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ORIGINAL ARTICLE

Minimal quantity lubrication-MQL in grinding of Ti–6Al–4V titanium alloy

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Abstract Titanium and its alloys are attractive materials due to their unique high strength–weight ratio that is maintained at elevated temperatures and their exceptional corrosion resistance. The major application of titanium has been in the aerospace industry. On the other hand, titanium and its alloys are notorious for their poor thermal properties and are classified as difficult-to-machine materials. The problems that arise during grinding of titanium alloys are attributed to the high specific energy and high grinding zone temperature. Significant progress has been made in dry and semidry machining recently, and minimal quantity lubrication (MQL) machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics. A number of studies have shown that MQL machining can show satisfactory performance in practical machining operations. However, there has been few investigation of MQL grinding of special alloys like titanium alloys and the cutting fluids to be used in MQL grinding of these alloys. In this study, vegetable and synthetic esters oil are compared on the basis of the surface quality properties that would be suitable for MQL applications. The cutting performance of fluids is also evaluated using conventional wet (fluid) grinding of Ti–6Al–4V. As a result, synthetic ester oil is found to be optimal cutting fluids for MQL grinding of Ti–6Al–4V.

Keywords Grinding · Near-dry grinding · MQL · Ti–6Al–4V titanium alloy · Surface quality · Grinding forces

1 Introduction

In metal cutting processes, the use of cutting fluids is the most common strategy to improve the tool life, the product surface finish, and the size accuracy. Cutting fluids also make chip-breaking and chip-transport easier. However, the introduction of cutting fluids often produces airborne mist, smoke, and other particulates in the shop floor air quality. These products bring the environmental, health, and safety concerns. In addition, the cost of using cutting fluids is several times higher than tool costs. Therefore, the conventional cutting fluids utilized in grinding are considered a problem for manufacturers since these substances can seriously damage human health and environment. Environmental concerns have become increasingly important to productive processes, allied with their economic and technological aspects. Large quantities of emulsion-based cooling fluids for machining are still widely used in the metal working industry, generating high consumption and discard costs and impacting the environment. The increasing need for environmentally friendly production techniques and the rapid growth of cutting fluid disposal costs have justified the demand for an alternative to machining processes using fluids [1–4]. Dry machining and minimum quantity lubricant (MQL) machining have become the focus of attention of researchers and technicians in the field of

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machining as an alternative to traditional fluids [1–7]. Silva et al. [1, 2] investigated the effects of grinding parameters on ABNT 4340 steel using MQL technique. They found that the surface roughness, diametral wear, grinding forces and residual stress improved with the use of the MQL system in grinding process due to better lubrication of grinding zone and providing better slipping of grain at the contact zone [1]. The specific function of cutting fluid in the machining process is to provide lubrication and cooling to minimize the heat produced between the surface of the part and the tool [1]. However, by eliminating these fluids, their positive influence on machining is also lost since cutting fluid is an important technological parameter in machining [1]. Their drastic reduction or even complete elimination may undoubtedly lead to increased temperatures in these processes, decline in cutting tool performance, loss of dimensional precision and geometry of the parts, and variation in the machine's thermal behavior [1–5]. When abrasive tools are used, a reduction in cutting fluid can make it difficult to keep the grinding wheel's pores clean, favoring their tendency to clog and thereby aggravating the aforementioned negative factors [1]. The relative importance of each of the functions also depends on the material being machined, the type of tool employed (defined or undefined geometry), the machining conditions, the surface finishing, and the dimensional quality and shape required [1–9].

This paper deals with an investigation of the grind ability of titanium alloy Ti–6Al–4V with MQL technique. The experiments, conducted under different grinding environments, showed the performance of the grinding fluids based on an evaluation of grinding surface quality. It could be found that grinding fluids like MQL with vegetable and synthetic oil are preferable compared to conventional soluble oil with AL_2o_3 wheel. The purpose of this work is to evaluate the performance of the MQL technology applied to minute flow rates as an environmentally correct alternative for the cutting fluid used in surface grinding of Ti–6Al–4V titanium alloy. The small amount of lubricant is atomized in a compressed air stream, reducing the undesirable effects by supplying lubricant and cooling. The evaluation of the technical performance of MQL in the grinding process consisted of experimentally analyzing the behavior of the surface roughness, surface and subsurface microhardness, and metallurgical analysis.

2 Minimum quantity lubricant (MQL) and titanium alloys

Minimal quantity lubrication (MQL) or semi dry machining has been accepted as a successful near dry application because of its environmentally friendly characteristics, based on environmental preservation and the research for conformity with the ISO 14000 standard. But in metal cutting, cooling and lubricating of machining contact zone between tool and work piece are still essential to the economically feasible service life of tools and the required surface qualities [1–13]. This makes the minimum quantity of lubrication an interesting alternative because it combines the functionality of cooling with an extremely low consumption of fluids (usually <100 ml/h) [1]. These minimal quantities of oil suffice, in many cases, to reduce the tool's friction and to prevent the adherence of materials. The minimization of cutting fluids has gained increasing relevance in the past decade [1, 5, 10, 11]. The limitations of dry operations can be overcome, in many cases, through the introduction of minimum quantity lubrication systems (near-dry machining-MQL) that act based on the principle of total use, without residues, applying lubricant flows from 10 up to a maximum of 100 ml/h at a pressure from 4.0 to 6.5 bar [1]. In this technology, the lubricating function is ensured by the oil, and the cooling function is provided mainly by the compressed air [1, 2]. This small amount of fluid suffices to reduce friction in cutting, diminishing the tendency of adhesion in materials with such characteristics. A comparison with conventional cooling revealed numerous advantages [1, 8, 11, 15]. Minimum quantity lubrication systems employ mainly cutting fluids that are nonsoluble in water, especially mineral oils [1]. Due to the very small amounts of cutting fluids used, one must consider that the costs should not prevent the use of high technology compositions in the field of basic and additive oils [1]. Vegetal-based materials are being increasingly used. These oils, inhaled in the form of aerosol, reduce the health hazard factor [1, 6, 13]. Hafenbraedl and Malkin [16] found that the MQL technique provides efficient lubrication, reducing the grinding power and the specific energy to a level of performance comparable or superior to that obtained from conventional soluble oil (at a 5% concentration and 5.3 l/min flow), while at the same time, it significantly reduces grinding wheel wear. However, MQL presented slightly higher superficial roughness values (Ra). The grinding performance was also evaluated in the dry condition. The results with MQL were obtained in the plunge cylindrical grinding process using quenched and tempered AISI 52100 steel with an average hardness of 60 HRC using an aluminum oxide grinding wheel. Titanium alloys were developed in order to satisfy the need for a class of strong and lightweight materials for aircraft engine and airframe manufacture because of their outstanding strength to density ratios. They possess exceptional resistance to corrosion, which provides savings on protective coating like paints that will otherwise be used in the case of steel. Titanium alloys can also be used as airframe structure where the operating temperature exceeds 130°C, the

Table 1 Composition of Ti–6Al–4V

Content	C (Max)	Fe (Max)	N (Max)	O (Max)	Al	Si (Max)	*V*	H (Max)	Ti
Composition (wt.%)	0.1	0.3	0.05	0.15	5.5–6.8	0.15	3.5–4.5	0.015	Balance

conventional maximum operating temperature for aluminum alloys [17]. In aero-engines, titanium alloys are widely used in both low- and high-pressure compressors and for components subjected to high centrifugal loads such as disks and blades that have reduced flow diameters as well as for components which operate under severe fatigue conditions [17]. However, it is very difficult to machine these alloys. Among all titanium alloys, Ti–6Al–4V is most widely used. Thus, it has been chosen as the work piece material in this study, which specially is Ti–6Al–4V bar (ASTM B265 Grade 5). Its nominal composition (weight percent) and mechanical properties are shown in Tables 1 and 2, respectively [17].

Due to the poor thermal properties of titanium alloys, most of the heat that is generated during the intense cutting deformation process is concentrated in a very narrow area of the primary cutting band, described under the preceding headings [18]. During the chip segment formation stage, the intense cutting action existing between this segment and the one that has just been generated makes the latter slide through the tool rake face, starting at its very nose, so that most of the heat generated in the tool itself is dissipated [18]. This hot surface, with a high degree of cutting in contact with the tool surface, causes a very quick chemical reaction, and it is, without any doubt, responsible for the great wear on the tool rake face [18].

Encouraging results had been observed in grinding, milling, and turning applications. These improvements in machining can be attributed to the lubricating oil that was able to get very close to the tool-chip and tool–work piece interfaces under pressure, therefore reducing friction and component forces generated during machining [19]. Temperature reduction at the grinding contact zone in MQL systems is achieved mainly by the cooling effect of the compress air and partially by evaporation [19]. Significant amount of heat is absorbed to effect the evaporation of the lubricants, thus contributing to a significant temperature reduction at the cutting zone [19]. Pressure welding of chips to the cutting edge is the main cause of tool failure when milling titanium alloys with HSS tools [19]. With MQL, this failure mode can be drastically reduced, causing significant improvement to surface finish of the machined components [19]. The MQL system has shown encouraging potentials for precision machining at low-feed and high-speed conditions [19]. Literature review shows the lack of study on grinding of Ti–6Al–4V using MQL system instead of conventional wet grinding. Therefore, it is necessary to study MQL grinding and investigation MQL parameters and oils on grinding performance.

3 Experimental procedure

The tests were carried out with aluminum oxide (Al_2O_3) grinding wheels having the following characteristics at grinding conditions in Table 3: grinding wheels code 91A46I8AV produced by the Golpasab Company (Iran) grinding wheel manufactured with a vitrified binder. The dressing operation was kept constant in all the tests, using a six-point diamond dresser (dressing speed (V_d)=5 mm/s, total depth of dressing (a_d)=0.03 mm). Plates of alpha–beta Ti–6Al–4V alloy with dimensions 50 mm×20 mm×10 mm were prepared for these grinding experiments. MQL grinding tests were done through the 20-mm width using FAVRETTO MB100 CNC surface grinder. There are few indications of cutting parameters for MQL conditions, and there are no indications of these numbers for grinding Ti–6Al–4V. A series of preliminary tests was carried out to determine the best lubricant and compressed air flow ranges, as well as the best choice of the various types of lubricants using the MQL technology. Four types of lubricants manufactured by Behran Oil Company (Iran) were subjected to preliminary testing (vegetable oil, synthetic oil, Behran cutting oil 34, and Behran cutting oil 53). Vegetable and synthetic oil lubricants supplied by the Behran oil Company displayed the best surface quality performance; therefore, all the results reported here refer to these two types of lubricant. The equipment utilized to control the MQL was the sophisticated home-made MQL system (Fig. 1), which uses the oil supply pump system and allows the compressed air and lubricant flows to be adjusted separately and allowed the quantification of the

Table 2 Mechanical properties of Ti–6Al–4V

Work piece material	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Modulus of elasticity (GPa)	Hardness (HV)
Ti–6Al–4V	993	830	14	114	265

Table 3 Grinding conditions

Grinding mode	Plunge surface grinding, down cut
Grinding wheel	Al_2O_3 (91A46I8AV)
Grinding machine	FAVRETTO MB100 CNC surface grinder
Wheel speed (V_s)	V_s=15 m/s
Work speed (V_w)	V_w=20, 30, 40 m/min
Depth of cut (DOC)	a=0.002, 0.005, 0.007 mm
Environments	Wet and MQL
Conventional wet grinding fluid	Soluble oil (Blaser BC35) in a 5% concentration
MQL flow rare	Q=20, 40, 50, 60, 70, 100, 140 ml/h
Air pressure	P=3, 4, 5, 6 bar
MQL oil	Vegetable oil, synthetic oil, Behran cutting oil 34, and Behran cutting oil 53
Work piece material	Ti–6Al–4V (50 mm×20 mm×10 mm)
Dresser	Six point diamond dresser
Dressing depth	Total depth of dressing (a_d)=0.03 mm
Dressing speed	V_d=5 mm/s

effectiveness of the proposed method. The jet of MQL was delivered at the grinding zone, as shown in Fig. 1, through the specially designed nozzles of nominal diameter 2 mm at a pressure of 4 bar, which impinge on the surface of the job from a distance of 45 mm. The creation of the nozzle allowed oil and compressed air mist to penetrate effectively into the grinding contact zone, favoring their lubrication and cooling. The input parameters [grinding wheel cutting speed (V_s), peripheral work piece speed (V_w), grinding depth (a), MQL flow rate (Q), and compressed air pressure

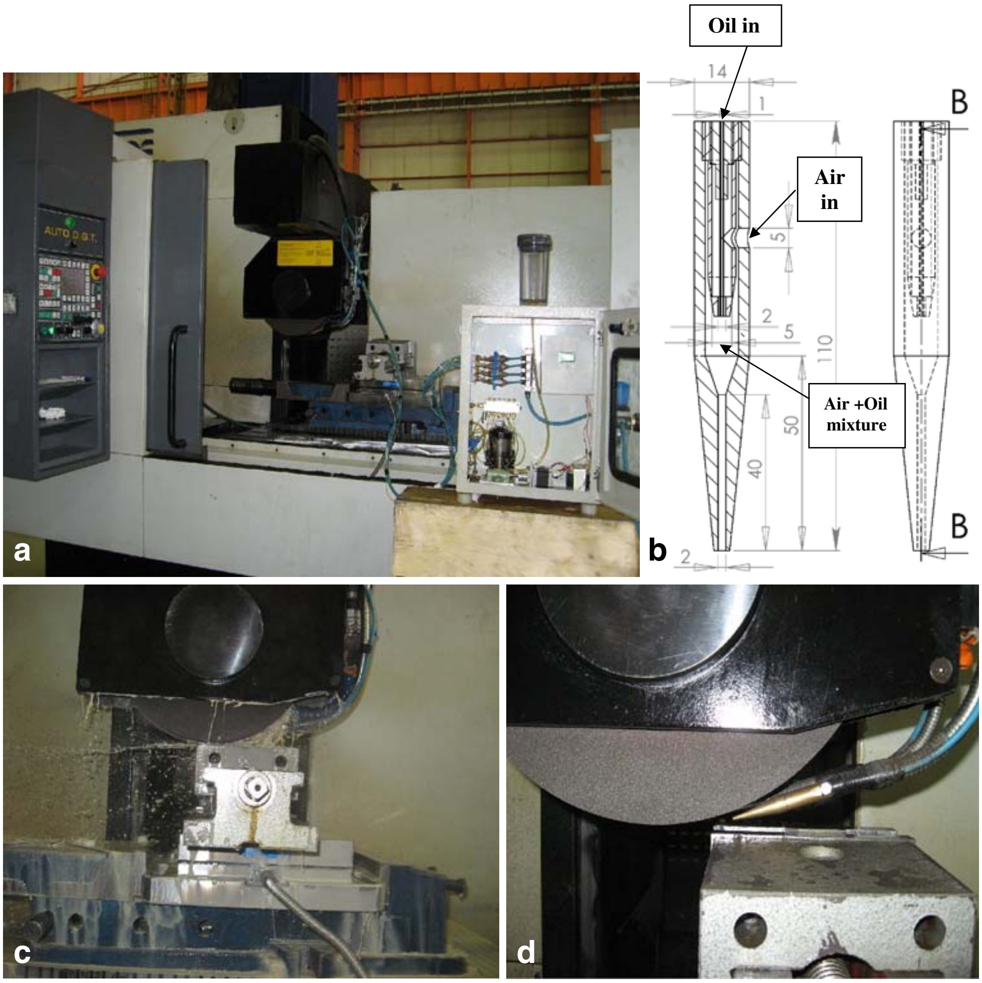

Fig. 1 Experimental set up: **a** MQL equipment and CNC surface grinder, **b** nozzle designed for MQL experiments (all dimensions are in mm), **c** conventional flood grinding process, **d** set up showing the location of nozzle near the wheel and work piece contact zone

(*P*)] were selected based on preliminary testing. The cutting conditions selected after testing preliminary to the definitive tests were: V_s=15 m/s; V_w=40 m/min (average speed); *a*= 0.002, 0.005, 0.007 mm; *Q*=20, 40, 50, 60, 70, 100, 140 ml/h; and *P*=3, 4, 5, and 6 bar. Soluble oil (Blaser BC35) in a 5% concentration was used in the conventional cooling condition. The maximum flow supplied by the pump and by the machine's original nozzle was 8.4 l/min. Before each experiment, the wheel was dressed in conditions mentioned above. The surface roughness and metallurgical analysis were performed after the fifth pass. The work piece roughness was measured by Mahr Perthometer (mobile roughness measurement) with a cut-off length of 0.8 mm (according to DIN EN ISO 3274:1998). At the end of each test, the arithmetic mean roughness values, Ra, were measured at five different points of ground surface.

Surface morphology and subsurface of ground part investigation were performed on a Philips model XL Series (XL30), and microhardness of the machined surfaces were measured across the cross-section of the ground work pieces on Bohler microhardness tester. The load during measuring the microhardness was 981 mN. The grinding force components were recorded using a piezo-electric transducer-based dynamometer (type Kistler 9255B) positioned under the work piece clamping system.

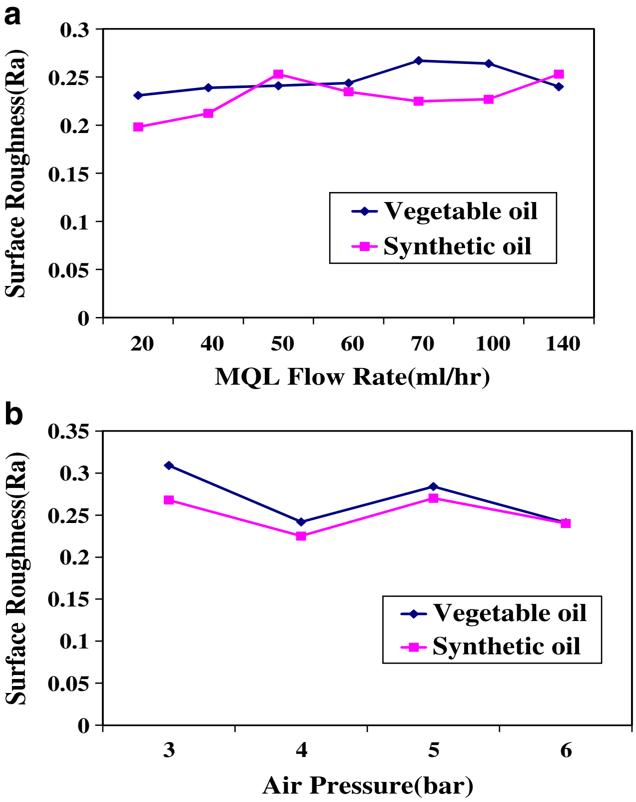

Fig. 2 Effects the MQL modes on surface roughness (grinding experiments were conducted with V_w=40 m/min, V_s=15 m/s, DOC= 0.005 mm and **a** *P*=4 bar, **b** *Q*=60 ml/h)

4 Results and discussion

Surface quality is usually characterized by surface roughness, oxidation, scaling, residual stresses, burning, microcracks, microstructural changes, and plastic deformation [1, 2]. The results below refer to the best cutting, lubrication, and cooling conditions found in the surface grinding of Ti–6Al–4V alloy for performances evaluated here.

4.1 Surface roughness of the ground part

It is well known that the surface finish can significantly affect the mechanical strength of components when the latter are subjected to fatigue cycles [1]. Figure 2 compares the mean values of the Ra parameter with the Al_2O_3 grinding wheel using MQL technique with vegetable and synthetic oil vs. MQL flow rate and compressed air pressure. The values were obtained after five stages, each pass of 0.005 mm with work speed of 40 m/min and wheel speed of 15 m/s. In order to investigate the MQL flow rate, the pressure was kept at 4 bar and in the stage of compression of compressed air pressure effects on MQL performance and the MQL flow rate was kept at 60 ml/h. Five measurements were taken of the Ra variation in different positions of machined parts. The surface roughness of a machined part is mainly affected by the size of the abrasive grain, dressing conditions, material removal rate, and lubrication and cooling conditions [1]. Figure 2a shows that the application of synthetic oil in MQL grinding gives the better surface finish than vegetable oil. In the other hand, by increasing MQL flow rate, surface roughness increases up to 100 ml/h flow rate, and then it decreases for vegetable oil and for synthetic oil; by increasing MQL flow rate, surface roughness of ground pieces increases until 50 ml/h, then it decreases until 60 ml/h, and after, it increases until 140 ml/h. However, in 140 ml/h flow rate, the surface roughness values of both types of oil are the same. Additionally, it can be seen from Fig. 2b that by increasing compressed air pressure, surface roughness decreases until 4 bar, then increases until 5 bar, and then decreases in 6 bar. In this case, the lower normal and tangential forces and lack of burning were observed in the 60 ml/h flow rate and 4 bar conditions; therefore, the following experiments for comparison of MQL and wet grinding were done at *Q*=60 ml/h and *P*=4 bar. Figure 3 compares the Ra parameter in grinding of Ti–6Al–4V using the conventional (flooding or wet) condition against those obtained with MQL technique. The values were obtained with difference depths of cut (DOC) and work speeds (V_w).

It can be shown that in the conditions with constant DOC, in small work speed, the surface roughness values of MQL are comparable with those from wet grinding. Additionally, in the conditions with constant work speed, in high DOC values, the surface roughness of MQL is comparable or better than those from wet grinding. Generally, it can clearly be seen that the application of MQL grinding did not give the expected results in respect to the surface roughness. Figure 3 shows that for MQL grinding, the roughness values are greater throughout the experimental domain. In MQL grinding, the lubrication is expected to be higher than for dry and wet grinding, which makes the tangential cutting force values decreased as the test progressed, improving the slipping of the grains between the tool and the piece. On the other hand, the peripheral velocity of the piece was reduced since its rotation was kept constant, providing a lower tangential cutting force. In this case, the grits retain sharpness for a longer period, and thus, metal removal takes place mostly by shearing and fracturing, producing sharp ridges and hence more roughness. In dry and wet grinding, there is a certain stabilization of the tangential cutting force, possibly through the loss of the material removal capacity, that plastic deformation of the high ridges takes place, which is evident from scanning electron microscopy (SEM) micrographs. This behavior allows to state that the MQL system was able to more efficiently penetrate into the region of contact between the grinding wheel and the piece. Also, it is important to emphasize that the dry condition in grinding of Ti–6Al–4V caused the work piece to become very hot, making it impossible to remove it from the machine without protective gloves and resulted to work piece burnout. Very high temperatures cause thermal dilation of the part, which may lead to imprecision in its diameter, impairing one of

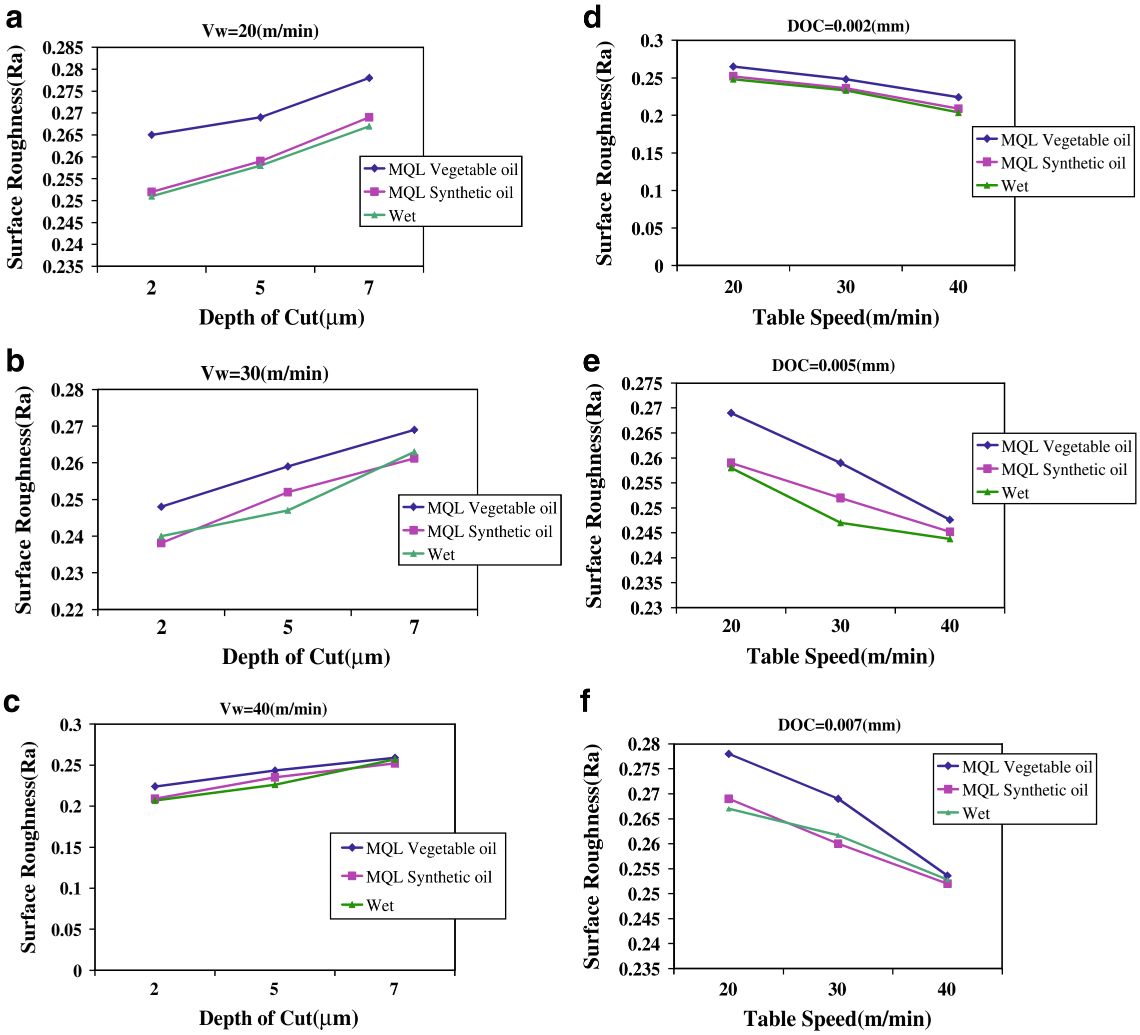

Fig. 3 Effects of the cooling modes on the surface roughness (grinding experiments were conducted with Q=60 ml/h, P=4 bar for MQL, V_s=15 m/s for all tests) and variable DOC with: **a** V_w=20 m/min, **b** V_w=30 m/min, **c** V_w=40 m/min and variable table speed with **d** DOC=0.002 mm, **e** DOC=0.005 mm, **f** DOC=0.007 mm

the main functions of the grinding process since the purpose of grinding is normally to confer tight dimensional tolerances on a piece [1, 2]. Therefore, dry grinding of Ti–6Al–4V generate burn surface on, and hence, in this study, only wet and MQL conditions were investigated.

4.2 Surface morphology and analysis of microstructure

Surface integrity is considered of crucial importance for the acceptance of any finishing method for safety critical components [20]. This is because certain levels/types of work piece surface damage (e.g., grit embedment, appearance of recast layer) of components working at high level of cyclical stresses and elevated temperatures can lead toward fatigue deficit and thus to part failure if no precautions are taken to eliminate them via component reworking and/or surface treatment (e.g., shot peening) [1, 2]. Work piece surface morphology analysis has been carried out on some testpieces ground with MQL and flood technique. The above-mentioned surfaces have been selected to identify the influence of applying MQL using a succession of roughing and finishing operations and to compare its cooling efficiency with that of conventional wet grinding operation. The chemical analysis using EDX proved that there was no grit embedment on the polished components after MQL or flood grinding methods. Figure 4 shows that in wet grinding of Ti–6Al–4V plastic deformation, side flow and thermal damage such as strong adhesion of chip to abrasive grain, wheel loading, grain pull-out, and redeposition are present on the ground surface, indicating low lubrication and severe rubbing by the grain wear flats. It also indicates ploughing and plastic deformation to be the predominant mode of material removal. MQL surfaces showed lesser such defects, especially no plastic deformation, indicating a higher lubrication and shearing as the mode of material removal. Ground surfaces studied at any MQL rates and MQL oil type indicate the same results. Redeposition is a process whereby metal is picked up on the top of the grinding grits as they pass through the cutting zone and then carried around on the periphery of the wheel and redeposited onto the ground work piece surface prior to the grits reentering the cutting zone. The metal redeposited onto the ground surface is heavily deformed and is usually smeared across the surface. The heat generated during redeposition results in residual tensile stresses in the surface layers and in some cases surface cracking, both of which are detrimental to fatigue life [21]. Redeposited material on the machined surface occurred when machining with both conventional and MQL coolant supplies. The deposited material originated from fine chip particles produced during the grinding process. Figure 4 shows that they are welded onto the ground surface to form a composite surface. This is possible because the cutting conditions investigated are capable of generating local temperatures at the grinding interface that can enhance the welding/adhesion process. Such redeposited materials are detrimental to the functioning of critical machined components as they are liable to disengage from the surfaces and may contaminate the hydraulic oil system as debris as well as aid the abrasion of contacting surfaces in relative motion. Material redeposition onto machined surfaces appears to occur under all the grinding conditions investigated. After grinding Ti–6Al–4V alloy, a thorough washing process was carried out to remove most of the deposited materials from the machined surface. Physical damage like cracks were not observed on surfaces generated after grinding with conventional and MQL coolant supplies. Generally, redeposition can be virtually eliminated, and consequently, optimum surface finish obtained if special grinding conditions such as high table speed, freshly dressed wheel (coarse dress) prior to taking finishing passes (about ten) at small wheel down feed, low wheel speed (10–15 m/s), and special cutting oil grinding fluid are used [20]. The cutting forces and specific energy requirement in grinding are generally contributed by (a) shearing or actual cutting process, (b) ploughing action, (c) fracturing of the work surface, and (d) friction between the bond material and the work surface [20]. Grinding fluids reduce the amount of redeposition as they affect the process whereby metal picked up on the grinding grits is redeposited back onto the ground surface. With the exception of using MQL, it was found that grinding fluids did not prevent the pick up of work piece material onto the tops of abrasive grits. Even when grinding with cutting oil, there was appreciable pick up of work piece material onto the grinding grits (except at small wheel depths of cut). However, the redeposition of this material onto the ground surface is in effect a friction welding process, and it appears that the cutting fluids (specially cutting oil) prevent good metal to metal contact, particularly when grinding Ti–6Al–4V, so making redeposition more difficult [21].

Conversely, the results indicate that cutting fluids are not effective in penetrating the cutting zone and preventing metal being picked up on the abrasive grits. Using MQL, however, is a means of providing a lubricant in the cutting zone, and hence, MQL oil acts in two ways: (a) by reducing the pick up of metal onto abrasive grits and (b) by reducing the redeposition of metal onto the ground surface, thereby producing a very good surface particularly at small wheel depths of cut. The surface produced was more finely grooved and were relatively free from redeposition metal in contrast with the surface produced at Q=60 ml/h and P=4 bar (Fig. 4g). The surface finish produced when grinding Ti–6Al–4V in this way was better than that obtained from other MQL conditions and is shown in Fig. 2a and b. This is a further example (see Fig. 4b–e) of the beneficial effect of finish MQL grinding with vegetable oil than wet

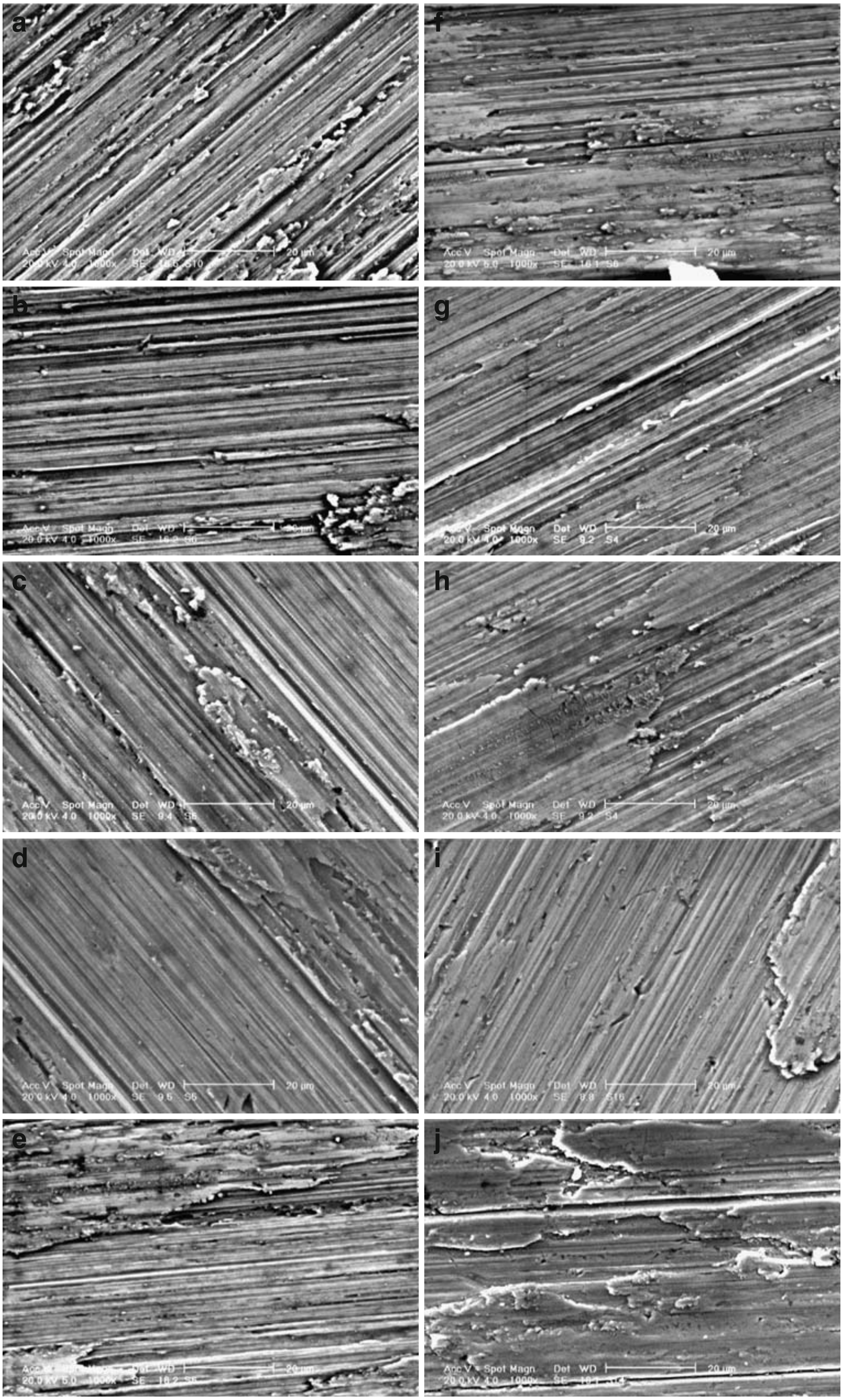

Fig. 4 Surface conditions and metallurgical analysis of surface obtained when grinding with V_w=40 /min, V_s=15 m/s, DOC=0.005 mm and **a** soluble oil; **b** vegetable oil with *Q*=20 ml/h, *P*=4 bar; **c** vegetable oil with *Q*=60 ml/h, *P*=4 bar; **d** vegetable oil with *Q*=140 ml/h, *P*=4 bar; **e** vegetable oil with *Q*=60 ml/h, *P*=6 bar; **f** synthetic oil with *Q*=20 ml/h, *P*=4 bar; **g** synthetic oil with *Q*=60 ml/h, *P*=4 bar; **h** synthetic oil with *Q*=140 ml/h, *P*=4 bar; **i** synthetic oil with *Q*=60ml/h, *P*=6bar; **j** synthetic oil with *Q*=60ml/h, *P*=3bar

grinding condition when surfaces with minimal amounts of redeposited metals are required. Furthermore, the amount of metal build up on the top of the grinding grits was even further reduced when grinding at MQL technique compared with conventional flood grinding. The surface finish produced by surface grinding of Ti–6Al–4V with MQL using compressed air pressure at 6 bar was also excellent, as shown in Fig. 4e and i, but in this case, the oil mist and oil particles in air were very harmful and are not suggested. The relative degree of contribution of the above factors depends on the type of work material, the wheel characteristics, and the process parameters and environment, which significantly govern the grinding temperature and work–grit interaction. It is important to note that unlike dry and wet grinding, MQL grinding is expectedly always to be free from burning, mainly due to lower temperature, retained grit sharpness, and less rubbing and ploughing. It is interesting to note that the specific energy and forces in wet grinding are more than those in dry grinding. This might be due to softening of the work material due to the higher temperature in dry grinding [22, 23]. The normal force has been found to be higher than the tangential force under all conditions due to the large negative rake and predominant rubbing action.

Work piece surface integrity analysis was carried by wire EDM cutting-up samples across feed direction, polished to reveal the metallurgical constituents and thus allowing the identification of possible surface damages (e.g., white layers, cracks, tearings, etc.). In depth, surface integrity analysis has been carried out using SEM. Figures 5 and 6 were micrographs of sample cross-sections illustrating the subsurface alterations that took place in the samples when the Al_2O_3 grinding wheel was used with conventional cooling and with the use of the MQL technique. Note that the subsurface alterations produced by the various lubrication and cooling conditions were minimal, without significant differences between the conditions tested. Sandpapering and polishing the samples manually to ensure their planeness for the desired magnification was not an easy task due to the material's great hardness. It can be noticed that the micrographs have not presented significant subsurface alterations in all conditions tested. Probably, the amount of heat and plastic deformation that entered the work piece during the grinding process regarding slight conditions of grinding was not sufficient to produce important subsurface alterations in the material microstructure. On the other hand, the contact time of the abrasive grains and the cooling time are very short, which make no meaningful difference in the subsurface. Similar results in the structure analysis were found in [24] for plunge cylindrical grinding when comparing the cooling by shoe nozzle (24 l/min) and MQL technique (215 ml/h). Regarding the microstructure, it has not been observed in [24] any important alteration when two flow rates were employed. Subsequent metallographic analysis revealed that the roughed only surface results with and evident recast layer (Fig. 5) that smoothes to some extent the microgroves characteristic to abrasive process; this was the result of elevated temperature developed in the contact area between the abrasive tool and work piece when conventional wet grinding is employed. In contrast with the previous results, the metallurgical analysis of MQL grinding with synthetic and vegetable oil samples (Fig. 6a–f) do not show evidence of any significant metallurgical changes beneath free surfaces. This was expected since sufficient MQL has been employed for generating ground surface. MQL supplied close to the cutting zone results in less heat transmitted to the work piece, and thus, the recast layer is smaller. However, the microstructure under MQL condition shows thinner white layer (recast layer) in the subsurface, which is probably due to higher temperature and slow cooling. All the energy spent in grinding is converted into heat in the grinding zone, which leads to higher temperatures and possible thermal damages in the work piece. These damages can be avoided if the grinding process is carried out in such a way that the maximum temperature in the grinding zone is kept below. It can be noticed, when analyzing the microstructures for grinding with conventional cooling, that there is a lack of meaningful circumstantial evidence of subsurface alterations in the microstructure when the MQL technique was employed. The metallurgical alterations clearly seen for all conditions tested (MQL and conventional wet grinding) were essentially restricted to the changes in the microstructure. Again, the MQL technique efficiency was also confirmed in the microstructure analysis, reinforcing the thesis of significant effects on cooling and lubrication, providing a positive aspect of the surface integrity of the work piece.

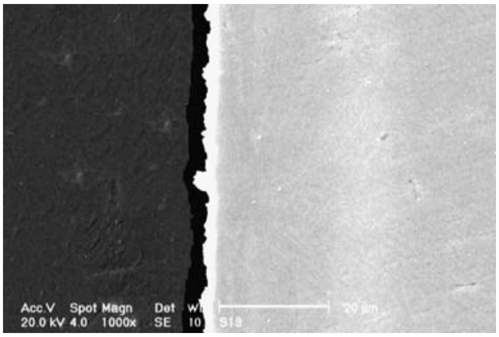

Fig. 5 SEM micrograph of surface and cross-section of conventional wet grinding sample with V_w=40 m/min, V_s=15 m/s, DOC= 0.005 mm

4.3 Hardness

The microhardness profiles given by Fig. 7 show the existence of surface softening for both cooling methods. However, the MQL is seen to induce lower softening at the outer layers of the ground surfaces. On the other hand, these profiles show that layer thickness, which undergoes work softening when MQL is used, is smaller than those generated when the conventional cooling is applied.

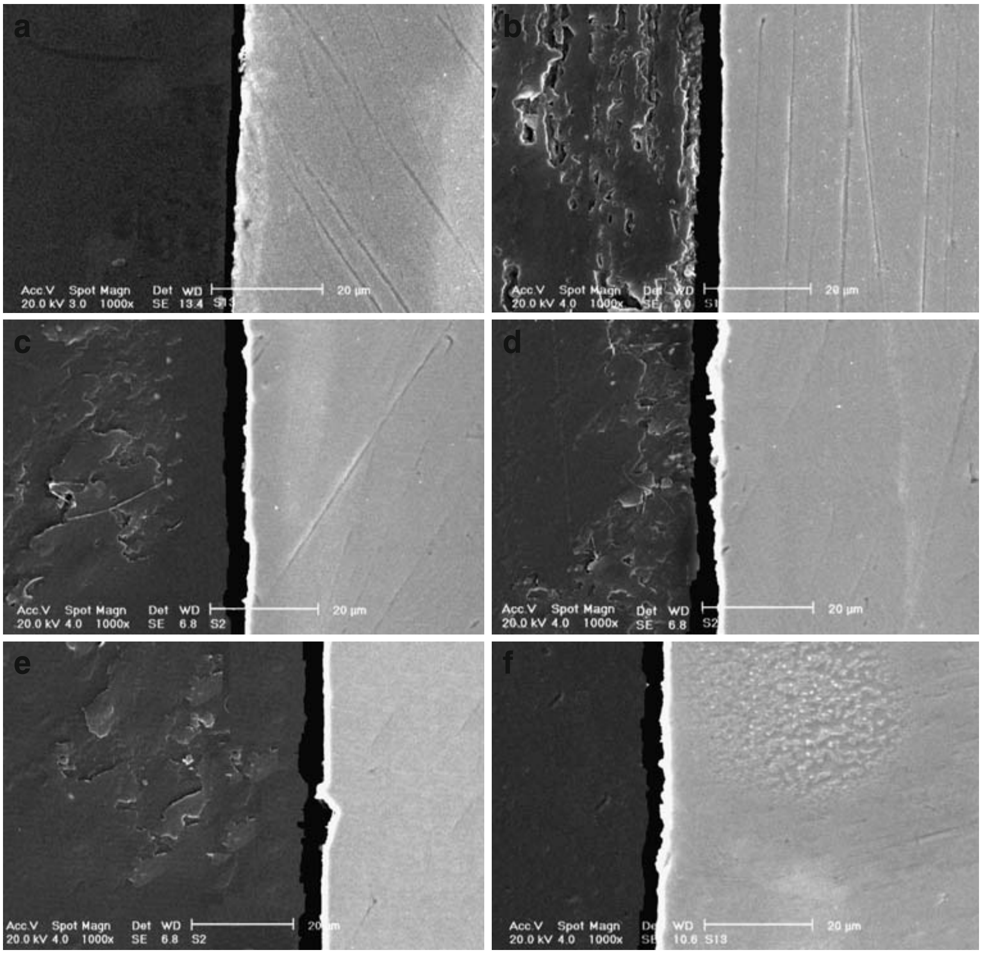

Fig. 6 SEM micrographs of surfaces and cross-sections of MQL grinding samples with V_w=40 m/min, V_s=15 m/s, DOC=0.005 mm and **a** vegetable oil with Q=140 ml/h, P=4 bar; **b** vegetable oil with Q=60 ml/h, P=4 bar; **c** vegetable oil with Q=20 ml/h, P=4 bar; **d** synthetic oil with Q=20 ml/h, P=4 bar; **e** synthetic oil with Q= 60ml/h, P=4 bar; **f** synthetic oil with Q=140 ml/h, P=4 bar

Additionally, when using MQL with vegetable oil, the softening is smaller, and the microhardness of surface layer is higher than MQL with synthetic oil. The difficulties experienced in grinding were attributed largely to the high temperatures generated because of the low thermal conductivity and volume specific heat of titanium and its reactivity with refractories at elevated temperatures. Generally, the hardening effect is due to high plastic flow rate combining with the heat generation at the primary shear zone [25]. Efficient coolant supply conditions increase access of the coolant to the chip–tool interface and contribute to reducing friction coefficient and the resistance to primary shear stress [25]. Heat generation is decreased and consequently lower temperatures and plastic flow, resulting in lesser hardening effect as well as microstructural damage [25]. There is a clear evidence of softening of machined surfaces due probably to the tempering effect of the high-temperature conditions at the grinding interface [25]. Softening of the machined surface implies improved ductility and yield strength of the Ti–6Al–4V alloy, thereby improving processability. Rapid heat treatment of fine grained Ti–6Al–4V alloy improves both the yield strength and tensile elongation as the cooling rates increased from 100°C/min (air cooling) to 800°C/min (water quenching) [26]. Extensive grinding work that has done before, involving the study of wheel/work piece in interactions, showed that grindability of titanium alloys could be improved by the application of active coolant systems and most notably buffered phosphate salt solutions [25]. These greatly reduced chemical interactions between the wheel and the work piece and therefore reduced wheel loading and cutting forces. Unfortunately, such systems are a health hazard and are therefore not ideal

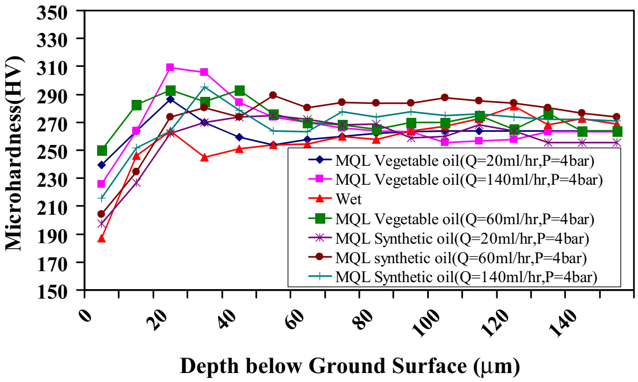

Fig. 7 Effects of the cooling mode on the microhardness HV (100 gf) profiles (grinding experiments were conducted at V_w=40 m/min, V_s=15 m/s, DOC=0.005 mm)

for use in industry, although the use of anti-corrosion agents is widespread as these offer a limited form of passivation. Malkin [27] stated that, in practice, it is interesting to combine the annealing behavior with a thermal analysis in order to predict the drop in hardness of the piece. Experimental results demonstrate that high temperatures and long periods of exposure of the work piece to such temperatures, at low velocities or with longer contact lengths of the work piece, lead to greater losses in hardness.

5 Discussion

The normal grinding force (F_n) has an influence upon the surface deformation and roughness of the work piece, while the tangential grinding force (F_t) mainly affects the power consumption, heat generation, and service life of the grinding wheel. Proper selection of grinding parameters as well as cutting fluids has great influence on grinding forces and therefore the heat generation. The fluid in the contact zone influences the chip formation process by building up a lubricant film, thus lowering the friction forces. By reducing friction forces, friction heat is reduced and therefore also the total process heat. The recorded grinding force components—tangential and normal forces—vs. quantity of lubricant are shown in Fig. 8 for vegetable and synthetic cutting oil. As illustrated in Fig. 8a and b by increasing quantity of lubricant up to 60 ml/h, both tangential and normal forces decrease, while the quantity of lubricant more than 60 ml/h results in an increase in mentioned grinding force components. It can be seen from this figure that the application of synthetic oil gives lower tangential force than vegetable oil.

A series of test was performed in order to evaluate the effect of compressed air pressure on tangential and normal forces in MQL grinding (Fig. 9). It can be seen that grinding forces exhibit a falling and rising trend against compressed air pressure. In other words, both force components—tangential and normal—reach their minimum value at 4 (bar). According to Figs. 8 and 9, quantity of lubricant 60 (ml/h) and delivery pressure 4 (bar) are the most appropriate quantity of lubricant and delivery pressure that minimize both tangential and normal forces. Figure 10 illustrates the grinding forces vs. depth of cut for MQL and wet grinding at the constant work speed of 40 m/min. It is obvious that in MQL grinding, the force components are smaller than that of wet grinding. Using synthetic oil rather than vegetable oil as MQL medium gives lower tangential force. The forces applied in grinding process are based on different physical–mechanical sources. In other words, in abrasive machining as a grain interacts with a work piece, three stages of material deformation (cutting, ploughing, and rubbing) can be considered. In the rubbing mode of deformation, only relative motion between grain and work piece has taken place, and the force on each grain is too small to cause large penetration of the work piece; in this mechanism, material removal is negligible, although friction is apparent. Lubricants play an important role in reducing this sliding friction by contaminating the surface of the grits and the work piece. Ploughing occurs when the penetration of the grains is increased, and ridges are formed on work surface. At the plowing stage, the energy consumed by grain is in two aspects: (1) plastic deformation energy required for creating plowing groove and (2) friction energy used up at rubbing between grain and groove. The degree of side flow plowing depends upon the

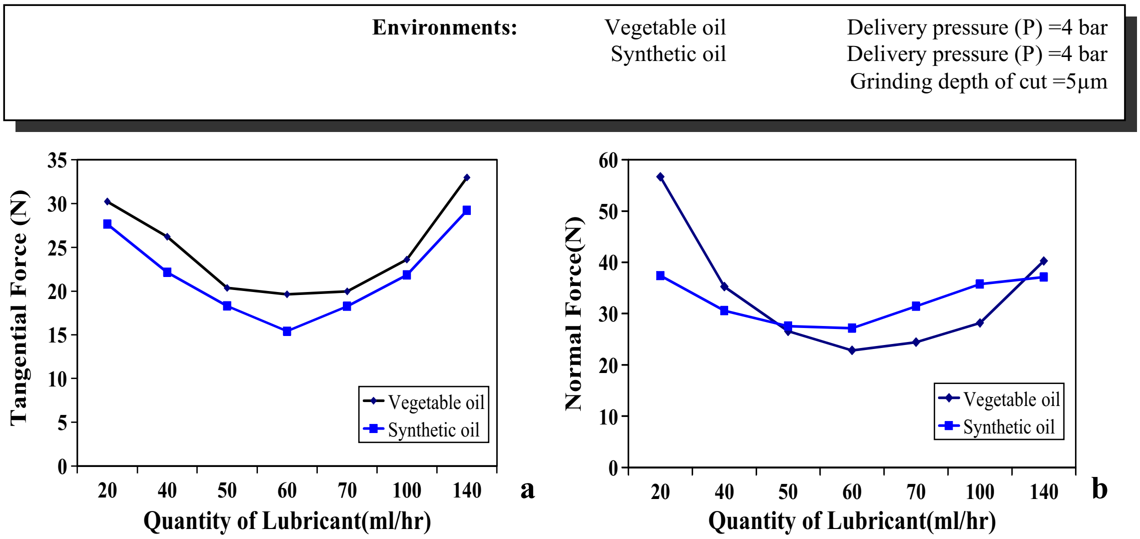

Fig. 8 Grinding forces vs. quantity of lubricant in MQL grinding with V_s=15 m/s and V_w=40 m/min: **a** tangential force vs. MQL flow rate, **b** normal force vs. MQL flow rate

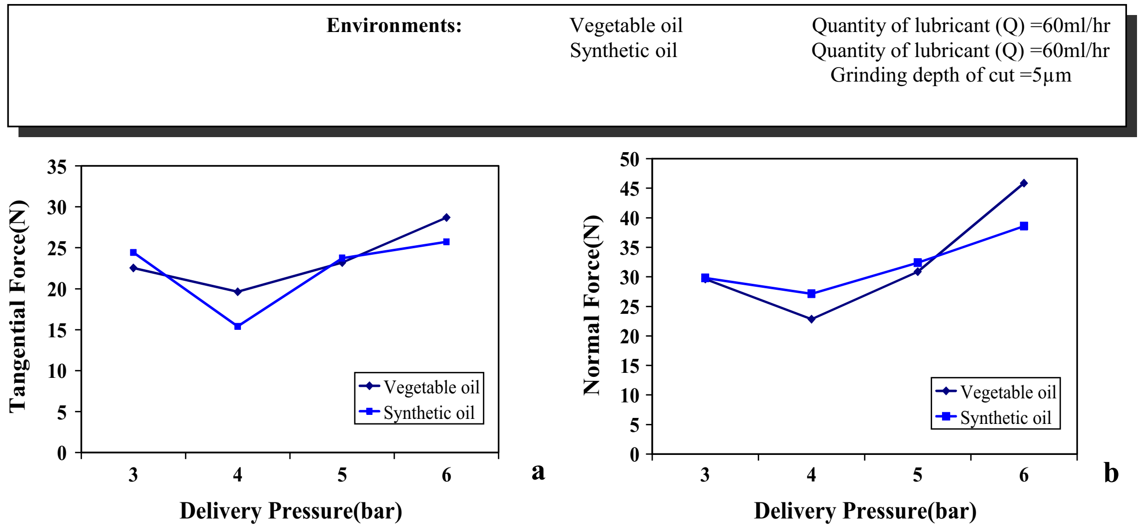

Fig. 9 Grinding forces vs. delivery pressure in MQL grinding with V_s=15 m/s and V_w=40 m/min: **a** tangential force vs. air pressure, **b** normal force vs. air pressure

particular work piece material being ground, local lubrication, and the sharpness of the grits [28]. Metals which are more adhesive, such as titanium, tend to exhibit more sideways flow. However, effective lubrication not only maintains the sharpness of the grits for a longer time but also tends to change wear mode from ploughing to cutting. By more penetration of the grains, material removal rapidly increases, and chips are produced. Here, the adsorption layer of lubricant on the grains and work piece decreases the interfacial coefficient of friction and facilitates cutting. Grinding fluids are referred to as coolants and lubricants, but their role as lubricants is often more important. Cutting oils are generally found to be better lubricants than soluble oils as higher G-ratios, lower grinding forces, and better surface quality are attributed to cutting oils. The reason why the oil shows lower forces compared with emulsion relates to the better lubrication property of oil, which causes lower friction and better chip removal properties. As discussed in the previous sections, in grinding of Ti–6Al–4V by emulsion as coolant wheel loading and redeposition of work material to the ground surface was observed. When the wheel is used in loaded condition, friction between the loaded chip particles and the work piece contributes substantially toward the total grinding force. That is why

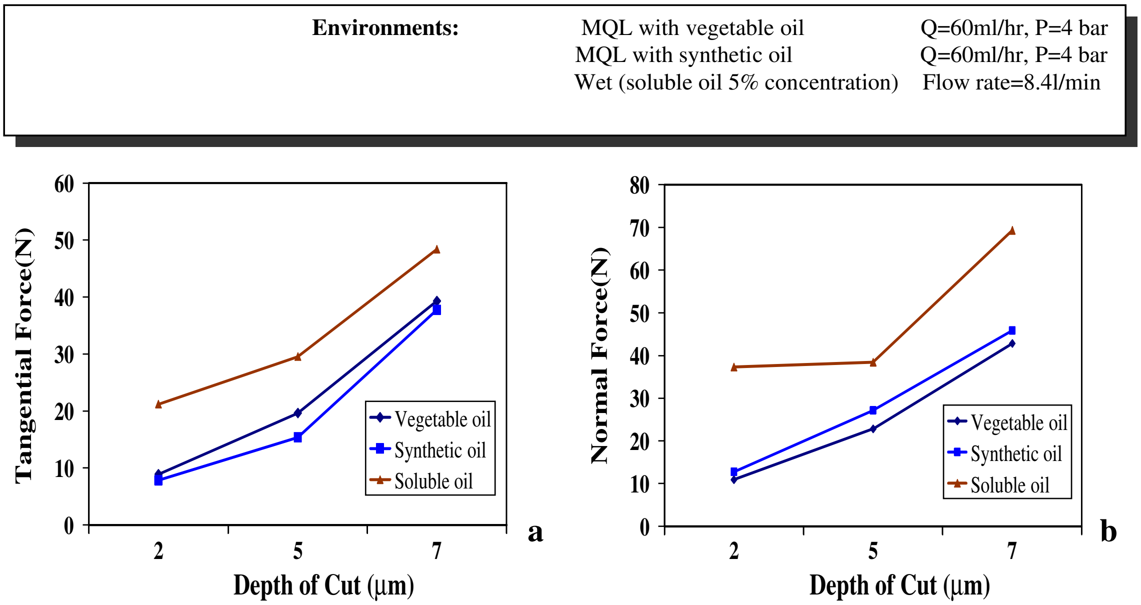

Fig. 10 Grinding forces vs. depth of cut for MQL and wet grinding with V_s=15 m/s and V_w=40 m/min: **a** tangential force vs. DOC, **b** normal force vs. DOC

the grinding forces in wet environment are more than MQL grinding. These improvements in MQL grinding compared with wet grinding can be attributed to the lubricating oil that is able to get very close to the wheel–work piece interfaces under pressure. Minimum quantity lubrication influences the chip formation process by building up a lubricant film, lowering of friction along the chip flow line, i.e., between the chip, the grain cutting edge, and the grinding wheel bond thus reduces the friction forces. Application of MQL seems to control the stability of grits against wear and to retain the sharpness for a longer period of time. In near-dry grinding, redeposition of chip particles from the wheel surface on the work surface and hence the force required to remove redeposited materials is reduced. Synthetic fluids and vegetable oils can be alternatives to mineral cutting oils and identified as the preferred lubricants for MQL machining. One particular area where synthetic fluids may be better lubricants than soluble oils and cutting oils is for grinding of titanium alloys [27]. This is due to the fact that synthetic oils have good lubricity with good film strength and maintain their integrity at elevated temperatures and can reduce friction force more effectively than vegetable oils. That is why the application of synthetic oil gives lowers tangential force (lower friction) than vegetable oil. However, it must be noted that the results could be different if other types of oil or emulsion were chosen. The important factors are viscosity and additives in the oil. Concentration and mixing properties also play an important role with the emulsions.

However, it was found that for the lubrication and cooling conditions (with synthetic oil and vegetable oil, $P=$ 4 bar and $Q=60$ ml/h), the surface finish improved significantly with the use of the MQL technique. It is worth pointing out that no significant thermal dilation (burned surface) was found at the end of the cycle when using MQL, indicating that the use of this fluid combined with compressed air provided adequate cooling. In general, the MQL technique produced higher surface roughness under most lubrication and cooling conditions using the Al_2O_3 grinding wheel, probably because of the effective lubrication of the tool's abrasive grains in the cutting region. With efficient lubrication, the chip slips across the tool's surface more easily, thus allowing for a better surface finish. The tangential cutting force was decreased with MQL, possibly due to the presence of lubricant around the grinding wheel, providing better slipping of the grain at the piece–tool interface. The application of cutting fluid with MQL allowed the cutting edges of the grinding wheel to remain sharp for longer periods before they were renewed. Study of the ground surfaces indicates also that in MQL grinding, the metal removal rate takes place mostly by shearing and fracturing, unlike prevalence of plastic deformation, grain pull-out, and ploughing in conventional grinding. Surface damage such as cracks, redeposition, plastic deformation, and grain pull-out are absent in MQL grinding, even at very high depths of cut. The surface roughness in MQL grinding is found to be larger than in conventional grinding due to retained sharpness of grits and less temperature: The grits leave distinct shearing marks without plastic deformation of the high ridges, resulting in the higher roughness in MQL grinding. MQL grinding enables significant reduction in forces and specific energy for all of the steels explored, which may be attributed to reduced ductility of the material, retained grit sharpness, ideal chip formation mechanism, and shorter chips [1, 2]. Also, it can be seen from the results that MQL grinding with synthetic oil generate the best surface quality (lower surface roughness, no burned surface, better surface morphology and structural analysis) and lower grinding forces than vegetable oil, whereas vegetable oil has better cooling effects in the grinding contact zone.

6 Conclusions

An analysis of the experimental data of this study led us to reach the following conclusions regarding the near-dry grinding or MQL grinding of Ti–6Al–4V. The analyses of the various results indicated that the MQL technique can achieve similar or better grinding performance as with conventional lubrication methods. It provides environmentally friendly and technologically relevant gains. An analysis of the results of applying conventional cutting fluid and the MQL technique indicated that, in general, the application of cutting fluid with MQL to the Al_2O_3 wheel resulted in a good performance for MQL technique, possibly by providing greater fluid penetration efficiency into the cutting region, but the material redeposition and white layer in the ground surface remain as unsolved problems when MQL grinding is applied. This needs a further investigation.

Based on the results of the present experimental investigation, the following conclusions for grinding performances in MQL grinding can be drawn:

1. Quantity of lubricant 60 ml/h and delivery pressure 4 (bar) were the most appropriate quantity of lubricant and delivery pressure in MQL grinding of titanium alloy Ti–6Al–4V that minimized grinding forces.
2. MQL compared to flood cooling could considerably reduce process perpendicular and tangential forces.
3. In MQL, grinding cutting forces increase steadier and have less fluctuation. Synthetic oil with respect to vegetable oil shows better performance.
4. Generally, in MQL grinding, the application of synthetic oil gave lower tangential force than vegetable oil.

5. In general, the MQL technique produced higher surface roughness under most lubrication and cooling conditions using the Al_2O_3 grinding wheel, probably because of the effective lubrication of the tool's abrasive grains in the cutting region.
6. The flow rates selected for application with MQL did not result in dispersion of the mist, contributing toward environmentally correct manufacturing and allowing for easy viewing of the grinding operation.
7. The results allowed us to demonstrate that the method and quantity of lubricant and cooling are factors that influence the grinding process.
8. The surface roughness in MQL grinding is found to be larger than in conventional grinding due to retained sharpness of grits and less temperature: The grits leave distinct shearing marks without plastic deformation of the high ridges, resulting in the higher roughness in MQL grinding.
9. It can be seen from the results that MQL grinding with synthetic oil generate the best surface quality (lower surface roughness, no burned surface, better surface morphology and structural analysis) and lower grinding forces than vegetable oil, whereas vegetable oil has better cooling effects in the grinding contact zone.

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