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Surface Grinding of Ti-6Al-4V Alloy with SiC Abrasive Wheel at Various Cutting Conditions

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Abstract

Ti-6Al-4V alloy is mostly used in biomedical and aerospace industries, as well as in automotive and cutting implements, like scissors and knives due to its high strength-to-weight ratio and excellent resistance to corrosion in many environments. However, Ti-6Al-4V alloy is referred as difficult-to-cut material due to its unique combination of low thermal conductivity and high chemical reactivity with most cutting tools, especially with ceramics, and rapid work hardening during machining,. This will accelerate tool wear and generally adversely affects surface quality of the component. This becomes more critical in grinding operation due to conventional abrasive wheels that have poor thermal conductivity and small dimension of chips, which in turn contributes to more heat to be concentrated in the cutting zone. Depending on the temperature gradient and workpiece, this heat can cause damage to the component surface. So, it is important to control the amount of heat entering the workpiece and prevent damages like burning, surface cracks and other metallurgical alterations in the workpiece. In this context, this work investigates the surface quality of the Ti-6Al-4V alloy in terms of surface roughness e microhardness, after surface grinding with silicon carbide wheel under various cutting conditions. The morphology of the machined was also analyzed in a Scanning Electron Microscope to understand the cutting mechanisms. Conventional and MQL coolant delivery techniques were tested. A specially designed nozzle was tested in the experiments with the MQL. Results showed that surface roughness is dependent on both radial depth of cut and coolant system; and the lowest results were recorded after machining with the combination of the lowest depth

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of cut and MQL technique. With respect to microhardness, little variation was observed after machining with the MQL technique, unlike when machining with conventional method, irrespective the depth of cut employed.

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Keywords: Grinding; Ti-6Al-4V alloy; MQL technique; Depth of cut; Surface roughness; Microhardness.

1. Introduction

Grinding is a finishing machining process that can provide smooth surfaces and very accurate dimensions on the machined components, compared to other machining process that uses geometrically defined cutting edges, such turning, for example. However, grinding is a low efficiency process since the specific energy is much larger than other metal-cutting operations, which means that a large amount of energy is used to remove a low volume of material [1]. On other hand, grinding process could achieve quickly the needed workpiece geometry and finishing required in one single pass, as the creep feed operation in materials like Ti-6Al-4V alloy. The most part of the energy spent in the grinding process is dissipated into heat that, depending on the quantity, is transferred to workpiece, thereby causing damage of it surface integrity. This damage can be reduced by applying a proper coolant to remove the heat generated as well as lubricate wheel-workpiece interface, so that the friction is reduced [2]. Therefore, the cutting fluid plays an important role in preserving the integrity (surface and shape) of the workpiece and, so, it becomes practically indispensable in the grinding process.

Besides the type of cutting fluid used in the process, proper selection of coolant delivery and its flow rate are equally important to improve grinding process efficiency. Several works focusing on investigation of type of fluid, delivery technique and nozzle positioning to improve efficiency of grinding process have been found in the specific literature [2, 3].

Since the 1990 decade, due to environmental appeals to reduce/eliminate cutting fluids, dry machining and Minimum Quantity of Lubricant (MQL) technique have been attracting attention of machining researchers as an alternative way to the use of conventional cutting fluids on grinding operations. Benefits of using MQL technique in grinding have been reported by [4, 5, 6, 7]. These authors in general observed lowest grinding wheel wear and improved finishing. However, the use of MQL technique have been more extensively studied in the machining of steel, nickel and titanium alloys, regarding to the usage of nanofluids, super-abrasive wheels (diamond and cubic boron nitride – cBN) and, most of them, whit Al2O3 grinding wheel, as summarized in [8]. Few works reported results for the study using combination of the MQL technique and silicon carbide wheel in surface grinding of the Ti-6Al-4V alloy, what was the one of the motivation of this study.

When grinding titanium, the use of cutting fluid is even more necessary to prevent occurrence of surface burning [9]. Furthermore, it also important to guarantee that proper penetration of coolant in cutting zone, thus preventing metal being picked up on the abrasive grits [10]. Ti-6Al-4V alloy is referred as difficult-to-cut material due to some characteristics, such as chemical affinity, low elasticity modulus, low thermal conductivity, and high tendency of hardening during machining [11]. Also, it has high chemical affinity with most of cutting tools, especially with ceramics. Despite of several works carried in grinding of titanium and its alloys, there is not yet a common sense in the literature with regard the appropriated abrasive wheel type, since aluminum oxide and silicon carbide are the typical conventional abrasives available. With regard aluminum oxides, it could be used different kind, as also mono crystalline grains or seeded gel ceramic grains, within different shapes. These materials have poor thermal conductivity, relatively low fracture toughness and high reactivity with titanium alloys [12]. According to [13], due to the poor thermal properties of titanium alloys, most of the heat being generated during the intense cutting deformation process is concentrated in a very narrow area of the primary cutting band. In the study about grinding of Ti-6Al-4V [10] with aluminum oxide wheel under different lubri-coolant techniques and various cutting conditions (table speed – v_w – of 20, 30 and 40 m/min, depth of cut values of 0.002, 0.005 and 0.007 mm and v_s = 15 m/s, which was kept constant), reported that the abrasive grains retained sharpness for a longer period, and thus, metal removal takes place mostly by shearing and fracturing hence providing sharp ridges and higher roughness values after machining MQL technique. Ra values were lower than 0.3 µm for all the conditions tested. On the other hand, these authors reported that abrasive grains probably lost their cutting capacity when machining under conventional coolant flow, despite of better finishing.

Although several works have been developed in grinding Ti-6Al-4V alloy, there is still no consensus about the conventional abrasive wheel material to be used in grinding of such material. Although diamond and cBN wheels have provided great results, their application in grinding of titanium alloys is still questionable due to their higher cost compared to conventional abrasive wheels. So, the use of the conventional abrasives as Al_2O_3 and SiC is still encouraged in grinding with lower cutting conditions than those for super-abrasives. With regard to research costs with the use of MQL, many works use commercially available systems with complex and fine assembly or construction, these systems can cost a significant amount of resources that could be designated for other applications. So, developing special devices is a practice that should be encouraged, as the novel specially designed nozzle and pumping system used in this work. It comes as an option to incite the creative production to reduce costs without lost in quality of process.

In this context, this work envisages to evaluate the influence of several machining conditions on the surface quality of Ti-6Al-4V alloy after grinding with silicon carbide abrasive wheel and with coolant delivered via a specially-designed nozzle for the MQL technique.

2. Experimental Procedure

The grinding trials were carried out on a surface grinding machine, MELLO, model P36, 3 HP powered and maximum speed of 2400 rpm. A silicon carbide grinding wheel with 39C46 KVK designation and dimensions of 250.8 mm x 25 mm x 76 mm (external diameter x width x internal diameter) was employed. The workpiece material was the titanium alloy Ti-6Al-4V with dimensions 37 mm of length x 15 mm of width x 15 mm of height. The cutting speed (v_s) and workpiece speed (v_w) were kept constant for all tests and equal to 32 m/s and 6.8 m/min, respectively. Two radial depth of cut (a_e) values were tested, 10 and 20 µm. The summary of machining conditions is shown in Table 1. The nozzle outlet position was kept constant for all the experiments (Fig. 1). Each machining condition was replicated once.

Two different coolant delivery techniques were tested: the conventional one at a flow rate of 545 L/h (Fig. 2a) and the Minimum Quantity of Lubrication (MQL) at a flow rate of 240 mL/h (Fig. 2b).

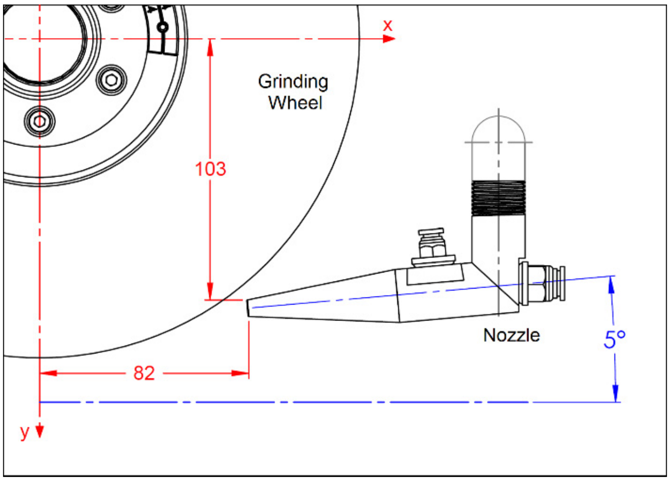
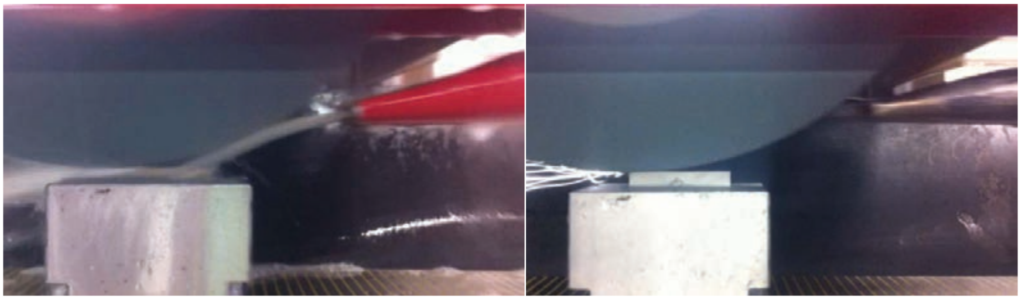


Fig. 1. Details of nozzle positioning.

Table 1. Experimental conditions

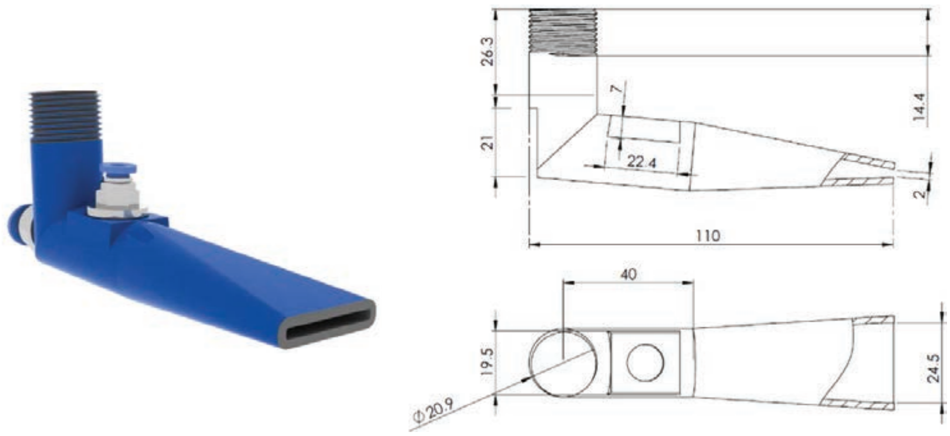
Machine tool	Peripheral surface grinder - MELLO P36 Operation: traverse surface grinding
Workpiece material	Ti-6Al-4V alloy
Size	37 mm x 15 mm x 15 mm
Hardness	381 HV
Abrasive wheel	SiC straight grinding wheel with designation 39C46 KVK
Dimensions	250.8 mm x 25 mm x 76 mm
Input parameters	
Cutting speed	32 m/s
Workpiece speed	6.8 m/min
Radial depth of cut	10 µm (0.01 mm) and 20 µm (0.02 mm)
Depth of cut per longitudinal pass	0.72 mm
Test stop criterion	11.1 mm^3 (Material Removal Volume)
Dressing parameters	
Type of dresser	Single pointed synthetic diamond dresser
Point radius	0.3 mm
Depth of dressing	10 µm (single pass)
Traverse dressing speed	105 mm/min
Cutting fluid	
Type	Water-soluble synthetic oil, ME-3 designation, at a concentration of 5%, from Tapmatic do Brasil Ind. e Com Ltda
Coolant Delivery Techniques	
Conventional	Flooding
Flow rate	545 L/h
MQL	
Flow rate	240 mL/h (0.240 L/h)
Air pressure	0.3 MPa
Nozzles distance from cutting zone	82 mm (see Fig. 1)



(a) (b)

Fig. 2. Images of fluid flow and nozzle position for: (a) conventional coolant technique and (b) MQL technique.

The system for MQL techniques delivery, nozzle and pump device, were especially developed and manufactured at the Laboratory for Education and Research in Machining (LEPU) from Federal University of Uberlandia. Manufacturing of nozzle was based on the geometry to the one used for conventional method, nozzle that belongs to the grinder machine. The 3D model and construction detail of the nozzle are shown in Figs. 3a and 3b, respectively. The novelty of this implement lies in the simpler construction used, based on two Push-in connectors attached to a flat nozzle body, perpendicularly set between them, that could be attached in the same way as the conventional flood nozzle (see “MQL Nozzle” exposed in Fig. 4), thus, the nozzle’s outlet position could be preserved for both coolant delivery techniques. Commercial MQL nozzles are generally composed by modular hoses, which can deflect during compressed air loading, and requires especially concentric set of tubes that is more expensive than a simple tube used in pneumatics and in this simplified model of MQL nozzle.



(a) (b)

Fig. 3. (a) 3D model and (b) construction details for the designer MQL nozzle applied in the tests

A syringe pump was also designed and manufactured in order to control the flow rate of cutting fluid conducted into the nozzle. One of the ends of the syringe is attached to system having a threaded rod with known pitch that is driven by a stepper motor rotation. The control is based on an Arduino controller and a precision potentiometer for variation of rotation. The schematic for the whole pumping system used in MQL technique can be seen in Fig. 4.

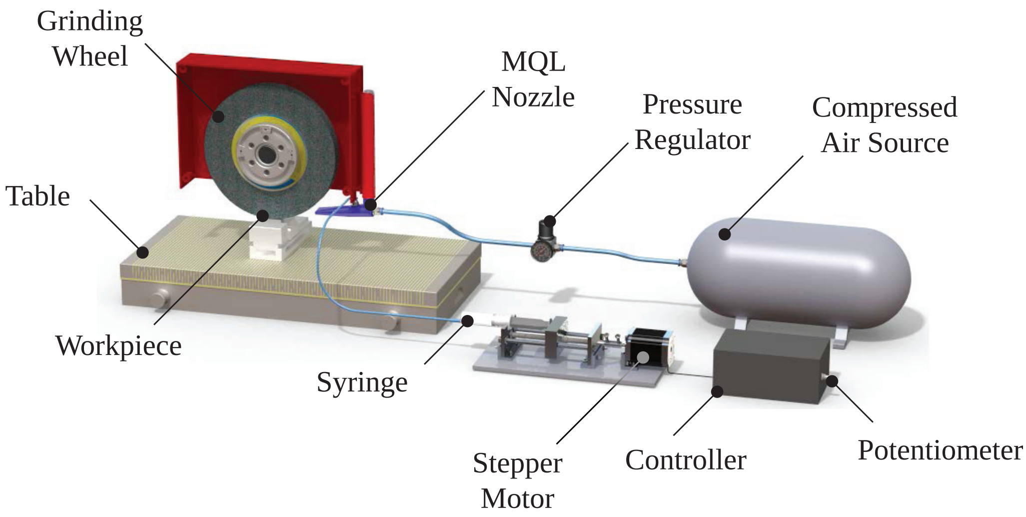


Fig. 4. Schematic of the MQL coolant system delivery.

The titanium workpiece sample was held in a precision vise from Gin manufacturer mounted on the grinder table. This vise is proper to hold workpieces of up to 90 mm width.

The cutting procedure followed a reciprocating motion of the table with an incremental traverse movement (a_p) towards the workpiece after each end of longitudinal course, as it is shown in Fig. 5.

The surface roughness parameter Ra was measured at the end of each machining condition with a portable surface roughness tester, SJ-201P model, from Mitutoyo, and with 0.8 mm cut-off. Five equidistant measurements were taken along the length of the machined surface and the average of measurements was calculated.

The microhardness measurements were taken at a SHIMADZU micro hardness tester HMV-2 series with a load of 245.2 mN (HV0.025) for 15 s. The measurements started from a depth of 20 µm below the machined surface and were taken up to 200 µm, keeping the intervals of 20 µm. Three sections were taken on a surface perpendicular to the machined surface for the measurement: one in the middle of the face, while the selection of the other two was equally distant from the first point, but in opposite directions.

Scanning electron microscope (SEM) images of machines surfaces were obtained using a HITACHI TM-3000 tabletop microscope with 30,000 times of magnification with secondary electrons mode.

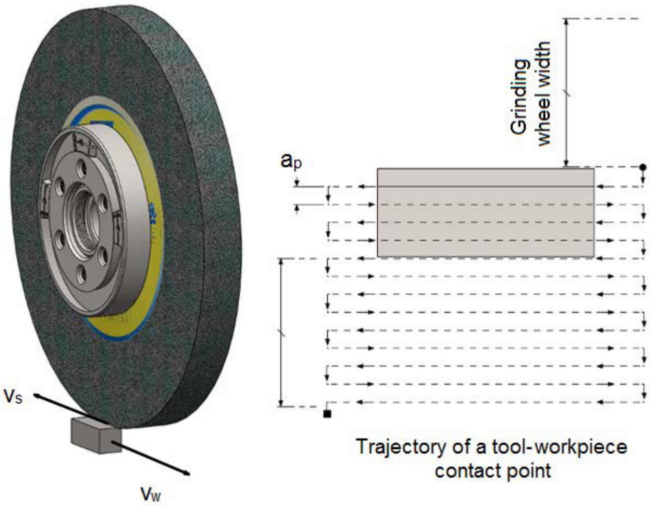


Fig. 5. Schematic of the trajectory performed by the workpiece during grinding.

3. Results and Discussions

In Figs. 6a and 6b are shown the results of surface roughness, Ra and Rt parameters respectively, and the dispersion of the measurements with a 95% confidence interval.

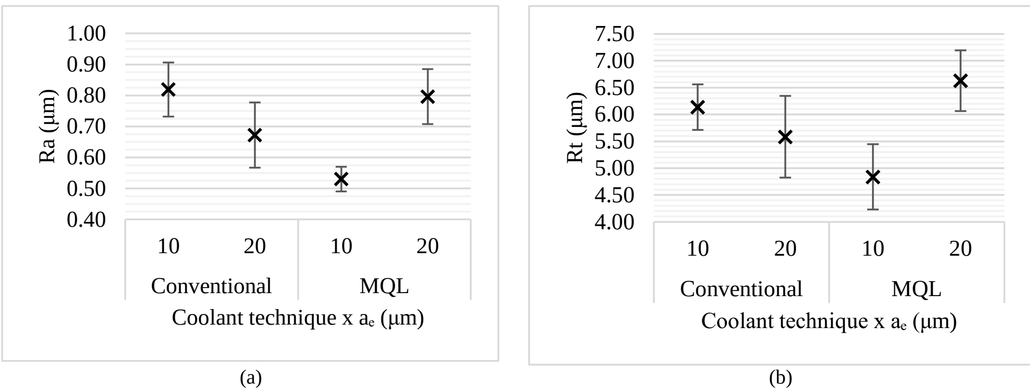


Fig. 6. Surface roughness (a) Ra and (b) Rt parameters of Ti-6Al-4V alloy after grinding with two values of depth of cut (a_e) and lubri-cooling conditions as presented in the Table 1.

The results in Fig. 6a show that roughness values decreased with increase of depth of cut when machining with conventional coolant technique, unlike for machining the MQL technique. In general, surface roughness deteriorates with increment in depth of cut when grinding most of materials. According to Marinescu et al. [14], both Ra and Rt surface roughness parameters are expected to increase with the equivalent chip thickness that, for a constant wheel/workpiece speed ratio, it is dependent on the radial depth of cut value (a_e).

The fact of the highest surface roughness values recorded when machining with the lowest depth of cut can be attributed to the poor machinability of Ti6Al4V alloy, specially its high chemical reactivity with ceramic tools at elevated temperatures (> 550ºC) [11]. In the particular case of the conventional abrasive wheel, this high chemical affinity leads to wheel clogging phenomenon, which is as result of the inefficient chip removal from the cutting zone, then the chips lodge inside the pores of abrasive wheel, thereby adversely affecting the quality and the finishing of the workpiece. In case of the grinding of Ti-6Al-4V, this phenomenon may sometimes occur randomly and cannot be predicted.

The lowest Ra value was recorded after machining with combination of the lowest depth of cut value and MQL technique. The superior performance of the MQL technique can be attributed to the capability of the coolant to reach the cutting zone due to the compressed air to transport the tiny oil droplets. Both cooling and lubricating functions may be achieved when machining under these conditions, thereby leading to improved tribological interactions at the wheel-workpiece interface. Sadeghi et al [10] carried out an experimental work in finish grinding of Ti-6Al-4V alloy under different lubri-cooling environments (dry, wet and with MQL technique) and reported superior performance of the MQL technique in terms of roughness, surface morphology and structural analysis of the workpiece, compared to dry and conventional coolant technique (wet). They also attributed such results to the ability of coolant delivered by the MQL to penetrate in cutting zone, thus preventing metal being picked up on the abrasive grits.

Also, it can be observed from Figs. 6a and 6b that all the surface roughness values for Ra and Rt parameters were below 1.00 µm and 7.50 µm, respectively. It has been reported by [1] that the upper Ra roughness limit for grinding operations is 1.6 µm, so the Ra values obtained in these work are below this reference value. It was reported that all the surface roughness values kept below 0.3 µm during the grinding of Ti-6Al-4V alloy under different lubri-cooling techniques [10], with aluminum oxide wheel, various values depth of cut and a constant cutting speed of 15 m/s. It was also found that the lowest Ra values, as well as no occurrence of burning, were achieved after machining with synthetic oil delivered by MQL technique, compared to vegetable oil.

In Fig. 7 are shown the values of the microhardness values of Ti-6Al-4V alloy obtained after various cutting conditions. It can be observed that microhardness decreased after machining with all cutting conditions up to 80 µm below the machined surface, with exception of the surface machined with the MQL technique and a_e = 10 µm, in which no variation was observed. The highest drop in microhardness values, up to 80 µm below the machined surface, was observed after machining with the conventional coolant technique and a_e = 10 µm. Similar behavior was also observed by [10] after grinding of Ti-6Al-4V alloy under various cutting conditions, that reported that the greatest drop in hardness occurred after machining with flooding technique, compared to MQL technique. According to these authors, the layer thickness with microhardness disturbance generated after machining with the MQL technique was smaller than those generated after machining with conventional coolant one. When an efficient coolant delivery technique is achieved, the access of coolant on the tool-workpiece interface is improved, thereby contributing to reducing friction and, somewhat, the heat generation [15]. If heat generation is decreased on the cutting region, less plastic flow can be observed, resulting in lesser hardening effect (softening) as well as microstructural damage [10].

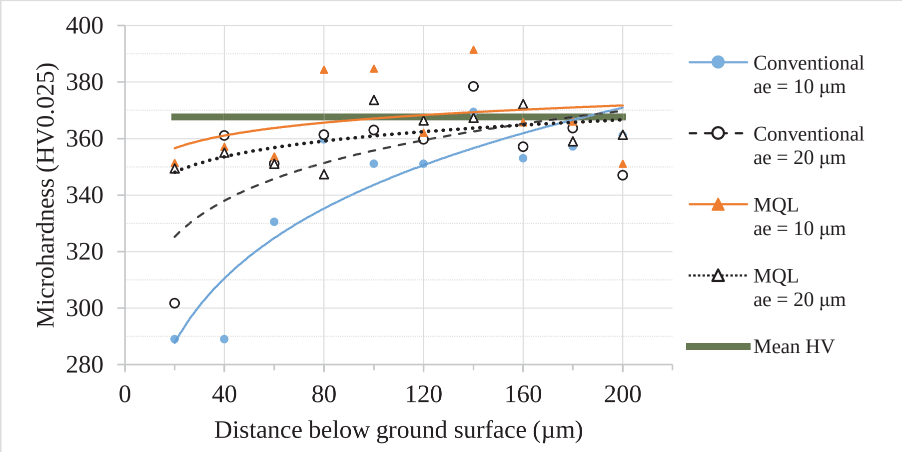


Fig. 7. Microhardness values.

In Figs. 8a to 8d are shown the SEM images of the machined surfaces after various cutting conditions. It can be seen that surfaces present some scratches and that grooves left by the abrasive grains are irregular, irrespective of the condition tested. The worst surface was observed after machining with conventional coolant technique with a_e = 10 µm, suggesting that this material was subjected to severe plastic deformation. Also, there was evidence that strong adhesion of chip to abrasive grain took place because of the morphology of the surfaces. Also, it can be seen redeposition of material on the ground surface (Figs. 8a, 8c and 8d), thereby suggesting that tribological interactions were not favorable because of the poor lubri-coolant efficiency. With the constant rubbing of the abrasive grains on the workpiece surface, the abrasives can wear and become dull, becoming flat shape, or even pull out from wheel. Increasing in wear flat area lead to gradually increase in grinding forces up to a point that where the grinding wheel will restore the its sharpness due to abrasive grain fracture. Since titanium alloys have high chemical affinity with ceramic tools during machining, abrasives wear is accelerated compared to other materials, thereby adversely affecting the chip formation during grinding. Machining with the MQL technique with the lowest depth of cut value of 20 µm provided a surface texture with less surface irregularities, despite of the small portions of plastically deformed material on the surface, which can be a result of the workpiece material that were stuck in the abrasive surface and lately are redeposited on the workpiece.

Metals such as nickel-base alloys, titanium and austenitic stainless steels, tend to exhibit more material displacement process, as called also plowing on the machined surface as well as more intense adherence with the abrasive grain contact area [1, 9]. Besides, these grades of materials, known as difficult-to-machining metals, seem to exhibit more extensive cratering and leaving grits embedding on the machined surfaces, as have been observed in most of the workpiece samples examined in this work. In Fig. 9a is shown the morphology of a machined surface with evidence of a grit pullout that has been stuck to the surface.

Another thermal damages known as microcracks were detected on the sample after machining with MQL technique and a_e = 20 µm (Fig. 9b). Such region is a source of concentrated stress that can lead to failures of the component during operation, showing adverse effects on in-service strength and fatigue properties [1]. The appearance of cracks on the surface can be an evidence of generation of tensile residual stresses that remain in the surface after machining because of the intense heat generated in the cutting point during machining. According to Turley [16], who has investigated the factors that play influence on finishing during grinding of several grades of titanium alloys, stated that cracking occurs mostly on the redeposited material layers on the surface, and that they are formed when this layer is subsequently cooled. Redeposited material on the machined surfaces was also observed in the works carried out by [10, 17], who have evaluated the performance of conventional coolant and MQL techniques in grinding of titanium alloy in different cutting conditions.

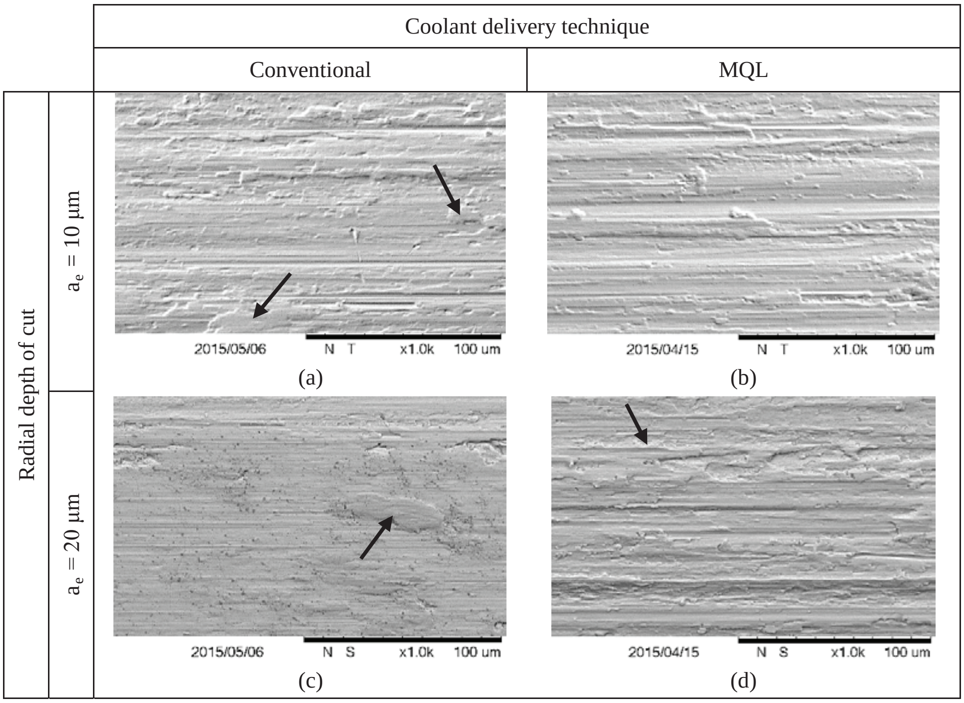


Fig. 8. SEM images of the Ti-6Al-4V alloy machined surfaces after grinding with silicon carbide wheel under different cutting conditions. The arrows indicate some points of redeposition of material on the ground surface.

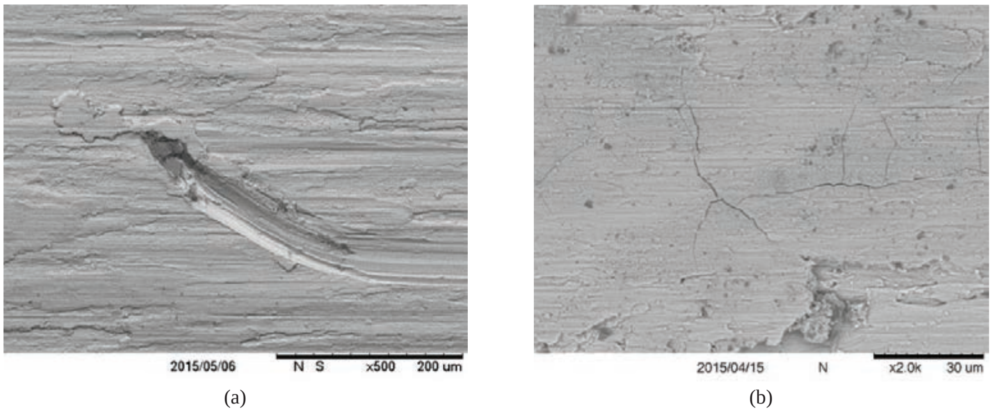


Fig. 9. (a) Embedded abrasive and (b) microcracks found on the machined surface of Ti-6Al-4V alloy after grinding with SiC wheel and MQL technique at a_e = 20 µm.

4. Conclusions

The following conclusions that can be drawn from this work:

1. The successful of grinding Ti-6Al-4V alloy in terms of low Ra and Rt surface roughness parameters was demonstrated in this work. Surface roughness is dependent on the combination of coolant delivery technique and depth of cut employed;

2. All surface roughness Ra values were below 1.00 μm, which is within the range attained for grinding processes;
3. The lowest Ra values were recorded after machining with the MQL technique and depth of cut of a_e = 10μm;
4. Microhardness decreased after machining with all cutting conditions up to 80 μm below the machined surface, with exception of the surface machined with the MQL technique and a_e = 10 μm, in which no variation was observed;
5. Machining with the conventional coolant technique outperformed the MQL technique in terms of finishing at more severe cutting conditions;
6. The highest drop in microhardness values, up to 80 μm below the machined surface, was observed after machining with the conventional coolant technique and a_e = 10 μm;
7. SEM of the machined surfaces showed the presence of scratches and non-regular grooves left by the abrasive grains, irrespective of the condition tested. Machining with the MQL technique with a_e = 10 μm provided a surface texture with less surface irregularities. The worst surface was observed after machining with conventional coolant technique with a_e = 10 μm, suggesting that this material was subjected to severe plastic deformation under this machining condition. Also, it was observed redeposition of material on most of machined surfaces, thereby suggesting that tribological interactions were not favorable because of the poor lubri-coolant efficiency.
8. Microcracks on the machined surface were detected after machining with MQL technique and a_e = 20 μm.

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