter, W. A., 1956, Metal Machining, Part VI, Cutting Fluids, Machinery Lloyd, Overseas Edition
8. Seah KHW, Li X, Lee KS (1995) The effect of applying coolant on tool wear in metal machining. J Mater Process Tech 48(1–4): 495–501

9. Lee WY, Kim KW, Sin HC (2002) Cutting conditions for finish turning process aiming: the use of dry cutting. Int J Mach Tools Manuf 42(8):899–904
10. Simon, H., Thoma, M., and Maier, K., 1979, "Coolants with chlorine extreme pressure additives,"," WT Z. Ind. Furtgung 69 [German], pp. 79–82
11. El Baradie MA (1996) Cutting fluids: part II. Recycling and clean machining. J Mater Process Technol 56(1–4):798–806
12. Cantero JL, Tardio MM, Canteli JA, Marcos M, Miguelez MH (2005) Dry drilling of alloy Ti-6Al-4 V. Int J Mach Tools Manuf 45(11):1246–1255
13. Klocke F, Krieg T (1999) Coated tools for metal cutting—features and applications. CIRP Ann. - Manuf. Technol. 48(2):515–525
14. 2004, "Cutting Fluid Health Hazards, (Retrieved 01/02/2016); /http://www.mfg.mtu.edu/cyberman/index.html"
15. Byrne G, Scholta E (1993) Environmentally clean machining processes—a strategic approach. Ann CIRP 42(1):471–474
16. Pusavec F, Krajnik P, Kopac J (2010) Transitioning to sustainable production—part I: application on machining technologies. J Clean Prod 18(2):174–184
17. Sreejith PS, Ngoi BKA (2000) Dry machining: machining of the future. J Mater Process Technol 101(1):287–291
18. Kelly JF, Cotterell MG (2002) Minimal lubrication machining of aluminium alloys. J Mater Process Technol 120(1–3):327–334
19. Lugscheider E, Knotek O, Barimani C, Leyendecker T, Lemmer O, Wenke R (1997) Investigations on hard coated reamers in different lubricant free cutting operations. Surf. Coatings Technol. 90(1–2):172–177
20. Dhar NR, Islam MW, Islam S, Mithu MAH (2006) The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. J Mater Process Technol 171(1):93–99
21. Rahman M, Senthil Kumar A, Salam MU (2002) Experimental evaluation on the effect of minimal quantities of lubricant in milling. Int J Mach Tools Manuf 42(5):539–547
22. Tasdelen B, Wikblom T, Ekered S (2008) Studies on minimum quantity lubrication (MQL) and air cooling at drilling. J Mater Process Technol 200(1–3):339–346
23. Raza SW, Pervaiz S, Deiab I (2014) Tool wear patterns when turning of titanium alloy using sustainable lubrication strategies. Int J Precis Eng Manuf 15(9):1979–1985
24. Pervaiz, S., Deiab, I., Rashid, A., Nicolescu, M., and Kishawy, H., 2013, "Performance Evaluation of Different Cooling Strategies when Machining Ti6Al4V," International Conference on Advanced Manufacturing Engineering and Technologies, Newtech 2013, , Stockholm, Sweden
25. Davim JP, Sreejith PS, Gomes R, Peixoto C (2006) Experimental studies on drilling of aluminium (AA1050) under dry, minimum quantity of lubricant, and flood-lubricated conditions. Proc Inst Mech Eng Part B Journal Engineering Manu-facture 220:1605–1611
26. Rahim EA, Sasahara H (2011) A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. Tribol Int 44(3):309–317
27. Zeilmann RP, Weingaertner WL (2006) Analysis of temperature during drilling of Ti6Al4V with minimal quantity of lubricant. J Mater Process Technol 179(1–3):124–127
28. Wang ZG, Rahman M, Wong YS, Neo KS, Sun J, Tan CH, Onozuka H (2009) Study on orthogonal turning of titanium alloys with different coolant supply strategies. Int J Adv Manuf Technol 42(7–8):621–632
29. Cai XJ, Liu ZQ, Chen M, An QL (2012) An experimental investigation on effects of minimum quantity lubrication oil supply rate in high-speed end milling of Ti-6Al-4 V. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 226(11):1784–1792
30. Klocke F, Sangermann H, Kramer A, Lung D (2011) Influence of a high pressure Lubri-coolant supply on thermo-mechanical tool load and tool wear behaviour in the turning of aerospace materials. Proc Inst Mech Engineers, Part B J Eng Manuf 225:52
31. Yasir MSA, Hassan CCH, Jaharah AG, Nagi HE, Yanuar B, Ghusri AI (2009) Machinability of Ti6Al4V under dry and near dry condition using carbide tools. The Open Industrial Manuf Eng J 2:1–9
32. Jianxin D, Wenlong S, Hui Z (2009) Design, fabrication and properties of a self-lubricated tool in dry cutting. Int J Mach Tools Manuf 49(1):66–72
33. Xu J, Zhu MH, Zhou ZR (2004) Fretting wear behavior of PTFE-based bonded solid lubrication coatings. Thin Solid Films 457(2): 320–325
34. Vamsi Krishna P, Nageswara Rao D (2008) Performance evaluation of solid lubricants in terms of machining parameters in turning. Int J Mach Tools Manuf 48(10):1131–1137
35. Xu J, Zhou ZR, Zhang CH, Zhu MH, Luo JB (2007) An investigation of fretting wear behaviors of bonded solid lubricant coatings. J Mater Process Technol 182(1–3):146–151
36. Suresh Kumar Reddy N, Venkateswara Rao P (2006) Experimental investigation to study the effect of solid lubricants on cutting forces and surface quality in end milling. Int J Mach Tools Manuf 46(2):189–198
37. Shen B, Malshe AP, Kalita P, Shih AJ (2008) Performance of novel MoS2 nanoparticles based grinding fluids in minimum quantity lubrication grinding. Trans NAMRI/SME 36:357–364
38. Park K-H, Ewald B, Kwon PY (2011) Effect of Nano-enhanced lubricant in minimum quantity lubrication balling milling. J Tribol 133(3):031803
39. Su Y, He N, Li L, Li XL (2006) An experimental investigation of effects of cooling/lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4 V. Wear 261(7–8):760–766
40. Yildiz Y, Nalbant M (2008) A review of cryogenic cooling in machining processes. Int J Mach Tools Manuf 48(9):947–964
41. Sun S, Brandt M, Dargusch MS (2010) Machining Ti–6Al–4 V alloy with cryogenic compressed air cooling. Int J Mach Tools Manuf 50(11):933–942
42. Bermingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS (2011) New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4 V. Int J Mach Tools Manuf 51(6):500–511
43. Sharma VS, Dogra M, Suri NM (2009) Cooling techniques for improved productivity in turning. Int J Mach Tools Manuf 49(6): 435–453
44. Hong SY, Ding Y (2001) Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V. Int J Mach Tools Manuf 41(10):1417–1437
45. Silva MB, Wallbank J (1999) Cutting temperature: prediction and measurement methods-a review. J Mater Processing Technol 88: 195–202
46. Abukhshim NA, Mativenga PT, Sheikh MA (2006) Heat generation and temperature prediction in metal cutting: a re-view and implications for high speed machining. International J Mach Tools Manufacture 46:782–800
47. Majumdar P, Jayaramachandran R, Ganesan S (2005) Finite element analysis of temperature rise in metal cutting processes. Appl Therm Eng 25(14–15):2152–2168
48. Ng E-G, Aspinwall DK, Brazil D, Monaghan J (1999) Modelling of temperature and forces when orthogonally machining hardened steel. Int J Mach Tools Manuf 39:885–903
49. Groover MP, Kane GE (1971) A continuing study in the determination of temperatures in metals cutting using remote thermocouples. Trans ASME, J of Engineering Ind 93(2):603–608
50. Hong SY, Broomer M (2000) Economical and ecological cryogenic machining of AISI 304 austenitic stainless steel. Clean Techn Environ Policy 2:157–166

51. O'Sullivan D, Cotterell M (2001) Temperature measurement in single point turning. J Mater Process Technol 118:301–308
52. Kitagawa T, Kubo A, Maekawa K (1997) Temperature and wear of cutting tools in high-speed machining of Incone1718 and Ti-6 A1-6 V-2Sn. Wear 202(2):142–148
53. Chen WC, Tsao CC, Liang PW (1995) Determination of temperature distributions on the rake face of cutting tools using a remote method. Int Comm Heat Mass Transf 22(6):779–790
54. Komanduri R, Hou ZB (2001) Thermal modelling of the metal cutting process—part III: temperature rise distribution due to the combined effects of shear plane heat source and the tool–chip interface frictional heat source. Int Journal Mech Sci 43:89–107
55. Ay H, Yang W-J (1998) Heat transfer and life of metal cutting tools in turning. Int J Heat Mass Transf 41(3):613–623
56. Chou YK, Evans CJ (1997) Tool wear mechanism in continuous cutting of hardened tool steels. Wear 212:59–65
57. Groover, M. P., 1996, Fundamentals of modern manufacturing, materials, processes, and systems, Prentice-Hall Inc., Upper Saddle River, NJ , 569
58. Minton T, Ghani S, Sammler F, Bateman B, Fürstmann P, Roeder M (2013) Temperature of internally-cooled diamond-coated tools for dry-cutting titanium. Int Journal of Mach Tools Manuf 75:27–35
59. Liu, Z. Q., Ai, X., Zhang, H., Wang, Z. T., and Wan, Y., 2002, "Wear patterns and mechanisms of cutting tools in high-speed face milling," Journal of Materials Processing Technology, 222–226
60. Casto SL, Valvo EL, Lucchini E, Maschio S, Russi VF (1997) Wear rates and wear mechanisms of alumina-based tools cutting steel at a low cutting speed. Wear 208:67–72
61. Liao YS, Lin HM, Wang JH (2008) Behaviors of end milling Inconel 718 superalloy by cemented carbide tools. J Mater Process Technol 201(1–3):460–465
62. Pittala GM, Monno M (2011) A new approach to the prediction of temperature of the workpiece of face milling operations of Ti-6Al-4 V. Appl Therm Eng 31(2–3):173–180
63. Merchant ME, Field M (1949) Mechanics of formation of the discontinuous chip in metal cutting. Trans. ASME 71:421
64. Shaw MC (1986) Metal cutting principles. Oxford University Press, Oxford
65. ISO 3685, Tool life testing with single-point turning tools, ISO 231Standard, 3685 (1993) (E)
66. Aggarwal A, Singh H, Kumar P, Singh M (2008) Optimization of multiple quality characteristics for CNC turning under cryogenic cutting environment using desirability function. J Mater Process Technol 205(1–3):42–50
67. Astakhov VP (2006) Tribology of metal cutting. Tribol Met Cut 52:227
68. El Baradie MA (1996) Cutting fluids: part I. Characterisation. J Mater Process Technol 56(1–4):786–797
69. Trent, E. M., and Wright, P. K., 2000, Metal Cutting
70. Wang ZY, Petrescu G (2004) Stress analyses of CBN insert in hybrid machining of RBSN ceramic. Mach Sci Technol 8(1):1–19
71. Willaiams JA, Tabor D (1977) The role of lubricants in machining. Wear 43:275–292
72. Jawaid A, Che-Haron CH, Abdullah A (1999) Tool wear characteristics in turning of titanium alloy Ti-6246. J Mater Process Technol 92-93:329–334
73. Corduan N, Himbart T, Poulachon G, Dessoly M, Lambertin M, Vigneau J, Payoux B (2003) Wear mechanisms of new tool materials for Ti-6AI-4 V high performance machining. CIRP Ann. - Manuf. Technol. 52(1):73–76
74. Elmagrabi N, Che-Hassan CH, Jaharah AG, Shuaeib FM (2008) High speed milling of Ti 6Al 4 V using coated car-bide tools. Eur J Sci Res 22(2):153–162
75. Li J, Yuan Z, Zhou M (1989) Cryogenic ultra-precision machining of ferrous metals with natural diamond tools. Chinese Journal Mech Eng 25(1):69–72
76. Hwang YK, Lee CM, Park SH (2009) Evaluation of machinability according to the changes in machine tools and cooling lubrication environments and optimization of cutting conditions using Taguchi method. Int J Precis Eng Manuf 10(3):65–73
77. Kalyankumar K, Choudhury S (2008) Investigation of tool wear and cutting force in cryogenic machining using design of experiments. J Mater Process Technol 203(1–3):95–101
78. Rajemi MF, Mativenga PT, Aramcharoen A (2010) Sustainable machining: selection of optimum turning conditions based on minimum energy considerations. J Clean Prod 18(10–11):1059–1065
79. Vieira JM, Machado AR, Ezugwu EO (2001) Performance of cutting fluids during face milling of steels. J Mater Process Technol 116(2–3):244–251
80. Dahmus, J. B., and Gutowski, T. G., 2004, "An environmental analysis of machining," Proc. of IMECE, ASME International Mechanical Engineering Congress and RD&D Expo
81. Munoz AA, Sheng P (1995) An analytical approach for determining the environmental impact of machining processes. J Mater Process Technol 53:736–758
82. Drake, R., Yildirim, M. B., Twomey, J. M., Whitman, L. E., Ahmad, J. S., and Lodhia, P., 2006, "Data collection framework on energy consumption in manufacturing," Proceedings from Institute of Industrial Engineers Research Conference
83. Kordonowy DN (2002) A power assessment of machining tools. Massachusetts Institute of Technology, Cambridge, Massachusetts
84. Diaz, N., Redelsheimer, E., and Dornfeld, D., 2011, "Energy consumption characterization and reduction strategies for milling machine tool use," Glocalized Solutions for, pp. 263–267.
85. Kara S, Li W (2011) Unit process energy consumption models for material removal processes. CIRP Ann. - Manuf. Technol. 60(1):37–40
86. Shan Z, Qin S, Liu Q, Liu F (2012) Key manufacturing technology & equipment for energy saving and emissions reduction in mechanical equipment industry. Int J Precis Eng Manuf 13(7): 1095–1100
87. Reddy NSK, Rao PV (2006) Experimental investigation to study the effect of solid lubricants on cutting forces and surface quality in end milling. International J Machine Tools Manuf 46(2):189–198
88. Dudzinski D, Devillez A, Moufki A, Larrouquère D, Zerrouki V, Vigneau J (2004) A review of developments towards dry and high speed machining of Inconel 718 alloy. Int J Mach Tools Manuf 44(4):439–456
89. Strieder, E. H., 1951, "Application of Cutting Fluids to Machining," Sci. Lubr
90. Taylor FW (1907) On the art of cutting metals. Trans ASME 28: 31–58
91. Runge, P., 1987, "Lubrificantes nas Indústrias (Lubricants in the Industries), Editora Tribo Concept, São Paulo, Brazil, (in Portuguese).."
92. Machado AR, Motta MF, da Silva MB (1997) Performance of synthetic and mineral soluble oil when turning AISI 8640 steel. Trans ASME, J Manuf Sci Eng 119:580–586
93. Oberg, E., Jones, F. D., Horton, H. L., and Ryffel, H. H., Machinery's Handbook & Guide to Machinery's Handbook, Industrial Press
94. Mendes OC, Ávila RF, Abrão Pedro Reis AM, Davim JP (2006) The performance of cutting fluids when machining aluminium alloys. Ind Lubr and Tribol 58(5):260–268
95. Sheng, P. S., and Oberwalleney, S., 2016, "Life-cycle planning of cutting fluids—a review," 1(November 1997), 1–10
96. Grzesik W (2008) Advanced machining processes of metallic materials: theory, modelling and applications. Elsevier Science, Oxford

97. W, B., M, G., and D, P., 1999, “Assessment of the environmental release of chemicals used in metal-cutting and forming fluids. industry, IC8,” Emission scenario document – metal extraction industry, refining and processing, Dortmund, Germany
98. Donachie, J. M. J., 2000, Titanium—a technical guide, ASM International
99. Brandão LC, Coelho RT, Rodrigues AR (2008) Experimental and theoretical study of workpiece temperature when end milling hardened steels using (TiAl)N-coated and PcBN-tipped tools. J Mater Process Technol 199(1):234–244
100. Gisip J, Gazo R, Stewart HA (2009) Effects of cryogenic treatment and refrigerated air on tool wear when machining medium density fiberboard. J Mater Process Technol 209(11):5117–5122
101. Hong SY (2006) Lubrication mechanisms of Ln2 in ecological cryogenic machining. Mach Sci Technol 10(1):133–155
102. Dhananchezian M, Pradeep Kumar M (2011) Cryogenic turning of the Ti-6Al-4V alloy with modified cutting tool inserts. Cryogenics (Guildf) 51(1):34–40
103. López de Lacalle LN, Angulo C, Lamikiz A, Sánchez JA (2006) Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. J Mater Process Technol 172(1):11–15
104. Feng, S. C., and Hattori, M., 2000, “Cost and process information modeling for dry machining,” Proceedings International Work. Environ. and Manufacturing, Natl. Institute Stand. Technology
105. Klocke, F., and Eisenblatter, G., 1997, “Dry Cutting,” Ann. ClRP, 46(2)
106. Hong SY, Zhao Z (1999) Thermal aspects, material considerations and cooling strategies in cryogenic machining. Clean Techn Environ Policy 1:107–116
107. COSHH essentials for machining with metalworking fluids [online], health and safety; 2011. http://www.hse.gov.uk/metalworking/ecoshh.htm〉 (Ac-cessed 01–11 2011)
108. Karadzic I, Masui A, Fujiwara N (2004) Purification and characterization of a protease from Pseudomonas Aeruginosa grown in cutting oil. J Biosci Bioeng 98(3):145–152
109. Mattsby-Baltzer I, Sandin M, Ahlström B, Allenmark S, Edebo M, Falsen E, Pedersen K, Rodin N, Thompson RA, Edebo L (1989) Microbial growth and accumulation in industrial metal-working fluids. Appl Environ Microbiol 55(10):2681–2689
110. Sutherland JW, Kulur VN, King NC, von Turkovich BF (2000) An experimental investigation of air quality in wet and dry turning. CIRP Ann. - Manuf. Technol. 49(1):61–64
111. Dhar NR, Islam S, Kamruzzaman M, Paul S (2006) Wear behavior of uncoated carbide inserts under dry, wet and cryogenic cooling conditions in turning C-60 steel. J Brazilian Soc Mech Sci Eng 28(2):146–152
112. Theodosatos, A., and Haight, R., 2010, “Occupational dermatology,” Preventive Dermatology, pp. 103–113
113. Kopac J (2009) Achievements of sustainable manufacturing by machining. Journal of Achievements in Materials and Manufacturing Engineering 34(2):180–187
114. Kustas FM, Fehrehnbacher LL, Komanduri R (1997) Nanocoatings on cutting tools for dry machining. CIRP Ann. - Manuf. Technol. 46(1):39–42
115. Jawahir, I.S., and Dillon Jr., O. W., 2007, “Sustainable manufacturing processes: new challenges for developing predictive models and optimization techniques,” Proceedings of the 1st International Conference on Sustainable Manufacturing (SM1), Montreal, Canada
116. Weinert K, Inasaki I, Sutherland JW, Wakabayashi T (2004) Dry machining and minimum quantity lubrication. CIRP Ann. - Manuf. Technol. 53(2):511–537
117. Brinksmeier E, Meyer D, Huesmann-Cordes AG, Herrmann C (2015) Metalworking fluids - mechanisms and performance. CIRP Ann. - Manuf. Technol. 64(2):605–628
118. Nedić B, Perić S, Vuruna M (2009) Monitoring physical and chemical characteristics oil for lubrication. Tribol Ind 31(3–4): 59–66
119. Meyer, D., 2011, “Online monitoring of the chemical and microbial properties of metalworking fluids the electronic nose.,” Proceedings of the Fourth Symposium on Metal Removal Fluids, Barcelona, Spain, pp. 121–127
120. David R (2011) Monitoring and maintaining MWFs. Tribol Lubr Technol 67(3):80
121. Rakić R, Rakić Z (2002) The influence of the metal working fluids on machine tool failures. Wear 252(5–6):438–444
122. Koch T, Passman F, Rabenstein A (2015) Comparative study of microbiological monitoring of water-miscible metalworking fluids. Int Biodeterior Biodegrad 98:19–25
123. Bock, W., 2001, “Lubricants and the environment: specifications of the rapidly biodegradable lubricants,” Proceedings of the International Tribology Conference, Technical Academy Esslingen
124. Winter, M., Öhlschläger, G., Dettmer, T., Ibbotson, S., Kara, S., and Herrmann, C., 2012, “using jatropha oil based metalworking fluids in machining processes: a functional and ecological life cycle evaluation,” 19th CIRP International Conference on Life Cycle Engineering, Berkeley, pp. 311–316
125. Lea CW (2002) European development of lubricants derived from renewable resources. Ind Lubr Tribol 54(6):268–274
126. Herrmann, C., Hesselbach, J., Bock, R., and Dettmer, T., 2007, “Coolants made of native ester—technical, ecological and cost assessment from a life cycle perspective,” 14th CIRP Conf. Life Cycle Eng. Adv. Life Cycle Eng. Sustain. Manuf. Businesses, pp. 299–303
127. Dettmer, T., 2006, “Nichtwassermischbare Kühlschmierstoffe auf Basis nachwachsender Rohstoffe, Vulkan-Verlag, Essen, Germany”
128. Lawal SA, Choudhury IA, Nukman Y (2012) Application of vegetable oil-based metalworking fluids in machining ferrous metals - a review. Int J Mach Tools Manuf 52(1):1–12
129. Oda Y, Kawamura Y, Fujishima M (2012) Energy consumption reduction by machining process improvement. Procedia CIRP 4: 120–124
130. Shimoda, M., 2002, “LCA Case of Machine Tool,” Proc. Symposium of the Japan Society for Precision Engineering Spring Annual Meeting., pp. 37–41
131. Denkena B, Helmecke P, Hülsemeyer L (2014) Energy efficient machining with optimized coolant lubrication flow rates. Procedia CIRP 24 :25–31Mic
132. Nouari M, Ginting A (2006) Wear characteristics and performance of multi-layer CVD-coated alloyed carbide tool in dry end milling of titanium alloy. Surf Coatings Technol 200(18–19):5663–5676
133. Dearnley P, Grearson A (1986) Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318. Mater Science and Technology 2:47
134. Krain HR, Sharman ARC, Ridgway K (2007) Optimisation of tool life and productivity when end milling Inconel 718TM. J Mater Process Technol 189(1–3):153–161
135. Nabhani F (2001) Machining of aerospace titanium alloys. Robot Comput-Integ Manuf 17:99–106
136. Liu J, Yamazaki K, Ueda H, Narutaki N, Yamane Y (2002) Machinability of pearlitic cast iron with cubic boron nitride (CBN) cutting tools. J Manuf Science and Engineering 124:820
137. Nouari M, List G, Girot F, Coupard D (2003) Experimental analysis and optimisation of tool wear in dry machining of aluminium alloys. Wear 255(7–12):1359–1368

138. Noorul Haq A, Tamizharasan T (2005) Investigation of the effects of cooling in hard turning operations. International J Adv Manuf Technology 30:808–816

139. Jen TC, Gutierrez G, Eapen S, Barber G, Zhao H, Szuba PS, Labataille J, Manjunathaiah J (2002) Investigation of heat pipe cooling in drilling applications. Part I: preliminary numerical analysis and verification. Int J Mach Tools Manuf 42(5):643–652

140. UNIST. UNIST, Inc., Official Website (Online). http://www.unist.com/aboutus.htm〉 (Accessed 5 January 2012), 2012

141. Kamata Y, Obikawa T (2007) High speed MQL finish-turning of Inconel 718 with different coated tools. J Mater Process Technol 192-193:281–286

142. Sales W, Becker M, Barcellos CS, Landre J Jr, Bonney J, Ezugwu EO (2009) Tribological behaviour when face milling AISI 4140 steel with minimum quantity fluid application. Industrial Lubr Tribol 61:84–90

143. Veiga C, Davim JP, Loureiro AJR (2013) Review on machinability of titanium alloys: the process perspective. Rev Adv Mater Sci 34(2):148–164

144. Timmerhaus, K. D., and Reed, R. P., 2007, Cryogenic engineering: fifty years of progress, Springer

145. Zhao Z, Hong SY (1992) Cooling strategies for cryogenic machining from a materials viewpoint. J Mater Eng Perform 1(5):669–678

146. De Chiffre L, Andreasen JL, Lagerberg S, Thesken IB (2007) Performance testing of cryogenic CO2 as cutting fluid in parting/grooving and threading austenitic stainless steel. CIRP Ann. - Manuf. Technol. 56(1):101–104

147. KAKINUMA Y, YASUDA N, AOYAMA T (2008) Micromachining of soft polymer material applying cryogenic cooling. J Adv Mech Des Syst Manuf 2(4):560–569

148. Evans C, Bryan JB (1991) Cryogenic diamond turning of stainless steel. CIRP Ann. - Manuf. Technol. 40(1):571–575

149. Venugopal K a, Paul S, Chattopadhyay AB (2007) Tool wear in cryogenic turning of Ti-6Al-4V alloy. Cryogenics (Guildf) 47(1):12–18

150. Su Y, He N, Li L, Iqbal A, Xiao MH, Xu S, Qiu BG (2007) Refrigerated cooling air cutting of difficult-to-cut materials. Int J Mach Tools Manuf 47(6):927–933

151. Bhattacharyya D, Allen MN, Mander SJ (1993) Cryogenic machining of kevlar composites. Mater Manuf Process 8(6):631–651

152. Ghosh R (2005) Interrupted hard turning with cryogenically cooled ceramic tools. Transactions North Am Manufacturing Res Inst SME 33:161–169

153. Ahmed MI, Ismail AF, Abakr YA, Amin AKMN (2007) Effectiveness of cryogenic machining with modified tool holder. J Mater Process Technol 185(1–3):91–96

154. Hong SY, Ding Y (2001) Micro-temperature manipulation in cryogenic machining of low carbon steel. J Mater Process Technol 116(1):22–30

155. Khan AA, Ahmed MI (2008) Improving tool life using cryogenic cooling. J Mater Process Technol 196(1–3):149–154

156. Lockheed Martin's F-35 stealth fighter plane http://www.lockheedmartin.com/news/press_releases/2011/110915ae_f35_newtitanium.htm Accessed 6 January 2012)

157. Pereira O, Català P, Rodríguez A, Ostra T, Vivancos J, Rivero A, López-de-Lacalle LN (2015) The use of hybrid CO2 + MQL in machining operations. Procedia Eng 132:492–499

158. WolfinbargerJr, L., Sutherland, V., Braendle, L., and Sutherland, G., 1996, "Engineering aspects of cryobiology," Advances in Cryogenic Engineering, pp. 1–12

159. Pušavec F, Kopač J (2011) Sustainability assessment: cryogenic machining of inconel 718. Stroj Vestnik/Journal Mech Eng 57(9):637–647

160. Pigott R, Colwell A (1952) Hi-jet system for increasing tool life. SAE Tech Pap 3:547

161. Ramaiyengar HS, Salmon R, Rice WB Some effects of cutting fluids on Chip Fornation in metal cutting. ASME J Eng Ind Ser B 87:36–38

162. Mazurkiewicz M, Kubala Z, Chow J (1989) Metal machining with high-pressure water-jet cooling assistance—a new possibility. J Eng Ind 111(1):7–12

163. Wertheim R, Rotberg J, Ber A (1992) Influence of high-pressure flushing through the rake face of the cutting tool. CIRP Ann - Manuf Technol 41(1):101–106

164. Gandarias A, de Lacalle LNL, Aizpitarte X, Lamikiz A (2008) Study of the performance of the turning and drilling of austenitic stainless steels using two coolant techniques. Int J Mach Mach Mater 3(1–2):1–17

165. Liu J, Kevin Chou Y (2007) On temperatures and tool wear in machining hypereutectic Al-Si alloys with vortex-tube cooling. Int J Mach Tools Manuf 47(3–4):635–645

166. Rahman M, Kumar AS, Salam M-U, Ling MS (2003) Effect of chilled air on machining performance in end milling. Int J Adv Manuf Technol 21(10–11):787–795

167. Kim SW, Lee DW, Kang MC, Kim JS (2001) Evaluation of machinability by cutting environments in high-speed milling of difficult-to-cut materials. J Mater Process Technol 111(1–3):256–260

168. Yalcin B, Ozgur AE, Koru M (2009) The effects of various cooling strategies on surface roughness and tool wear during soft materials milling. Mater Des 30(3):896–899

169. Nandy AK, Gowrishankar MC, Paul S (2009) Some studies on high-pressure cooling in turning of Ti-6Al-4 V. Int J Mach Tools Manuf 49(2):182–198

170. 2013, High pressure coolant machining for better productivity and results, Fair Lawn, New Jersey: Sandvik Coromant, 2013

171. ISCAR, "HELITURN" [Online]. Available: http://www.iscar.com/Products.aspx/CountryId/1/ProductId/5438. [Accessed: 13-May-2016]

172. Tools, S., "Developed Jetstream Tooling®—a revolutionary new coolant system" [Online]. Available: https://www.secotools.com/en/Global/Products/Turning/Jetstream-Tooling/. [Accessed: 13-May-2016]

173. Drlička R, Kročko V, Matúš M (2014) Machinability improvement using high-pressure cooling in turning. Res Agr Eng 60:70–76

174. ChipBlaster, "Fixed Volume High Pressure System (D30–35)" [Online]. Available: http://www.chipblaster.com/view-resource/76. [Accessed: 13-May-2016]

175. Sørby K, Tønnessen K (2006) High-pressure cooling of face-grooving operations in Ti6Al4V. Proc Inst Mech Eng Part B J Eng Manuf 220(10):1621–1627

176. Herranz S, Campa FJ, de Lacalle LNL, Rivero A, Lamikiz A, Ukar E, Sánchez JA, Bravo U (2005) The milling of airframe components with low rigidity : a general approach to avoid static and dynamic problems. Proc Inst Mech Eng , Part B J Eng Manuf J Eng Manuf 219:789–801