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ORIGINAL ARTICLE

Application of cutting fluids in machining of titanium alloys—a review

Rukmini Srikant Revuru[1] · **Nageswara Rao Posinasetti**[1] · **Venkata Ramana VSN**[2] · **Amrita M**[2]

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Abstract Titanium alloys are widely used in aerospace, biomedical, and other engineering areas due to their superior properties. However, machining of titanium alloys has always been a challenge due to the high temperatures and tool wear rates. Dry machining has a limited range of permissible cutting conditions and is hence not suitable for industrial production. As a solution, flood cooling using cutting fluids is conventionally used to reduce the cutting temperatures. However, it is often discouraged in light of the associated environmental and health hazards. In order to achieve sustainable machining, different strategies for applying the cutting fluids are developed. Some of the prominent methods include minimum quantity lubrication (MQL), minimum quantity cooled lubrication (MQCL), and cryogenic cooling. This paper provides a comprehensive review of the available recent literature on such studies. Each of these techniques and results obtained in the studies has been discussed with emphasis on the advantages and limitations of each method. Major conclusions drawn are that coated carbides are better and machinability is greatly affected by the microstructure of the material. MQL certainly improved compared to other methods while cryogenic or super cooled cutting fluid application (MQCL) has been found to be better for specific situations. Use of nanofluids for titanium is not very popular among the researchers.

✉ Rukmini Srikant Revuru
rrsrikant@gmail.com; rukmini.revuru@uni.edu

1 Department of Technology, University of Northern Iowa, Cedar Falls, IA 50614, USA

2 Department of Mechanical Engineering, GIT, GITAM University, Visakhapatnam, AP, India

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1 Introduction

With the advancements in material science, newer materials with enhanced properties are being produced. Based on the requirements, alloys with properties like high strength and hardness are replacing the conventional metals and alloys in various engineering applications. While such materials are functionally useful, they pose problems during machining.

Increased strength and hardness of the materials generate high temperatures during machining and accelerate tool wear [1]. Such materials are known as "difficult-to-machine" materials. Titanium and nickel alloys are the most popularly used difficult to machine engineering materials. Titanium alloys are extensively used in the aerospace, structural, biomedical, and defense applications due to their superior properties like high fatigue strength, high yield strength, high strength to weight ratio, resistance to high temperatures, biocompatibility, and high corrosion resistance [2]. Though pure titanium is a soft metal, its alloys have superior properties comparable to nickel alloys. Still, the density of the alloys is low, almost similar to aluminum. This makes the alloys useful for aerospace applications. Due to the high hardness and strength, high temperatures are produced in the machining of titanium alloys [3, 4]. Further, titanium alloys retain their strength even at high temperatures, up to about 550 °C. As these alloys have very low thermal conductivity, heat generated in machining is not dissipated and is contained in the tool, leading to early tool failure. About 80% of the heat generated is conducted to the cutting tool [5, 6]. This problem aggravates at higher cutting speeds, where higher temperatures are produced. Also, high amount of spring back is experienced by these materials due to the low modulus of elasticity. This leads to greater deflection of thin-walled structures resulting in tool vibration, chatter, and poor surface finish.

It is reported in literature that optimum cutting speed for the alloy is about only 60 m/min while using tungsten carbide/physical vapor deposition (PVD)-coated tools [1, 7, 8], which are supposed to be the best tools for machining titanium alloys [9]. For uncoated carbide tools, the cutting speeds are less than 50 m/min, at a feed rate of 0.5 mm/rev. At higher speeds and feeds, the tool life is very short and results in poor surface finish. For instance, machining at speeds over 90 m/min had tool life less than 10 min [10]. Machining at low speeds and feeds results in reduced productivity.

As temperature is a major factor in machining of titanium alloys, diffusion and cater wears are dominant mechanisms responsible for tool failure. Further, titanium is highly reactive with the tool materials leading to increased wear of the tool [11]. This renders some of the hard tools like cubic boron nitride (CBN) not suitable for these alloys [12]. Tools like tungsten carbide have tool life of less than 5 min in dry machining of titanium alloys. Hence, tools with coatings are popularly used for machining titanium alloys. Tools with composite coatings were also used in literature, but the single-layer/single-phase coatings outperform the composite coatings [13, 14] due to their higher thermal stability. Since machining is usually done at lower cutting speeds, titanium alloys have high tendency to strain harden and lead to built up edge (BUE) during the course of machining [15]. BUE causes poor surface finish and dimensional control of the machined parts. Owing to the above reasons, machining of titanium alloys is a major challenge. Over the last few years, a considerable knowledgebase is formed by the contributions of various researchers on machining of titanium alloys.

2 Lubrication in machining of titanium alloys

Due to the wide spread use of titanium alloys and their poor machinability, machining of the alloys has received due attention. Various techniques are employed in machining of these alloys. Figure 1 shows the classification of various approaches usually adopted in conventional machining of titanium alloys. Different alloys of titanium are studied in the literature (Table 1). Table 1 gives the percentages (*w*/*w*) of the elements present in the alloy, the rest of the composition being titanium. It may be noticed that a majority of studies have concentrated on Ti6Al4V because of its wide usage.

2.1 Dry machining

Dry machining refers to machining without the use of any coolant. Many times, dry machining is encouraged due to the disadvantages of the coolants. However, dry machining

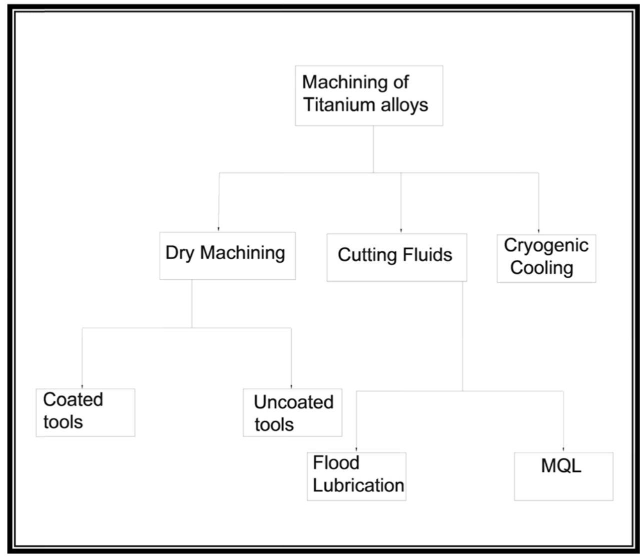

Fig. 1 Classification of machining processes for titanium alloys

results in high cutting temperatures and cutting forces, leading to short tool life. Various researchers have studied the efficacy of dry machining of different alloys having different machinability levels [16]. Usually, coated tools are preferred over uncoated carbide tools for machining of titanium alloys, as explained earlier. Sharif and Rahim [17] compared the performance of coated (TiAlN coating) drills with uncoated drill bits while drilling Ti6Al4V at different cutting speeds of 25, 35, 45, and 55 m/min. It was observed that uncoated tools had tool life less than 1 min, compared to coated tools which had about 8-min tool life at cutting speed of 25 m/min. It was reported that a micro layer of Al_2O_3 has formed on the tool as a protective mask from the atmosphere. This provided insulation to the tool, besides acting as a layer of lubricant. This helped in achieving longer tool life. Cantero et al. [18] studied the drilling of the same alloy using TiN-coated tools at cutting speeds of 50 m/min and feed of 0.07 mm/rev. In this study, the concentration was on the quality of the holes and tool wear. It was observed that attrition and diffusion wear led to tool damage over time. Since drilling was done at dry conditions, high temperatures were reached, which was evident from chip combustion. Chip combustion took place between 4 and 6 min of machining. It was observed that parts of the tool coatings were lost due to heat. The study suggests that dry machining is suitable only for a small time. Average surface roughness of about 2.5 μm was reported at the end of tool life. In a slightly different study, Armendia et al. [19] compared the machinability of Ti6Al4V and Ti54M alloys under dry machining using uncoated tools. Machining was done at constant feed of 0.1 mm/rev and depth of cut of 2 mm at different cutting speeds of 60, 70, 80, 90, and 100 m/min. Least tool wear was observed at 60 m/min, almost similar amount of wear for both materials. At higher speeds, Ti6Al4V gave higher tool wear. It was noted that tool life was about

Table 1 Different titanium alloys studied by researchers

Titanium alloy	Number of studies	Composition (%)							
		Al	Sn	Zr	Mo	W	Si	V	Others
BTi-6431S	1	6.13	3.0	3.0	1.28	0.38	0.12	–	Nb-0.14
Ti1023	2	3	–	–	–	–	–	10	Fe-2
Ti17	2	5	2	2	4	–	–	–	Cr-4
Ti40	1	–	–	–	–	–	0.2	25	Cr-15
Ti54M	2	5	–	–	0.6	–	–	4	Fe-0.4
Ti5553	3	5	–	–	5	–	–	5	Cr-3
Ti55531	1	5	–	–	5	–	–	5	Cr-3, Zr-1
Ti54M	2	5	–	–	0.6	–	–	4	Fe-0.4
Ti6246	2	6	2	4	6	–	–		
Ti6Al4V	56	6	–	–	–	–	–	4	Fe-0.25, O_2-0.2
TiAl	1	Variable	–	–	–	–	–	–	–
Ti-43.5Al-4Nb-1Mo-0.1B	1	43.5			1				Nb-4, B-0.1
Pure titanium	1	–	–	–	–	–	–	–	$O_2 < 0.5$

15 min for Ti6Al4V. In another work, Armendia et al. [20] studied the machinability of three titanium alloys, namely, Ti6Al4V, TIMETAL® 54 M, and Ti6246. Ti6246 showed highest tool wear due to its hardness. The other two alloys had similar mechanical properties but TIMETAL® 54 M was more machinable. This leads to an inference that mechanical properties alone do not dictate the machinability. The difference in machinability of the two alloys was attributed to microstructural changes due to heat treatment. It was observed that β annealing of the alloys led to more tool wear and cutting forces compared to other heat treatment processes. Also, it is advocated that as Ti54M has finer micro structure, better machinability, and hence can be a good replacement of Ti6Al4V in many applications. Similar results were obtained by Nouari and Makich [21] who studied the mechanics of machining Ti6Al4V and Ti55531. The study was aimed to understand the effect of cutting parameters through the analysis of chip formation. Cutting forces and temperatures followed different trends with change in cutting speeds. Cutting temperatures were found to be primarily responsible for increased tool wear. It was reported that while abrasion wear was prominent in machining Ti55531, adhesion, coating delamination, and diffusion were prominent in Ti6Al4V (Fig. 2). It was pointed out higher strength of Ti55531 compared to Ti6Al4V make it more difficult to be machined. This behavior increased with increase in cutting speed and rake angle of the cutting tool.

Khanna and Sangwan [22] carried out a similar work to investigate the machinability of heat treated Ti6Al4V, Ti54M and Ti1023 alloys. Friction coefficient, forces and temperatures were measured. It was found that at all the considered cutting conditions, the machinability followed the order of Ti1023 (solution treated and aged) > Ti1023 annealed > Ti54M β annealed > Ti6Al4V annealed > Ti54M annealed. So, the regular Ti6Al4V alloy that is often annealed for increased hardness has very low machinability. It may be noted

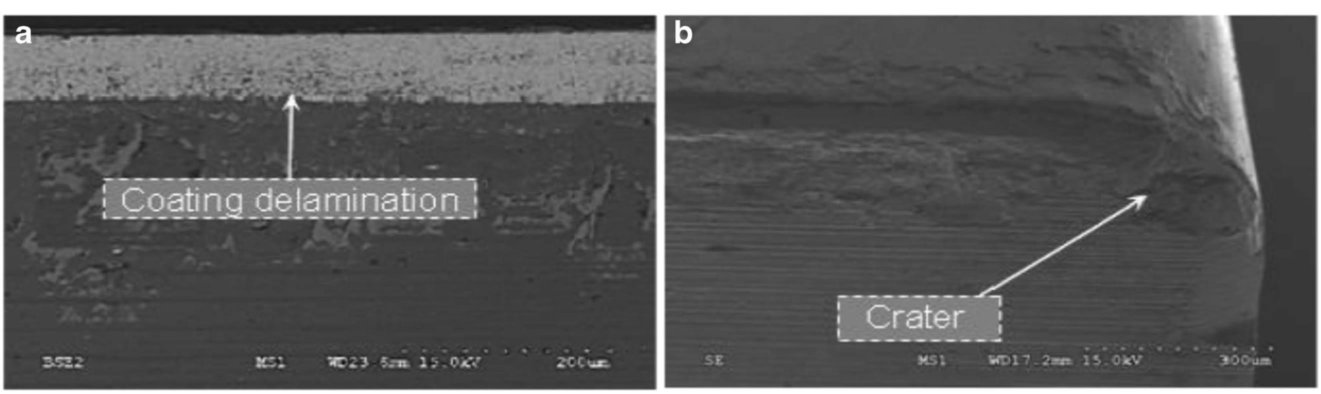

Fig. 2 BSE micrograph of tool used to machine. **a** Ti6Al4V **b** Ti55531 [21]

that among the available alloys of titanium, Ti6Al4V is used in over 50% of the applications worldwide [23, 24].

The mechanical properties of titanium alloys depend on the β-phase content. β-phase content influences the tool wear mechanism playing a critical role in the tool failure. Joshi et al. [25] machined three titanium alloys with different β-phase contents such as α, $\alpha + \beta$, and β-rich alloys with coated carbide tools. The wear mechanisms were investigated with scanning electron microscopy and energy-dispersive x-ray analysis of the tool surface. Abrasion wear, abrasion wear with BUE, and plastic deformation of tool were found to be prominent in these three alloys, respectively. Also, diffusion wear was observed in all the cases. Sacristan et al. [26] analyzed the machinability of $\alpha + \beta$ Ti6Al4V alloy with different contents of oxygen. Two different contents of oxygen, 1200 and 2000 ppm were considered. Machining was carried out at different cutting speeds of 50–70 m/min, feed of 0.5 mm/rev, and depth of cut of 3 mm. Cutting forces, chip morphology, and tool wear were studied in machining. It was observed that higher oxygen content led to poor machinability by almost 15%. This was attributed to the increased hardness and yield strength of the alloys with higher levels of oxygen content. Higher levels of diffusion wear were observed in high oxygen alloy. Similar results were obtained by Barkia et al. [27]. In this study, Ti40 (1600 ppm of oxygen) and Ti60 alloys (3200 ppm of oxygen) were tested. It was found that higher levels of oxygen content lead to increased shear stress and yield strength. Since temperatures produced in machining are primarily due to shear, this can have a major role in the machinability characteristics. In a study carried out on phase transformations of the alloy during machining, Zhang et al. [28] focused on modeling of stress distribution using Johnson-Cook's model. It was found that phase transformations influence the chip fracture characteristics of the alloy and hence the cutting temperatures. It may be noted that chip flow is greatly affected by the mechanical properties of the work materials. Hence, difference in chip fracture characteristics implies change in the mechanical properties of material, with the cutting parameters being constant. This is in line with the previous research that suggested influence of the phase on the properties and machinability of titanium alloys.

Vijay and Krishnaraj [29] studied the effect of cutting conditions on peripheral milling of Ti6Al4V alloy in dry machining. An uncoated carbide tool was used for machining at different cutting conditions selected through L16 orthogonal array. Machining was done in a range of 30–60 m/min of cutting speed, 0.01–0.025 mm/rev feed, and 2–3.5 mm depth of cut. Depth of cut was found to be the most influential parameter on cutting force, followed by feed rate. Optimal values of cutting speed as 40 m/min, depth of cut as 2 mm, and feed of 0.01 mm/rev were recommended for low cutting forces and better surface finish. It may be noted that the recommended values are the least values in the selected ranges. Mamedov and Lazoglu [30] machined Ti6Al4V using tungsten carbide end mill to study the forces and temperatures in micro milling. Machining was done at depths of cut of 100 and 150 μm, feed of 5, 10, and 15 μm/rev and speed of 10,000 rpm. Similar conditions were used to simulate the process for prediction of cutting temperatures. It was reported that high feeds lead to high temperatures, over 250% compared to low feeds. The results are similar to those claimed by Sun et al. [9]. In this study, Ti6Al4V was machined at 30–100 m/min. The work draws some interesting conclusions. It was observed that the temperatures are least at 80 m/min. This was supported by an argument that the higher the speeds, the amount of work piece material sticking to the tool decreases and thus friction is reduced. This leads to lower temperatures. Beyond 80 m/min, the effect of speed on work piece adhering to tool is weakened and hence temperatures increased. Higher feed rates increased the temperatures and surface roughness. Zhang et al. [31] found that apart from tool wear, machining of titanium alloys at higher speeds leads to increased residual stresses in the products. The combined role of tool wear and speeds was confirmed through microstructure analysis. It was shown that higher cutting speeds lead to higher rates of tool wear and thus increased residual stresses. The results were validated using numerical analysis. Zhu et al. [32] investigated the relation between tool wear and chip morphology while machining Ti6Al4V alloy at a speed of 80 m/min, feed of 0.1 mm/tooth and depth of cut of 0.8 mm. It may be noted that cutting conditions chosen are close to the conditions claimed to be optimal by Sun et al. [9]. Contrary to other works which report crater and diffusion wear to be the most influential mechanisms, this work reported that flank wear was dominant. This was attributed to the chipping of the tool due to high chatter. It was found that tool wear decreases the chip curl and increases the tool/chip contact area. This, in turn, leads to increased friction and temperature which further decreases the tool life. Wagner et al. [33] studied the relationship between chip formation, cutting process and tool wear for Ti6Al4V and Ti5553 alloys while machining at speed in the range of 35–65 m/min, depth of cut at 3 mm and feed at 0.2 mm/tooth. Serrated chips were observed at all cutting conditions for both the alloys. This is an interesting observation, which is not in line with other works reporting BUE at lower speeds and serrated chips at higher speeds. No change in the material properties of the chip were observed at low cutting speeds, but at higher cutting speeds, changes in the material properties and phase of the material were observed. Also, chip thickness decreased with increase in cutting speed. An analytical model was proposed to quantify stresses, temperatures, and friction. The study suggested that high cutting speeds can alter the properties of the product due to high temperatures. Similar results were reported by Sun et al. [9], Sima [34], and Nithyanandam et al. [35]. A unique aspect in the work by Sutter and List [36] is that machining is carried out at very high speeds in the range of 3000–4000 m/min. It was observed that at lower speeds in the range, softening of metal takes place due to high temperatures and in the median of the speeds, strain hardening dominates the thermal effects and hence forces do not reduce. At the highest values of speed, small fragments are expelled from the work piece and hence, cutting forces get reduced again. It was shown that cutting speed is the most influential parameter, followed by feed. Though the work suggests that higher speeds may be beneficial for machining titanium alloys, this inference cannot be applied for regular machining, as the speeds are very high and beyond the regime of regular machining.

In another study on high-speed machining, Wang and Liu [37] machined Ti6Al4V at different cutting speeds ranging from 50 to 3000 m/min and constant feed of 0.1 mm/tooth to find the influence of cutting speed on forces. Serrated chips were observed up to 2500 m/min and then discontinuous chips were obtained. It was observed that higher cutting speeds are required to attain lesser cutting forces, but since cutting speeds increase the temperature, dry machining at high cutting speeds is not practical for titanium alloys. In a slightly different study, Wu and Zhang [38] studied the effect of feed rate in end milling of Ti6Al4V at cutting speed of 150–450 m/min, feed of 1–10 m/min, and depths of cut as 0.5–2.5 mm. It was observed that cutting forces increased with cutting conditions. Beyond cutting speed of 350 m/min, the cutting forces decreased due to thermal softening of the work piece.

Rashid et al. [39] machined Ti6Al4V at constant cutting conditions to study the tool wear mechanisms. Machining was carried out at speed of 150 m/min, feed rate of 0.214 mm/rev, and depth of cut of 1 mm. Length of cut was varied from 95 to 110 mm. It was observed that adhesion, attrition, and diffusion led to increased crater wear. Diffusion of carbon, tungsten, and cobalt was observed from the tool to the flowing chip; this was followed by plastic deformation of the tool due to high temperatures. Wagner and Duc [40] studied milling of Ti1023 with toroidal tool to investigate the influence of cutting conditions on cutting forces and tool wear. Cutting speeds were selected in the range of 20–120 m/min and feed in the range of 0.05–0.3 mm/tooth. It was observed that cutting forces and tool wear increase with the cutting conditions, in line with previous works. It has been reported that radial depth has to be kept lesser than tool radius to increase tool life and has to be larger to increase the material removal rates. This is because, as the depth decreases, stresses and temperatures are lowest and hence tool life increases.

Prasanna et al. [41] studied the influence of cutting parameters in dry drilling of Ti6Al4V. holes were drilled in plates of 0.4-mm thickness at different speeds of 2000, 3500, and 5000 rpm and feeds of 5, 10, and 15 mm/min. Forces and form accuracy of the holes were measured and Taguchi's analysis was carried out to identify the most significant parameter. It was reported that lower feeds produced higher thrust forces due to the increased machining time and hence was most influential. Also, titanium alloys react with carbide tools at higher temperatures. However, accuracy of the hole deteriorated with increase in feed rate due to increased tool wear. Cutting speed was found to be the most significant for hole quality. Through ANOVA and gray relation analysis the optimal settings were found out to be feed rate of 10 mm/min and speed of 5000 rpm. Yang and Liu [42] studied the influence of cutting parameters (cutting speed = 20–110 m/min, feed = 0.02–0.05 mm/tooth, depth of cut = 0.5–2 mm) in milling of Ti6Al4V alloy and tried to optimize the parameters. Machining was carried out under different levels of speeds, feeds, and depths of cut designed through Taguchi's method. Different surface defects like feed marks, scratches, adhered material particles, etc. were observed on the machined surfaces (Fig. 3). It was found that feed marks and scratches increased with feed rates. Cutting temperatures increased with speed. Best surface was obtained while machined at high cutting speed, low feed, and small depth of cut. However,

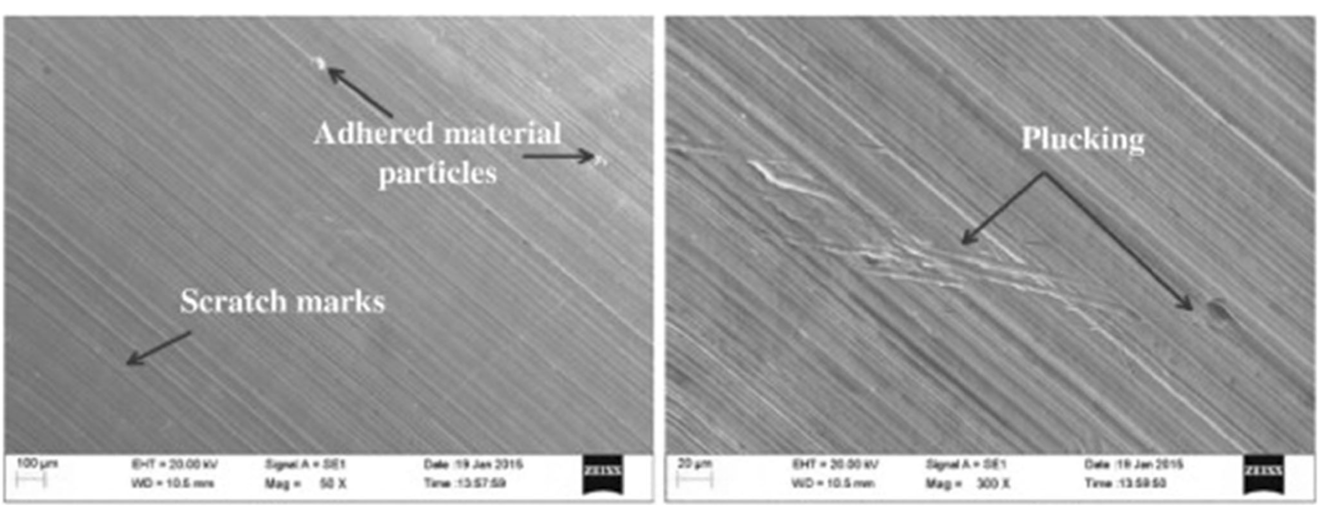

Fig. 3 Surface defects on machined surfaces [42]

adhesion and debris of microchips were observed at high cutting speeds.

It may be noted that in almost all the reported works, dry machining of titanium alloys is characterized by high temperatures and tool wear. It is generally reported that higher cutting speeds severely affect tool wear/product quality. Hence, the permissible cutting conditions in machining the alloy are limited for long tool life, leading to low productivity. This leads to the investigations on techniques to improve the machining process by reducing friction and temperature.

2.2 Cutting fluids

The conventional approach to restrain cutting temperatures and associated problems is the application of cutting fluids [43]. Cutting fluids are usually applied with the nozzle pointed at any of the three different directions, namely, behind the chip, on the rake face, or on the flank face (Fig. 4). The cutting fluid reaches the interface of the tool/chip through capillarity, forms a thin film and prevents the adhesion of the chip on the rake face of the tool [44]. This reduces friction and consequent heating. However, since the temperature is very high in the machining of titanium alloys, the cutting fluid evaporates before it reaches the tool/chip interface. To compensate for the loss due to evaporation, flood lubrication has been adopted in many studies.

2.2.1 Flood lubrication

Flood lubrication is the conventional method of applying cutting fluids in machining. Typically, flow rate of over 100 L/h is adopted. The cooling is mainly due to convention of the heat from the machining zone and a small quantity of the coolant may reach the tool/chip interface, depending on the direction of the coolant application. Among the various types of cutting fluids available, generally, water-based emulsions are applied in flood lubrication due to the high heat transfer capabilities and economy [43]. Narutaki et al. [45] used flood lubrication of water-based emulsion while machining titanium alloys with diamond tool. It was reported that cutting speeds of 3.33 m/s (200 m/min) were possible in flood lubrication. It was emphasized that coolant plays a critical role in the process. It was observed that at lower speed conditions, the interactions of the tool and work piece were not significant. Abrasion wear was found to be the major contributor of tool wear. Since abrasion wear is mainly due to friction, it may be inferred that flood lubrication cooled the work piece (evident by reducing diffusion wear), possibly by conduction and convection, but did not provide the required lubrication.

Nambi and Paulo [46] machined Ti6Al4V alloy using ceramic inserts containing 80% Al_2O_3 and 20% TiC. Cutting fluid containing 75% water was applied as a coolant compared to 95% of water that is normally used with water-soluble fluids. But, in this study, higher content of oil was used to improve the lubrication in machining. Machining was done at different cutting conditions with and without the application of the cutting fluid. Cutting speeds of 45, 90, and 135 m/min, feed rate of 0.1, 0.2, and 0.32 mm/rev, and depths of cut of 0.5 and 0.75 mm were chosen. It was reported that tool life has increased by over 30% with the application of cutting fluid compared to dry machining. Though attrition and adhesion wear lead to the failure of cutting tool, the wear was much less compared to the dry machining. In dry machining, diffusion wear was higher due to higher temperatures. Better surface finish was observed with the application of the cutting fluid. This was attributed to the lesser chances of adhesion wear. BUE was not noticed in wet machining. Further, permissible speeds and feeds are much higher with the application of cutting fluids.

Though flood lubrication is usually sufficient for effective cooling in machining of titanium alloys, high-pressure coolant delivery systems are preferred [47]. It is often reported that the low pressure of regular coolant may not be sufficient to break through the vapor blanket formed by the prevalent high temperatures and hence sufficient cooling may not be obtained. Since the increase in flow rate and velocity of the jet increases the heat transfer coefficient, higher pressures result in faster heat dissipation and are more advantageous. Further,

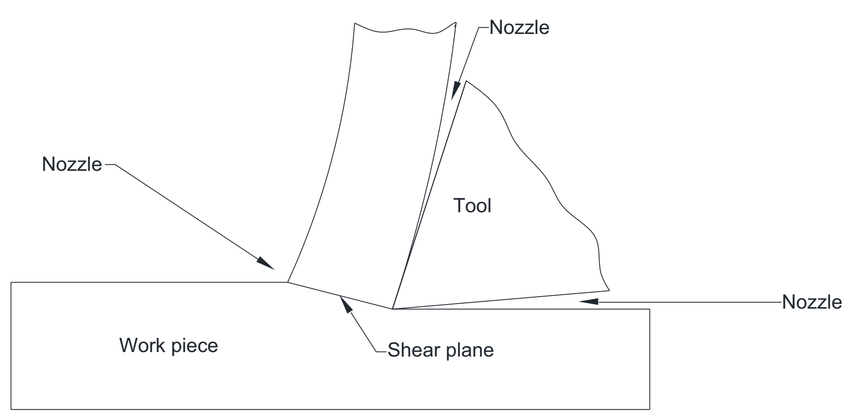

Fig. 4 Directions of application of cutting fluids

pressurized jet helps in chip breaking and prevents excessive contact of the chip with the rake face of the tool, thus reducing the friction. It is interesting to note that even jet cooling may not completely lubricate the machining zone and many times abrasion and diffusion wear of the tool were reported. In order to achieve effective lubrication, Ezugwu et al. [48] studied the surface integrity of Ti6Al4V samples machined under different cutting conditions and high pressures of coolants. Machining was done at cutting speeds of 175, 200, 250, and 250 m/min, feed rate of 0.15 mm/rev, and depth of cut of 0.5 mm. High-pressure coolant was supplied at 11 and 20.3 MPa, resulting in 18.5 and 24 L/min flow rates, respectively. The flow rates were chosen to ensure chip-breakage. It was reported that the surface finish was below the rejection criteria in all the cases (Fig. 5). Micro-structures were examined to detect plastic deformation, but no plastic deformation was found. It may be observed that the cutting speeds are higher than what are usually permitted for the machining of the alloys. Preventing plastic deformation at the chosen cutting speeds is a major contribution of the work. This was attributed to the softening of the machined surface under high coolant pressures and efficient cooling. On the other hand, conventional cooling hardened the material due to the quenching effect.

Da Silva et al. [11] also applied the coolant at increased pressures while machining Ti6Al4V. At high pressures, flow rates of 16.9, 18.5, and 20.3 L/min were obtained (for pressures of 7, 11, and 20.3 MPa, respectively), while the conventional flood lubrication was maintained at 2.3 L/min. The coolants were applied through a nozzle directed at the backside of the chip. Machining was done at different cutting speeds of 175, 200, 230, and 250 m/min. Tool flank wear, cutting forces, and surface roughness were monitored. Flank and nose wear are found to be dominant with the polycrystalline diamond (PCD) tools. Among the two forms, nose wear was found to be most influential. Nose wear was found to increase with increase in cutting speed in all cases. Tool wear was found to decrease with increase in the coolant pressure and flow rate. For instance, in Fig. 6, tool profile while machining at 7 MPa (a) was compared with 11 MPa (b). Among

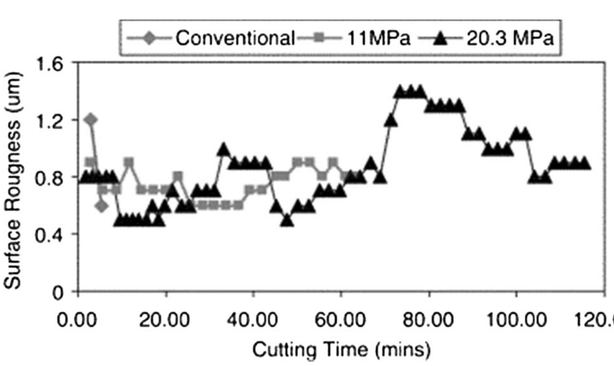

Fig. 5 Surface roughness in different lubricating conditions [48]

the considered flow rates, the 20.3 L/min flow rate resulted in minimum tool wear. However, the phenomenon was dominant at low cutting speeds and at high speeds, the effect of coolant pressure was not clear. Similar results were obtained for surface finish and cutting forces.

Hadzley et al. [49] performed a similar study on Ti6Al4V alloy and the results were substantiated using finite element analysis. Coolant pressures were taken as 7, 11, 15, and 20.3 MPa. Cutting forces, temperatures, and chip formation were simulated at constant cutting conditions. The flow of the cutting fluid was directed at the rake face of the tool through a channel in the tool holder. It was reported that the cutting forces and temperatures decreased with increase in the pressure of the coolant due to reduction in friction (Fig. 7). Also, it was reported that while conventional coolant supply resulted in continuous chips, increased pressure of the coolant produced segmented chips. As discussed earlier, this is helpful for curtailing friction in the machining zone.

Ayed et al. [50] rough machined Ti17 alloy using tungsten carbide tools under cooling with conventional flood lubrication and high-pressure water jet supply. Jet was directed between tool rake face and chip. This assisted in chip breaking and reduced friction. It may be noted that when applying the coolant on the rake face, the cutting fluid jet has to overcome the effect of the chip flow in order to reach the secondary shear zone and provide lubrication. Such lubrication is only possible under high speeds and pressures of the coolant jet. It was observed that cutting temperatures in flood lubrication were very high and caused premature tool failure. With the high-pressure coolant, the tool life increased by four times. Diffusion wear was significantly low under high-pressure coolant system. Crater wear was found to be more influential than the flank wear in such systems. This may be because of the pressure not sufficient to reach the machining zone to prevent crater wear by forming a lubricating film on the rake face. In another study, Ayed et al. [51] applied high-pressure water jet as coolant while machining Ti17 alloy using uncoated carbide tools. Cutting speed was varied from 50 to 100 m/min and water jet pressure was varied from 50 to 250 bar. The effect of water jet was dominant at low speeds. At 100 bar pressure, tool life was about nine times compared to dry machining. It was also suggested that cutting speeds may be increased while using water jet, up to about 15% and thus increase the productivity. This is in line with the results claimed by Ezugwu et al. [48].

Bouchnak et al. [52] machined Ti5553 alloy using a high-pressure coolant jet. Jet pressure was varied and results were compared with flood and dry machining. It was shown that higher productivity can be obtained through high-pressure jet cooling as higher cutting speeds are possible. This also led to better chip fragmentation and longer tool life. Surface finish was found to have increased. The results were attributed to the thermo-mechanical action of the coolant jet leading to reduced

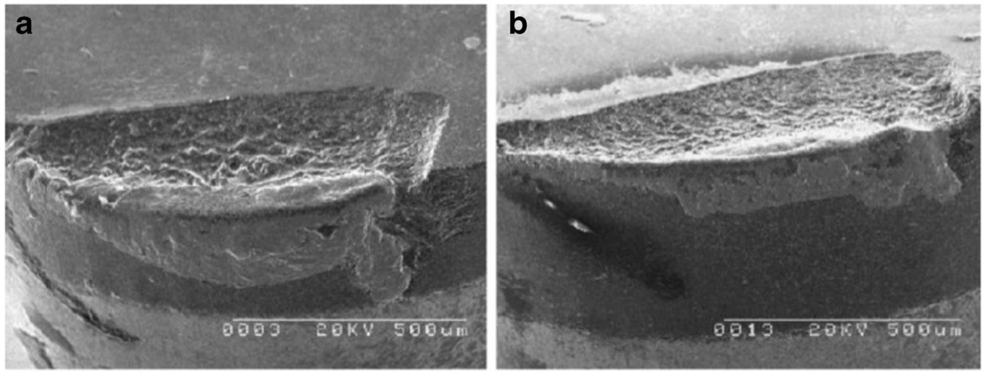

Fig. 6 Tool profiles at different coolant pressures. **a** 7 MPa. **b** 11 MPa [11]

coefficient of friction and hence, reduced cutting forces and temperatures. It is reported in almost the works using the high-pressure jet that the application of the jet helps in softening the work piece, thus lowering the cutting forces. A summary of research on dry machining and flood cooling in machining of titanium alloys is provided in Table 2.

Improved performance has led to the widespread application of the cutting fluid as high-pressure jets. This leads to increased consumption of cutting fluids causing serious environmental concerns. The effects of the fluids on workers' health, problems in handling and disposal of the fluid, environmental pollution, etc. have been a major concern for many industries [53]. Several industries spend huge amount of money for the safe disposal of cutting fluids. The ingredients in cutting fluids like the EP additives and emulsifier make the cutting fluid non-biodegradable. This often calls for special treatment before disposal and increases the disposal costs [54].

Due to the microbial contamination and effect of toxic ingredients in cutting fluids, nearly 80% of the occupational infections and diseases like dermatitis are caused [55]. Though individual ingredients may be safe, the chemical reactions on formulation of the fluids give rise to compounds that are complex and allergenic. International Agency for Research on Cancer (IARC) reported that cutting fluids containing petroleum-based additives can cause skin cancer [43]. Due to the hazardous substances and less biodegradability cutting fluids cause several health problems like lung cancer, respiratory disorders, and various dermatological diseases.

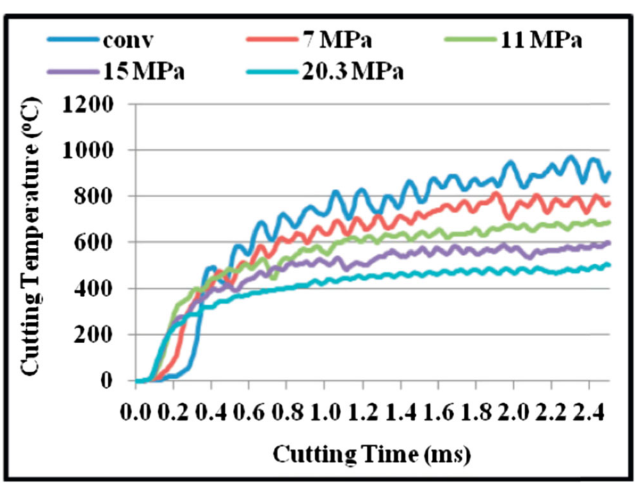

Fig. 7 Cutting temperatures at different coolant pressures [49]

Apart from the disposal problems, the reported growth of bacteria in cutting fluids is alarming. Aerobic bacteria grow exponentially in the cutting fluids in both storage and working conditions. The bacterial species is identified to be *Pseudomonas*. Being an opportunistic bacterium, though not invasive, *Pseudomonas* has a tendency to aggravate in case of an injury or burns. There are about 70 species in *Pseudomonas*, majority of which have the ability to break down the oils (which can crucially affect the cutting fluid). The organisms utilize the carbon present in the oils as their source of nutrition and deteriorate the oil into inorganic compound. *Pseudomonas* has the ability to survive in hostile conditions and is not suppressed even by biocides (it is common to find *Pseudomonas* even in hospital disinfectants) [56]. Further, the use of biocides in the cutting fluids is subjected to several constraints imposed by the environmental regulations of various organizations and needs special treatment during disposal. Addition of different additives like chlorinated paraffin to increase chemical stability, viscosity, flame resistance, etc. further aggravate the problem of disposal. These additives change to dioxin on heating and can lead to uncontrolled burning. Hence, such cutting fluids are classified as hazardous compounds [57]. With the increasing need for implementing green and sustainable manufacturing practices, the application of cutting fluids is often discouraged.

In an interesting study by Shokrani et al. [58], power consumption was estimated in both dry and flood lubrication conditions while machining Ti6Al4V. It was stated that flood lubrication consumed 40% more power compared to dry machining, due to the power consumption of the coolant pump. This is contrary to the belief that cutting fluids reduce the cutting forces and hence power consumption. It may be worth mentioning that the study used regular conventional flood lubrication and the quenching of the work piece may have increased the forces and hence the power consumption. This

Table 2 Summary of research on dry machining/flood cooling of titanium alloys

Reference(s)	Lubrication	Cutting fluid	Salient features	Observations/contributions	Inferences/remarks
[17]	Dry	–	Compared PVD and TiAlN tools	TiAlN gave better performance	Al2O3 formed a lubricating layer
[18]	Dry	–	Used TiN coated tools	Chips were combusted and coating was lost	Dry machining not suitable for production
[20]	Dry	–	Compared three alloys for machinability	Ti6246 was more machinable	Machinability depends on micro structure and grain structure. Not just hardness
[25]	Dry	–	Compared tool wear mechanisms of different phases	Similar mechanisms observed	Though phase changes affect machinability, similar forms of tool wear—abrasion, adhesion, and diffusion are found. Almost all the works on dry machining observed these three forms of tool wear
[26]	Dry	–	Studied machinability Ti with different oxygen levels	Higher ppm led to higher hardness and strength	Oxygen levels decreased the machinability
[9], [30]	Dry	–	Studied temperatures with different feed rates	Higher feeds increased the temperatures by over 2 times	[30]-Machining was done at very high speed—10,000 rpm, feeds were given in micrometers
[9], [33], [34], [35], [41], [42]	Dry	–	Studied effect of cutting parameters on work surface	No change at low speeds, but higher speeds led to change in material properties and phases	High temperature was probably responsible for the changes. High values of cutting conditions not suitable. For this reason and exacerbated tool wear, cutting conditions are kept low
[45], [46]	Flood	Water-based emulsion	Studied the effect of cutting parameters on tool wear	Abrasion and attrition are main forms of tool wear, diffusion decreased. Longer tool life with use of cutting fluid	Diffusion reduced on account of reduced temperatures, but abrasion remained due to inadequate lubrication
[11], [47], [48], [49], [50]	Flood-pressurized jet	Water-based emulsion	Used high-pressure jet, instead of regular flood cooling	Tool wear and surface roughness reduced with increase in pressure	High-pressure jet helped to break through the vapor blanket formed at the high temperature zone. Further high-pressures increase the momentum of the coolant and lead to better heat transfers. Higher cutting speeds may be used while employing high-pressure jet

phenomenon is not very prominent in metals like steels, but for titanium alloys, where the temperatures are very high, this is significant. The study suggested that flood lubrication is not always economical. If only the power consumption of the pump is considered, then high jet cooling requires more power than flood cooling. Hence, carbon foot print evaluation of cutting fluids discloses several surprising facts. Due to the associated problems, the use of cutting fluids is limited by different environmental agencies and the industries are looking for alternatives to replace the cutting fluids, without sacrificing the benefits [59].

2.2.2 Minimum quantity lubrication

Minimum quantity lubrication (MQL) is a strategy of applying low quantity of the cutting fluid as coolant in machining. This eliminates the disposal issue as almost all the quantity of the fluid is evaporated. Though flood lubrication was initially preferred in machining of titanium alloys due to the high temperatures generated, MQL is slowly finding its way in to the field. MQL can be applied in two forms, drop-by-drop or mist form, the second one being popular. In the mist method of application, the fluid is atomized by missing with compressed air and is applied as an aerosol spray. This increases the surface area of the lubricant exposed to the work piece and helps in better cooling. Further, cooling enhanced due to the high velocity of air and hence better heat transfer coefficient of the air/lubricant mixture. Several brands of commercial equipment are available in the market for regulating the flow rate and pressure of the applied lubricant.

Due to environmental issues, MQL with vegetable-based oils is preferred over the regular MQL. Vegetable oils are more readily biodegradable compared to the mineral oils and do not pose problems to the exposed workers. Use of different vegetable oils like canola oil, palm oil, sesame oil, sunflower oil, etc. is reported in literature [60]. Some works profess the application of synthetic fluids. Yang et al. [61] used phosphate-based ester to formulate a cutting fluid. The tribological behavior of the fluid was characterized using the standard ball-on-disk apparatus with the disks made up of Ti6Al4V alloy. It was reported that the formulated fluid had better properties compared with the water based emulsion. The formulated fluid had about 50% lesser wear and low adhesion characteristics compared to the water based emulsion. Fluid with 0.5% concentration of the ester had a friction coefficient of 0.15 and least adhesion mechanism. An adsorption film was observed on the work surface that prevented the direct contact and reduces friction. It may be noted that the developed coolant had sulfur-based extreme pressure additives, which can sustain high normal loads and provide better lubrication. However, these additives are harmful to environment and need to be treated for disposal.

Prakash and Ramana [62] applied MQL for machining Ti6Al4V. Palm oil-based cutting fluid was supplied at rate of 100 mL/h. The results were compared with dry and flood lubrication. Machining was carried out using uncoated and coated carbide tools. It was reported that tool wear and surface roughness remarkably decreased compared to the dry and flood lubrication. It may be noted that cutting conditions were different for dry, flood, and MQL. For dry machining, cutting speed was 63 m/min, feed was 0.206 mm/rev, and depth of cut 0.6 mm. For flood cooling, speed was 79 m/min, feed was 0.274 mm/rev, and depth of cut was 1 mm, whereas for MQL speed, feed and depth of cut were 99 m/min, 0.343 mm/rev, and 1.6 mm, respectively. It is encouraging to observe that even at 1.5 times the cutting conditions compared to dry machining, MQL gave better results. In a similar study, Shyha et al. [63] investigated the effect of applying vegetable oils in machining Ti6Al4V. Castor oil-based cutting fluid was used as the coolant. Machining was done at three levels of cutting conditions, the highest being speed of 120 m/min, feed of 0.2 mm/rev, and depth of cut of 1 mm. Different cutting tools and fluids were used for the study. The effect of different process parameters was established through ANOVA analysis. It was found that surface roughness was mainly affected by feed rate, while tool wear was affected by cutting speed. Tool wear was found to be consistently low compared with dry machining. It is reported that ceramic tools showed premature breakage and are hence not suitable for machining titanium alloys. PVD-coated tools were reported to be the best tools in terms of surface finish and tool wear.

Revankar et al. [64] machined Ti6Al4V with PCD tools under dry, flood lubrication, and MQL. It was reported that MQL results in lesser surface roughness and can accommodate higher levels of cutting conditions (leading to better material removal rate) compared to dry machining. Taguchi technique was used to optimize the results and it was found that cutting speed of 150 m/min, feed rate of 0.15 mm/rev under MQL was optimal for least surface roughness of the machined product. It was reported that since MQL provides better lubrication, it helps in reducing the friction and temperature generation. This helps in reducing the hardening of the work piece and improves the tool life. It may be noted that the optimal speed reported in this work is far higher than the cutting speed permitted for dry machining (60 m/min).

Liu et al. [65] studied tool wear rate/pattern and wear mechanisms of three different tools—uncoated inserts (R_1), tools with different coating materials—nc-AlTiN/a-Si_3N_4 (R_2), and nc-AlCrN/a-Si_3N_4 (R_3) in dry and MQL machining of Ti6Al4V. Flow rate of 16 mL/h was maintained for the MQL condition. Machining was done at constant cutting conditions of cutting speed as 120 m/min, feed rate of 0.1 mm/rev depth of cut as 1.2 mm. It was reported that MQL condition improved tool life compared to the dry condition for all the three inserts (Fig. 8) due to the cooling and lubricating effects. It was observed that MQL helps to form a lubricating layer between the tool rake face and chip. This helps to reduce the friction. It is interesting to note that the study used tools with composite coatings. These coatings are not preferred in dry machining, but evidently have good performance in MQL machining. It was reported that adhesive wear is the dominant tool wear mechanism in all the three inserts. The lubricant in MQL provided a protective layer and reduced the friction considerably. It is also reported that in MQL, the R_2 tool was affected only by adhesion wear but R_3 tool was affected by adhesive, diffusion, and oxidation wear.

Rahim and Sasahara [66] applied palm oil in MQL (MQLPO) for machining titanium alloys. The results were compared with MQL synthetic ester (MQLSE), air blow, and flood lubrication. Cutting forces, temperatures, and tool wear were monitored. It was found that the palm oil gave the minimum cutting forces compared to other conditions. Similar results were obtained for temperatures and tool wear (Fig. 9). Adhesion, attrition, and abrasion wear were found to be the dominant mechanisms for tool failure. Interestingly, both the oils gave similar tool life of about 314 s. This was attributed to the lubrication provided by both the oils. Adhesion, attrition, and abrasion forms of tool wear were found in all the

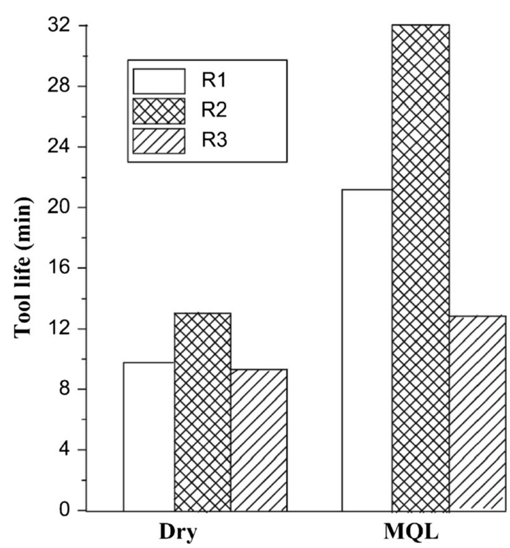

Fig. 8 Tool life under dry and MQL conditions [65]

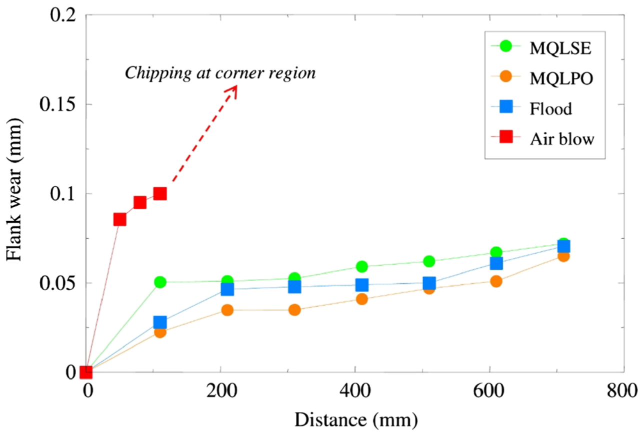

Fig. 9 Tool wear under different lubricating conditions [66]

conditions. Thermal cracks were found on the tool edge, but they did not lead to tool failure. This work observes that though MQL is effective in reducing the forces and temperatures, it is not clear whether MQL has a significant effect on tool life. Similar observations were made by Liu et al. [67] who analyzed friction and temperatures in end milling of Ti6Al4V under different cooling conditions such as MQL, high-pressure air, and dry machining. Machining was done at cutting speed of 60, 150 m/min, feed rate of 0.05 mm/tooth, and depth of cut of 1 mm. Compared to dry machining, both MQL and high-pressure air cooling reduced friction drastically. MQL and high-pressure air outperformed dry machining at lower cutting speed. The coefficient of friction was about 0.35 in case of dry machining, 0.3 in high-pressure air, and 0.15 in case of MQL. As a consequence, the cutting temperatures were lowest with MQL. It was observed that MQL leads to the formation of a thin film at the tool/chip interface and reduces the sliding friction between tool and chip. However, at higher cutting speed, all the three conditions had similar effect.

In another work, Rahim et al. [68] commented that tool life can increase by over four times while using MQL, in comparison to dry machining. In this work, synthetic ester-based MQL was used and it is reported that formulated fluid reduced the cutting temperature, force, and tool/chip contact length. Tool/chip contact length is a major contributor to the friction at chip/tool interface and plays a significant role in the crater wear of the tool. It may be noted that this work did not use vegetable oil-based MQL. Wakabayashi et al. [69] investigated the effect of MQL with atomized water-soluble cutting fluid in machining of Ti6Al4V. The results were compared with drop-by-drop lubrication and dry machining. It was reported that while drop-by-drop lubrication provided better tool life compared to dry machining, mist cooling was the most effective. Among the considered types of cutting fluids, synesthetic ester-based fluid gave the best performance. It may be noted that in this study, regular cutting fluid was used, not the vegetable oil-based coolant. In a similar study, Lv et al. [70] applied pneumatic mist MQL while machining Ti40 alloy using Ti(C,N)–Al_2O_3-coated cemented carbide tools. Milling was done at different speeds of 30, 60, 80, and 100 m/min, feed rate of 0.1 mm/tooth and 1-mm depth of cut. The study focused on the assessment of wear behavior of the tools. The results were compared with the regular flood cooling. It was observed that PMJIC gave lesser cutting temperatures compared to the flood lubrication. The effect was more pronounced at higher cutting speeds. This eventually led to reduced tool wear and enhanced tool life (Fig. 10). Abrasion and adhesion were found to be the dominant mechanism of tool wear responsible for tool failure. No delamination of the coating layer was observed in the tools in MQL. This is similar to the earlier discussed works that suggest use of coated tools, especially composite coatings, in machining of titanium alloys. Compared to flood cooling, MQL reduced all forms of wear, except cracks. Like the results reported by Rahim and Sasahara [66], the cracks did not lead to catastrophic failure of the tool.

Garcia and Ribeiro [71] milled Ti6Al4V using coated cemented carbide inserts under MQL conditions using a vegetable oil-based cutting fluid, dry machining, and flood lubrication with water-soluble cutting fluid for comparison. Machining was done at different cutting speeds and feeds. It was reported that MQL resulted in lesser surface roughness and longer tool life under similar cutting conditions as compared to dry/flood lubrication. Adhesion and abrasion were observed to be the most influential mechanisms of tool wear. Similar observations were reported by Hoyne et al. [72] and Sun et al. [73]. It may be noted that in almost all the works on MQL, diffusion wear is not reported to be influential. This is due to the control of cutting temperatures through proper lubrication.

Yang et al. [74] carried out an interesting study involving the use of tools with microgrooves on the rake face and machined Ti6Al4V alloy under MQL. Different microgrooves were tested to find out the optimal geometry of groove

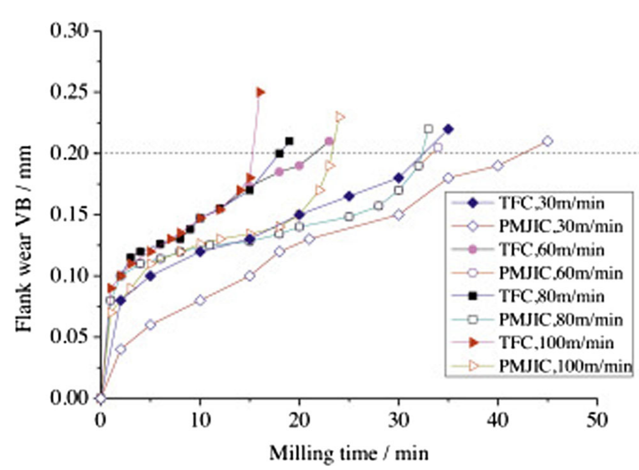

Fig. 10 Tool wear under different lubrication methods [70]

(Fig.11). It was reported that tool with microgrooves 29 μm in depth, 59 μm in width, with 53-μm spacing and 250 μm far from the main cutting edge helped to reduce adhesion and thus reduce the cutting temperatures and forces compared to other considered choices. It was advocated that reduction in tool/chip contact length, in addition to MQL, was the reason for improved performance. Though it is not highlighted in the paper, the geometry of the grooves may have acted as fins on the rake surface of the tool and helped to cool the tool faster. It is interesting to note that the tools with microgrooves performed better in MQL, compared to dry machining.

Bermingham et al. [75] studied milling of Ti6Al4V under different conditions: laser-assisted milling, dry milling, flood lubrication using a water-soluble cutting fluid (27 L/min), MQL with a vegetable oil (4 mL/h) and hybrid laser + MQL method. Laser was used to thermally soften the work piece. In the hybrid technique, MQL was applied with two nozzles at the back of the tool. Tool wear was monitored at different cutting speeds of 69, 90, and 104 m/min (Fig. 12). It was reported that at regular cutting conditions prescribed by the manufacturer, flood lubrication (27 L/min) and MQL (4 mL/h) were effective, but as the cutting speed increased, tool wear was rapid. Laser-assisted machining led to increased diffusion and adhesion wear. At high speeds, the application of laser had a negative effect on tool life, while at low speeds, the improvement over dry machining was negligible. This is because the material gets plastically deformed due to the laser flows over the rake face. This increases adhesion wear when the material is eventually dislodged. Hybrid method was found to be effective at high speeds compared to all other techniques as MQL in the method could remove the heat generated and thus reduce thermal-related tool wear. Tool life improved by over five times compared to regular laser-assisted machining.

It may be noted from literature, that MQL is not always effective in machining of Ti6Al4V, while works reported for

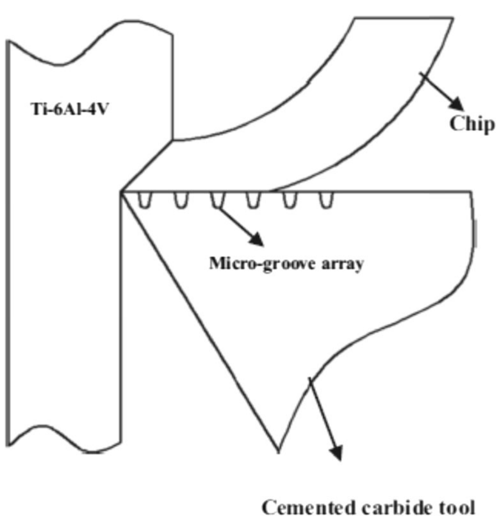

Fig. 11 Cutting tool with grooves [74]

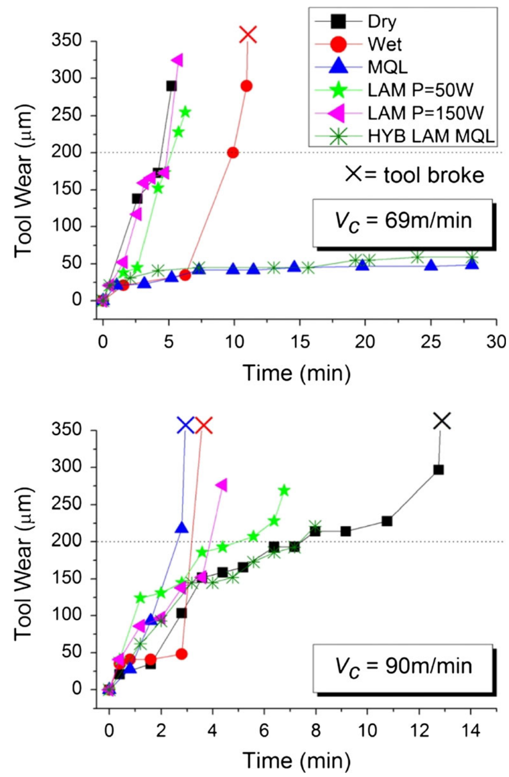

Fig. 12 Tool wear at different cutting speeds [75]

other materials advocate the superiority of MQL. For instance, Da Silva et al. [76] observed that MQL helps in extending the tool life compared to flood lubrication. This gap may be due to the properties of the lubricants considered for MQL, concentration levels, and flow rates, which are not often reported. Nevertheless, researchers have always tried to improve the performance of the MQL lubricants. Davis et al. [77] included 1-butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF_6), a low melting point salt, in MQL lubricant. Pure-grade titanium rods were machined at speed of 120 m/min, feed rate of 0.05 mm/rev, and depth of cut as 0.1 mm with uncoated CBN tools. It may be recalled from earlier discussion that CBN tools are not always preferred due to their affinity to reaction with titanium at high temperatures. Hence, the results from this study are interesting and allow wider range of cutting tools. The tool wear and cutting forces obtained with use of formulated fluid were compared with dry machining and regular MQL. It was found that tool wear reduced with the new formulation by about 60% compared to dry cutting and 15% compared to regular MQL, whereas cutting forces showed deviation of less than 10%. It is reported that formation of lubricating film has helped in reducing the tool wear.

Kolahdouz et al. [78] studied the surface integrity of gamma TiAl alloy machined in dry and MQL conditions (semi synthetic oil at flow rate of 50 mL/h), with cutting speed of 600 m/min for MQL and 300 m/min for dry machining, feed being constant at 0.005 mm/tooth, and depth of cut as 5 mm. It was reported that MQL led to lesser energy consumption compared with dry machining and the parts machined under MQL had better fatigue resistance, due to increased subsurface hardness. Plastic deformation was observed in both cases of lubrication, but for MQL, the depth of deformation was small. Also, MQL resulted in a better machined surface with lesser burrs.

Usually, the cutting fluids either in flood lubrication or MQL are applied in a single direction. In a striking approach, Banerjee and Sharma [79] machined Ti6Al4V using uncoated cemented carbide tools for machining of Ti6Al4V alloy at constant cutting conditions (speed = 76 m/min, feed = 0.24 mm/rev, and depth of cut = 1 mm) and supplied the cutting fluid in three different directions at flow rate of 36 mL/h in each nozzle. Air pressure was maintained at 2.8 and 5.8 bar. The first nozzle supplied the lubricant at the back of the chip, second nozzle on the rake face, and third nozzle on the flank face. Both neat oils and water miscible cutting fluids were used and compared. It was found that supply of the coolant at the rake face and back of chip were beneficial in terms of cutting forces and surface finish. It was proposed that localized flow and control of the lubricants in MQL is more beneficial than the regular strategy. Higher pressure was found to be more advantageous. At the considered cutting conditions, neat oils were found to give better performance compared to water miscible cutting fluids.

It is interesting to note that cutting speeds are not always high with the application of MQL. Sarıkaya and Güllü [80] studied the application of MQL in machining Ti6Al4V under different cutting speeds of 30, 40, and 50 m/min, constant feed of 0.15 mm/rev and depth of cut 0.1 mm. Different process parameters like type of cutting fluid, flow rate, and cutting speed were optimized in the study using Taguchi's method. Different flow rates of 60, 120, and 180 mL/h were considered. It was found that vegetable-based cutting fluid, 180 mL/h flow rate and cutting speed of 30 m/min was the optimal conditions for minimum tool wear. It may be observed that lowest speed and highest flow rate are obtained as optimal conditions. This hints towards the need for a better lubricant. It may be noted that on a work on MQL, Maruda et al. [81] added a chemical additive called Crodafos O4A-LQ-(MH) to the emulsion and applied it in machining. Over 80% improvement in surface finish was obtained. It is reported that the additive helped in formation of a more stable lubricating layer. Such strategies may be used to enhance the properties of the lubricant.

Inclusion of nano/microparticles in the coolants can increase the cooling capabilities of the cutting fluid. Mao et al. [82] added Al_2O_3 nanoparticles in cutting fluid. Upon testing with pin-on-disk apparatus, the friction coefficient was found to decrease by about 34%. It is proposed that the nanoparticles in the formed lubrication film share the normal load and reduces the friction. Also, the particles produce a ball-bearing effect by separating the sliding surfaces and reduce the friction. As the particles separate the surfaces, the plastic deformations caused by shear strength are caused in the nanofluids film but not on the sliding surfaces. This mechanism can drastically reduce the plastic deformation of the tool. It may be recalled that plastic deformation, adhesive, and abrasive wear are the main causes for tool failure in machining of titanium alloy, other than diffusion wear. With the ball-bearing effect, the forms of wear will be drastically reduced. Also, the viscosity of the fluids increases on nanoparticle inclusion. This is another reason for improved lubrication. Nguyen [83] tested the performance of nanofluids with vegetable oils as base fluids and nanographite/nanohexagonal boron nitride inclusions. The nanoparticles were selected as they are solid lubricants with lamellar structure. The structure helps in sliding of the layers over each other and reduces friction. The results were compared with MQL with pure oil and dry machining of Ti6Al4V. It was observed that the MQL with nanoparticles resulted in lesser tool wear and forces. In another work, Nguyen et al. [84] investigated the effect of vegetable oil-based MQL with graphite platelets in milling Ti6Al4V. It was advocated that in view of the micro-sized diameter of the platelets (though the thickness is in nanoscale), the particles are not harmful to humans and can be safely used. It was found that the tool flank wear decreased with the application of nanofluids in MQL compared to pure oil and dry machining.

In a similar work, Moura et al. [85] used two solid lubricants (MoS_2 and graphite) microparticles as inclusions in a synthetic cutting fluid by 20% *w/w*. The coolant was supplied in MQL as mist in machining of Ti6Al4V using TiAlN-coated tools. The average particle size of graphite was 40 and 20 μm while MoS_2 had size of 6 μm. Tool life, surface finish, cutting forces, and temperatures were measured. It was reported that tool wear reduced considerably with the inclusion of the particles (Fig. 13). It is advocated that tool life improves due to the possible penetration of the solid lubricant in the tool/chip interface. Cutting forces and temperatures reduced as a result. Highest temperature was observed in case of dry machining, followed by flood lubrication. Least temperature and tool wear were observed for MoS_2. Among the considered graphite sizes, the lesser size had a better effect.

Setti et al. [86] carried a similar work on grinding of Ti6Al4V alloy under MQL with inclusions of nano Al_2O_3 and CuO as both are known for their high thermal conductivities and cooling abilities. Different concentrations of nanoparticles, not more than 1% were dispersed in water with the help of a surfactant. Different flow rates of 50, 100, 150, 200, and 250 mL/h were considered in MQL. It was observed that over 30–50% reduction in normal force could be obtained for the nanofluids under MQL compared to dry machining. Higher tangential forces in dry machining cause grain break-out, reducing the material removal rate and wheel life.

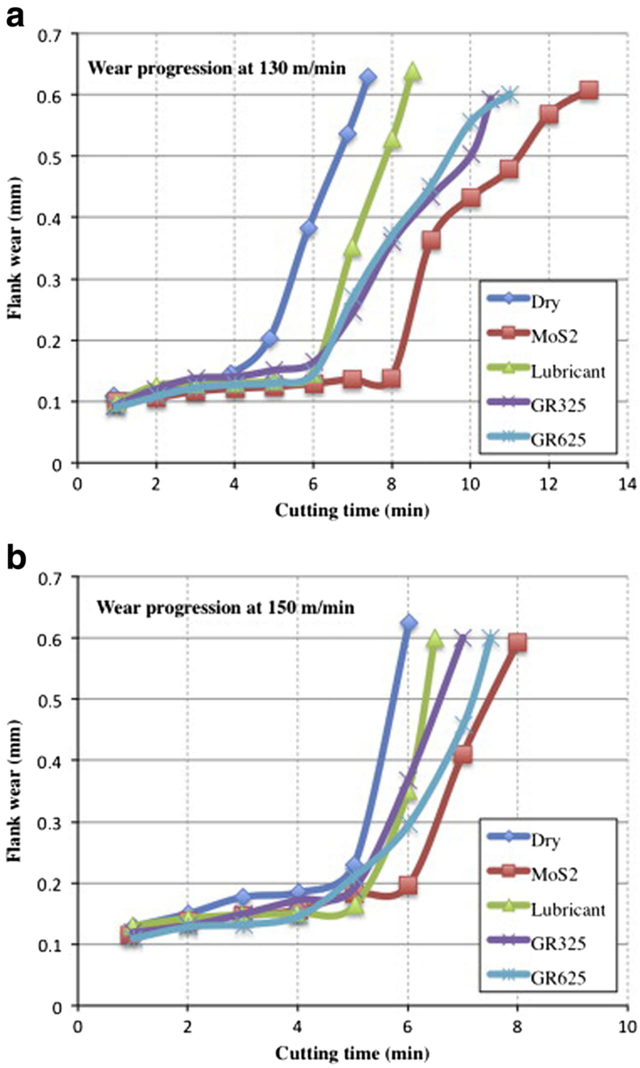

Fig. 13 Tool wear progression [85]

Santosh et al. [87] mixed different concentrations (5, 10, 15 wt%) of hexagonal boron nitride (hBN) with water and applied in MQL for in machining Ti6Al4V using TiAlN-coated tools at different feed rates. Cutting temperatures were compared with those obtained in dry machining. Cutting temperatures drastically decreased with the application of nanofluid compared to dry machining, but the decrease in temperature was almost similar for 10 and 15% concentrations. Hence, 10% was reported as the optimal concentration for sustainable machining.

In almost all the studies reported on application of MQL in machining titanium alloys, MQL was found to be advantageous compared to flood and dry lubrication in terms of performance and ecology. Lesser cutting forces, lesser temperatures, better tool life, and surface finish were observed with the application of MQL. Use of MQL is highly recommended as this strategy eradicates many of the environmental and disposal issues, especially when the cutting fluid is vegetable oil-based. Inclusion of micro/nanoparticles in the cutting fluids is found to increase the performance of the cutting fluids in MQL. It may be noted that nanofluids are not recommended in flood lubrication due to the high cost and low biodegradability [88].

Before moving to the next section, it will be interesting to discuss about the work carried out by Duschosal et al. [89]. Performance of MQL was tested for different tools and inner channels in milling cutter. The channels had orientations of 45°, 60°, and 75°. The internal channels helped in the flow of the lubricant from a central channel to the cutting edge. Though the work concentrated on finding the optimal channel orientation, it gave some interesting inference which can be used for MQL of titanium alloys. It was found the aerodynamic shape of the tool played a significant role in the cooling. Also, it was found that pressure of the MQL jet had a major role in the lubrication. These results are useful for MQL and other forms of cooling like cryogenic cooling. A summary of some of the works on MQL in machining of titanium alloys in provided in Table 3.

2.3 Cryogenic cooling

Cryogenics is the science of study and application of materials below −150 °C. Nitrogen is popularly used in this technique as it is abundant and non-toxic [90, 91]. In order to eliminate the effects of heat and temperature in machining, liquid nitrogen is applied at −196 °C. The application of liquid nitrogen at the low temperature (known as cryogenic cooling) carries away the heat and also provides a cushioning layer between the tool/chip interface, thus reducing the friction. Cryogenic machining is especially helpful to eliminate the failure of tool due to chipping and plastic deformation. Cryogenic cooling is found to effectively reduce the cutting temperatures, even at high cutting speeds. Further, the jet of cryogenic fluid helps to break the chip and thus reduce the chip contact length. Lately, cryogenic cooling is gaining prominence in cooling titanium machining process [92].

In some works, cryogenic cooling is compared with MQL using cooled lubricant (known as minimum quantity cooled lubrication (MQCL)). This technique is not well explored for titanium alloys, and only a few papers are available. This technique has been shown to be effective in reducing the temperatures and facilitate chip breaking due to the low temperatures of the lubricant [93]. Deiab et al. [94] compared different lubrication techniques in machining of Ti6Al4V alloy. Dry machining, flood cooling, MQL, MQCL, and cryogenic cooling were compared at different cutting speeds (90 and 120 m/min) and feeds (0.1, 0.2 mm/rev). The coolants for MQL and MQCL were prepared using rapeseed oil as a sustainable option. It was observed that while MQL/MQCL were better at lower cutting speeds, cryogenic cooling was a better option at higher cutting speeds over 90 m/min (Fig. 14). Similar trends were observed in energy consumption and

Table 3 Summary of research on MQL/MQCL cooling of titanium alloys

Reference(s)	Lubrication	Cutting fluid	Salient features	Observations/contributions	Inferences/remarks
[62], [63], [64], [65]	MQL	Vegetable oils	Tested MQL at different cutting conditions	MQL found to be more effective than dry machining/flood lubrication especially at higher cutting conditions	MQL provides better lubrication due to the cutting fluid reaching the tool/chip interface and forming a strong lubricating film. In flood cooling, most of the action is due to convectional cooling
[66], [67], [70]	MQL	Vegetable oils	Studied tool wear with MQL	Adhesion, abrasion, and attrition wear found. Though thermal cracks were observed, they did not lead to tool failure	MQL helps in better cooling through control of friction. However, many times, the lubricant in MQL is not capable of completely eliminating the damage due to temperatures
[71], [72], [73]	MQL	Vegetable oils	Tool wear mechanisms were studied	Abrasion and adhesion were observed.	MQL helps in better cooling through control of friction
[74]	MQL	Vegetable oils	Formed special tools with grooves on the rake surface	Grooves helped to reduce the tool/chip contact length, hence reduced friction	Tool/chip length is a major contributor to the friction. Further, the grooves may have acted as fins to dissipate the heat from the tool
[75]	MQL	Water-based emulsion	Used laser to thermally soften the work piece. Compared with dry, flood, laser (without MQL)	Laser + MQL helped in significant reduction of forces	Application of pure laser as a softening mechanism increased adhesion wear and led to failure
[79]	MQL	Neat oils and water--based emulsions	MQL supplied through three different nozzles in three directions	Higher pressure and localized control of the fluid gave beneficial results	Application of the fluid on the back of the chip and rake face was found to be the best
[80]	MQL	Vegetable oils	MQL applied at different cutting speeds	Optimal conditions were selected	Lowest values were obtained as optimal values. Hints towards the need of improved lubricant in MQL
[82], [83], [84], [85], [86], [87]	NanoMQL	Variable	Nanoparticles were dispersed in oils and nanofluids were applied as lubricants	Nanofluids helped in better reduction of wear, forces and temperatures compared to MQL	Nanofluids provide a stronger lubricant layer and help in better lubrication. Also, the nanoparticles provide ball-bearing effect and reduce the normal loads on the surfaces
[94], [95]	MQCL	Vegetable oils	Cutting fluids were cooled and applied in MQL	MQCL gave better performance in terms of tool wear and other parameters	MQCL uses cutting fluids with reduced temperatures and hence helps in better cooling of the machining zone. It has all the advantages of MQL, with the advantage of cooled lubricant

surface roughness. In a similar work, Raza et al. [95] machined Ti6Al4V using uncoated carbide tools under MQL, MQCL, dry, cooled air, flood, and cryogenic cooling. Machining was done at 90 and 120 m/min cutting speed. At lower speed, MQCL gave the best performance in terms of tool wear, other than flood lubrication. Micro chipping and abrasion are least in MQCL. BUE was very small for MQCL, due to improved lubrication. Diffusion wear was very low for MQCL due to reduced temperatures. However, at higher speed, cryogenics outperformed other options. This could be because of the high temperatures prevalent, which could not be controlled by other means. In all cases, cooled air led to higher abrasion than the other methods, due to the absence of a lubricant. Summary of MQCL research is included in Table 3.

Kanyak et al. [96] compared dry machining, MQL, and cryogenic cooling in machining of three different NiTi alloys. It was found that cryogenic cooling resulted in consistently lesser tool wear compared to the other two techniques. As shown in Fig. 15, tool wear increased in MQL after 4 min of machining. This is contrary to the belief that MQL lubricates the tool/chip interface. The reason for increase in tool wear was attributed to chipping of the tool nose. Abrasive wear mechanism was found to be prominent on the tool. Abbasi and Pingfa [97] studied four different types of cooling systems: flood lubrication with water miscible fluids, neat oils, MQL and cryogenic cooling in machining Ti6Al4V alloys with coated carbide cutting tools. Cutting temperatures, forces, and stresses on tool edge were observed. It was reported that cryogenic cooling led to lowest cutting temperatures,

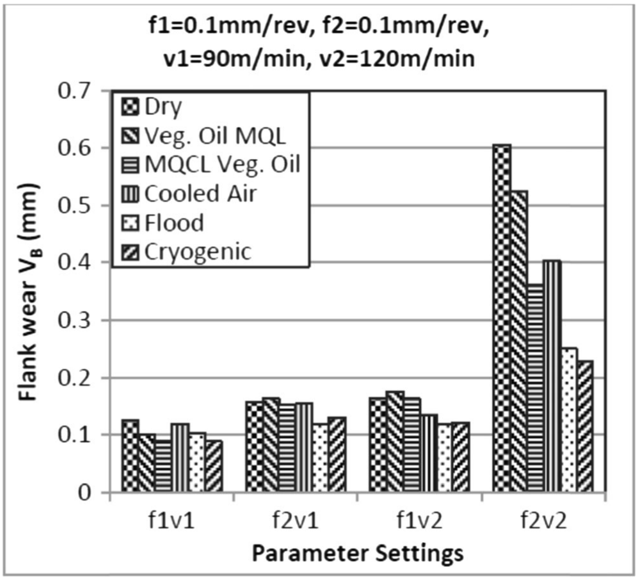

Fig. 14 Tool wear at different lubrications [94]

forces, and stresses among the considered alternatives. The results were validated with finite element analysis. Similar approach was followed by Sun et al. [98] who compared the cryogenic cooling in machining of Ti5553 alloy with flood lubrication and MQL. Nearly 30% reduction in cutting forces was reported with the use of cryogenics compared to MQL. This was explained to be due to lesser adhesion on the rake face of the tool in cryogenic cooling. Highest reductions in forces were observed at low feed rates due to smaller cutting temperatures and better cooling due to longer cutting time. Also, lesser tool wear was observed while using cryogenic cooling.

Park et al. [99] tested cryogenic cooling, nano-MQL (ester-based cutting fluid with nanoparticles) and flood lubrication in machining of Ti6Al4V. Also, the effect of internal and external spray methods of the cryogenic coolant was examined. Tool wear and cutting forces were measured in all cases. It was observed that nanoMQL + internal cryogenic cooling improved tool life by over 32% compared to flood lubrication. Cutting forces were also found to be low with this cooling method. It may be noted that in this lubricating system developed, cryogenic cooling reduces the temperatures, while nano-MQL provides the necessary lubrication. Lin et al. [100] applied water-soluble oils both internally and externally on the tool and compared the results with cryogenic MQL (−16 °C) in machining Ti6Al4V alloys at different speeds: 70, 90, and 110 m/min. Chip morphology, cutting forces, cutting temperatures, surface roughness, and tool wear were measured in all the cases. Tool wear was found to be similar for internally applied cutting fluid and cryogenic cooling. It was hypothesized that the lubricating strategy developed resulted in smaller droplets compared to other lubrications and hence leads to better results. Also, the formed lubricating film is stable at low temperatures. It is interesting to note the observation that the type of lubricant has little effect on the tool wear rate. It was suggested that coated tools are better than the uncoated tools in machining the alloys. At this point, it is worth mentioning about the work carried out by Maruda et al. [101]. They focused on assessing the influence of droplet size on the cooling abilities of lubricants in MQCL. A specially formulated mineral oil-based lubricant, called EMULGOL was used in the study. It was observed that the droplet size decreased with increase in air flow and thus the number of droplets increased. This led to increased wetting surface area. An interesting observation was made that the mass flow rate of the emulsion has no influence on the diameter of the droplet. Also, increasing the nozzle distance decreased the droplet diameter. These results are useful to set the air flow rate and nozzle position to achieve good lubrication in MQCL/MQL. It may be noted that the results are in line with the results claimed by Duchosal et al. [89].

Davoudinejad et al. [102] simulated dry and cryogenic

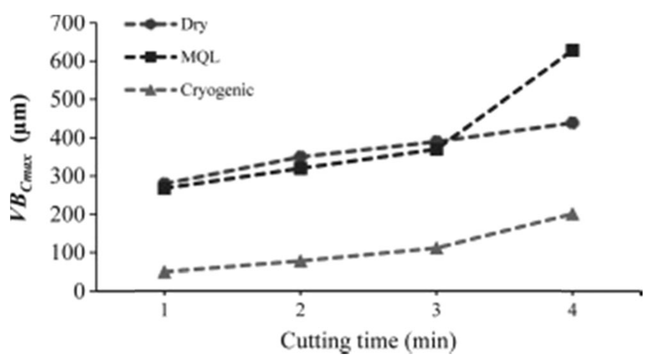

Fig. 15 Progression of tool wear [96]

cooling in machining of Ti6Al4V by using TiAlN-coated carbide inserts and validated the results using experimentation. It was reported that coefficient of friction is lower with cryogenic cooling. However, low values of cutting speed, viz. 40 and 50 m/min were considered. This study uses composite coatings on the tools, which are not commonly used. In an interesting work, Strano et al. [103] machined Ti6Al4V using three different tools, viz., uncoated tungsten carbide tool, tungsten carbide with TiAlN coating, and third tool with the TiAlN layer hardened by cryogenic cooling. Machining was done at speeds from 60 to 79 m/min at low speed; all the three tools gave similar performance. However, with increase in speed, the uncoated tool failed. At highest speed, the second tool failed due to delamination of coatings. However, the third tool sustained the speeds. Adhesive wear was observed for all tools. Similar results are reported by Thamizhmanii et al. [104].

Bordin et al. [105] compared cryogenic cooling and dry machining of Ti6Al4V. Two jets of liquid nitrogen were

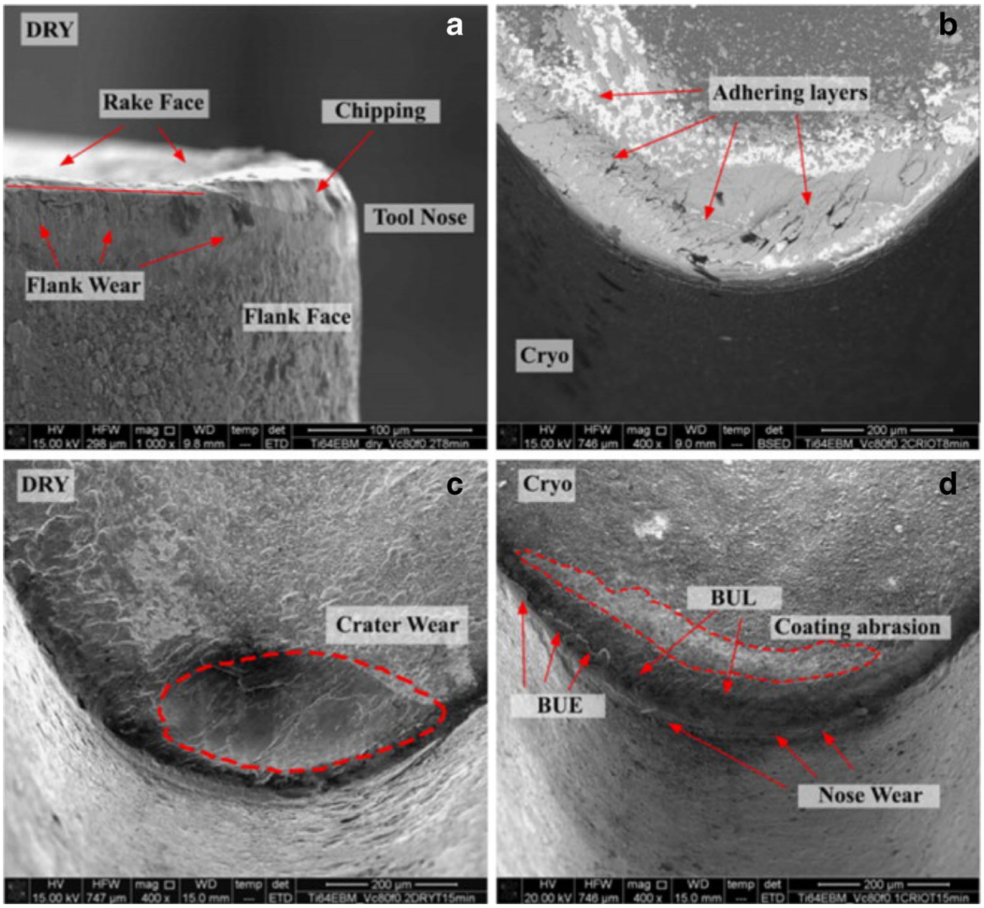

Fig. 16 Tool wear mechanisms [105]

focused on the rake and flank faces of the tool. Tool wear and surface roughness were monitored in the study. It was reported that adhesion was the dominant mechanism of tool wear, followed by abrasion (Fig. 16). Cooling by the liquid nitrogen on the rake face reduced the thickness of adhered layer and reduced crater wear compared to dry machining. Also, cryogenic cooling provided better surface finish compared to dry machining. Shokrani et al. [106] applied cryogenic cooling at different flow rates to cool Ti6Al4V machining process. Machining was done at different cutting conditions. Taguchi's technique was used to minimize the number of experiments. It was reported that cryogenic cooling at 20 kg/h drastically reduces tool wear at the considered cutting conditions. It is suggested that as tool wear is low with cryogenic cooling, higher cutting speeds can be used for reasonable tool life and attain increased productivity.

Lee et al. [107] performed cryogenic cooled milling Ti6Al4V with preheated work piece. It was reported that as cutting forces increased in preliminary experiments due to work piece hardening at cold temperatures, preheating was adopted. Preheating decreased the forces by about 65% compared to dry machining. Tool life increased by 50% in cryogenic cooling and by 90% in cryogenic + preheating compared to dry machining. Also, curved chips were observed with preheating leading to reduced friction. Priarone et al. [108] studied the machinability of Ti-43.5Al-4Nb-1Mo-0.1B alloy with coated/uncoated carbide tools, CBN and PCD cutting tools under flood lubrication and cryogenic cooling at constant cutting conditions (speed = 80 m/min, feed = 0.1 mm, depth of cut = 0.25 mm). Six percent emulsion was chosen as the cutting fluid. Under conventional cooling, uncoated tools had least tool life of 2 min, while PCD tool has life of 14 min. It is important to mention that such small values of tool life are obtained as the authors chose the limiting value of flank wear as 0.1 mm, whereas the ISO suggested general value is 0.6 mm. In all tools, abrasive wear was observed. In case of cryogenic cooling, PCD tools had life of about 30 min. The superior performance of PCD tools was attributed to the high thermal conductivity of tools which prevents accumulation of heat in the tool.

Sun et al. [109] studied the effect of cryogenic cooled air while machining Ti6Al4V at two cutting speeds, 150 and 220 m/min. Compressed air was sent at −196 °C. It may be noted that higher speeds than the usual practice are seen to estimate the performance of the lubrication. The results were compared to dry machining. Severe wear and BUE was observed in dry machining. This was attributed to the chemical reaction of the tool (uncoated carbide) with titanium. This phenomenon was found to be more significant at higher cutting speed. This was attributed to decreased plastic deformation because of cryogenic cooling. With the help of cryogenic cooling, tool life could be increased by about 37% at cutting speed of 150 m/min. The cause for failure of tool at this speed was flank wear, whereas, at 220 m/min, tool failed due to plastic deformation in dry machining. With the use of cryogenic cooling, plastic deformation was suppressed and tool life increased by over 100%. The reason for increased tool life was attributed to reduced chip contact length that results in reduced temperatures. This has also led to reduced cutting forces.

Machai et al. [110] applied CO_2 snow (−80 °C) at rake face, flank face, both rake and flank faces, combination of CO_2 snow + MQL (biodegradable oil at 30 mL/h) and flood lubrication while cutting grooves in β-titanium alloy. Cutting forces, tool wear, and temperatures were monitored. Up to cutting speed of 140 m/min, cutting force decreased with increase in speed due to thermal softening. But beyond 140 m/min, force increased. CO_2 snow cooling on flank face gave best results compared to other approaches. Since compressed CO_2 is cheaper than liquid nitrogen, the practicality of the results was advocated. In a similar study, Biermann et al. [111] machined two different alloys of titanium, viz., Ti6Al4V and high-strength titanium alloy Ti6246 using MQL, flood lubrication, and cryogenic cooling with CO_2 snow at −79 °C. It was reported that cryogenic cooling resulted in lesser tool wear while machining Ti6Al4V but had no effect above cutting speed of 80 m/min. Hence, a combination of cryogenic and MQL was applied to reduce tool wear. This resulted in a smoother chip underside and reduced friction.

Ahmed et al. [112] drilled titanium ASTM B265 grade 2 material with PVD-coated carbide inserts under flood lubrication and cryogenic cooling at different speeds and feeds. Cutting temperatures, thrust force, and surface roughness and hole quality (form features) were measured. It was reported that cryogenic cooling reduced the temperatures up to 59%; however, cutting forces were high and poor hole quality was observed. The extreme cooling was supposed to have caused dimensional/form inaccuracies. Research related to cryogenic cooling in machining of titanium alloys is summarized in Table 4.

From the available works, it can be seen that cryogenics demonstrate satisfactory performance in terms of tool wear and cutting temperatures. However, extreme cooling causes some disadvantages like hardening of the work piece. This is reported to cause increased cutting forces and poor dimensional quality of the work piece. Hence, cryogenic cooling is not always looked upon as a solution for cooling in machining of titanium alloys.

3 Conclusions

Titanium and its alloys are extensively used in different engineering and biomedical applications. Among the available alloys, Ti6Al4V is used in a majority of the applications and a large quantum of literature is devoted to the studies on this alloy. Based on the literature, the following conclusions may be drawn:

1. Due to the high hardness and low thermal conductivity of the alloy, high temperatures are generated during

Table 4 Summary of research on cryogenic cooling of titanium alloys

Reference(s)	Cutting fluid	Salient features	Observations/contributions	Inferences/remarks
[96], [97], [98], [99]	Liquid nitrogen	Liquid nitrogen was applied at high pressures	Cryogenic cooling provided better lubrication compared to other forms	Cryogenic cooling helps in better chip breaking and effectively reduces the friction, apart from providing the necessary cooling. Almost all the works reported adhesive and abrasion wear, but no record of diffusion wear can be observed
[107]	Liquid nitrogen	Work piece was preheated before cutting	Preheated work piece was used. This led to reduction of cutting forces	Preheating of the work piece led to thermal softening of the work piece and resulted in reduced cutting forces. This was necessary to reduce the hardening effects of cryogenics on the work piece
[111]	Liquid nitrogen + emulsion	Cryogenics, cryogenics + MQL were applied and tested	Cryogenics were found to not much effective at high temperatures, so a combination was used	At higher temperatures, the effect of hardening is more dominant
[112]	Liquid nitrogen	Drilling was done with PVD tools under cryogenic cooling	The surface of holes was damaged due to extreme cooling	Extreme cooling causes work hardening and can damage the work surface

machining and the heat is contained in the cutting tool. This leads to increased tool wear and poor quality of the work piece.

2. Coated tools are preferred over uncoated tools due to better protection of the tool from reacting with the work material. Uncoated tools are sometimes reported to have tool life less than 1 min.
3. The composition of the alloy, microstructure, metallurgical phase of the material, and method of processing of material greatly affect the machinability. Finer micro structure leads to greater machinability of the alloys.
4. Due to poor machinability, low cutting speeds, feeds, and depths of cut are permissible in machining of titanium alloys. Usually, speeds less than 60 m/min are preferred. Some works have reported that cutting speed of 80 m/min is advantageous. Higher values of feed lead to damaged surface and are not preferred. Depth of cut has to be kept low for increased tool life. This leads to decreased productivity. Hence, several researchers have worked on finding solutions to the problem.
5. Cutting fluids are conventionally used to cool the machining zone. However, low pressure jets cannot penetrate through the vapor formed due to high temperatures.
6. Use of pressurized jet of cutting fluid is recommended in literature to reduce the temperatures.
7. Though cutting fluids cool well, not much lubrication is provided as most of the coolant is not directed to the machining zone. Also, cutting fluids cause several health and environmental issues.
8. As an alternative, MQL is used as a strategy to cool and lubricate the machining zone. The reported works advocate better performance of MQL compared to dry machining and flood lubrication. The cutting fluid in the MQL reaches the tool/chip interface through capillarity and forms a film at the interface. This helps in lubrication and reducing temperatures.
9. It is often reported that conventional lubricant in MQL is not effective enough to combat the friction and associated effects. Hence, several blends of cutting fluids, including vegetable oils and synthetic fluids, are developed for MQL.
10. Addition of micro and nanoparticles was found to be advantageous compared to regular fluid. Nanoparticles like CuO and Al_2O_3 and solid lubricants like graphite is found in literature. However, due to high cost, the use of nanofluids is often restricted.
11. MQCL is a variant of MQL which is reported to have promising results compared to MQL. Better cooling capabilities help in reducing the problems associated with machining of titanium alloys.
12. Cryogenic cooling is an effective alternative to the cutting fluids/MQL. Better tool life and surface finish of the product, lesser forces, etc. are observed with the use of cryogenic cooling. Chip breaking is effective in cryogenic cooling and results in smaller chip contact length, reducing friction.
13. Hardening effects of cool N_2 jet lead to increased hardness of the work piece and hence produces higher cutting forces. Further, cryogenic cooling causes issues like dimensional inconsistencies and poor product quality due to extreme cooling.

Future work may be directed towards newer blends of lubricants for MQL and design of new tools for sustainable machining of titanium alloys.

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