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Milling and turning of titanium aluminides by using minimum quantity lubrication

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Abstract

When machining difficult-to-cut materials, the high temperature in the cutting area is one of the dominating phenomena affecting tool wear and process capability. Hence, cutting fluids are profusely used for cooling and lubrication purposes, in order to obtain satisfactorily process performances. The use of conventional fluids creates several problems, such as the environmental pollution due to chemical disassociation at high cutting temperatures, water pollution, soil contamination during disposal, and biological problems to operators. The implementation of green machining strategies to accomplish the increasing pressures for sustainability is therefore an open challenge for manufacturers and researchers. Aim of this paper is to evaluate the influence of the lubrication strategy on tool wear, surface quality and environmental impact when milling and turning Ti-48Al-2Cr-2Nb (at. %) intermetallic alloys. The workpieces were obtained by means of two production processes: vacuum arc remelting and electron beam melting (EBM). Coated carbide tools were used in cutting tests under different lubrication conditions. The results of dry cutting are compared to that of wet and minimum quantity lubrication (MQL) conditions. Overall, the experimental tests show that dry machining requires a sensible reduction of process parameters to preserve a stable process, although limiting the energy consumption and reducing to zero the lubricant consumption. Under the chosen cutting conditions, MQL appears to be an advantageous solution for milling, whilst in turning wet cutting is the best choice for reducing the tool wear, since the higher process temperatures require the higher cooling effect of the emulsion.

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1. Introduction

In recent years, major changes in the laws against pollution have been enacted. In particular, the aerospace industry is looking for new engines to meet the increasingly stringent environmental regulations that provide, by 2020, the reduction of fuel consumption, polluting emissions, and noises. In order to accomplish such objectives, new materials (as titanium aluminides) have been developed for the application in the most stressed parts of the powertrain. However, these intermetallic alloys appear to be difficult-to-cut: excessive tool wear, heat and forces affect the cutting processes,

together with the poor surface quality of the produced parts. When machining difficult-to-cut materials, one of the key phenomena is the excessive generation of heat in the cutting zone, which has a controlling influence on the wear rate of the tool. Research reports have proved that, a reduction in cutting temperature increases tool life [1]. Hence, cutting fluids are profusely used for cooling and lubrication purposes, and wet cutting is *de facto* a standard for industrial production. The primary functions of lubricoolants are to cool and to lubricate. The cooling effect increases tool life by retaining the cutting temperatures below the thermal softening temperature of tool material, decreasing thermally-induced tool wear mechanisms

as diffusion and adhesion. The lubricating effect reduces the mechanical wear, such as the abrasion on the tool rake face [2]. In addition, lubricoolants are responsible for secondary functions, as the conveyance of chips and the cleaning of tools/workpieces. Emulsions possess excellent heat transfer characteristics because of their high water content, whilst oils excel when a high degree of lubricity is required [3, 4].

1.1. Problems related to the use of cutting fluids

The application of conventional cutting fluids creates several environmental issues, such as the pollution due to the chemical disassociation at high temperatures, water pollution, soil contamination during disposal, and biological problems to the operators [5-7]. One problem is linked to the growth of bacteria and fungi. This lowers the service life (since the presence of bacteria could reduce the lubricity and change the pH of the cutting fluid) and may increase the health hazards (endotoxin have been detected in the shop floor atmosphere) [8]. The control of bacterial growth in metal working fluids is assured by using different kinds of bactericides, humectants and germicides. However, these chemicals additives are accounted as hazardous substances for both the environment and the workers' health. Many of the available biocides release formaldehyde, which is a potential carcinogen. The International Agency for Research on Cancer reported that, mineral oils used in metal working are carcinogenic and exposures to them could result in occupational skin cancer [9]. Also, non-formaldehyde releasing biocides are dangerous for the health and highly corrosive for the skin [8]. And there are many other chemicals which are hazardous: for example, chlorinated and sulphurised additives are considered as toxic substances. The National Institute of Occupational Safety and Health estimated that, 1.2 million workers around the world were exposed to the chronic toxic effects of lubricants. Cutting fluids in machining operations could be vaporised and atomised due to the high operating temperatures and pressures. The airborne particles of the resulting mist could be inhaled by workers, causing different kinds of lung diseases. Greaves et al. showed that chronic bronchitis, asthma, chest symptoms and airway irritation were linked to such aerosol exposures [10]. The effects could also increase the risk of oesophagus, stomach, pancreas, prostate, colon and rectum cancers. Skin exposure could also cause dermatitis [9].

Moreover, depending on the production conditions, the costs related to the use of lubricants are from 7 % to 17 % of the total costs of the manufactured part [12]. This range increase up to 20-30% when machining difficult-to-cut materials. The acquisition, care and disposal phases have to be taken into account. The cost of disposal can be up to four times the purchase price, since most cutting fluids are not biodegradable and require expensive treatments [11, 13].

1.2. Dry and near-dry machining

Various green strategies, as dry machining or minimum quantity cooling lubrication (MQCL), have been implemented by manufacturers. Such non-traditional lubrication techniques aim to satisfy the increasing pressures for sustainability by

reducing the consumption of oil, water and energy. Dry machining can totally avoid the use of cutting fluids, and it requires less power to be accomplished. On the other hand side, friction and cutting temperatures could be higher than that of wet machining. This reduces tool life and may cause thermally-induced geometrical deviations in the machined part. Furthermore, excessively worn tool generates greater surface deformation with residual stresses, poor surface finish and the presence of micro-cracks, factors all undermining the fatigue strength of the components. For these reasons, the implementation of dry machining cannot be accomplished by simply turning off the lubricant supply. The improvement of cutting tool performances by introducing better tool geometries, materials, and coatings is needed [14, 15].

In many machining operations, MQCL has been employed as a successful near-dry lubrication condition, because of its environmentally friendly characteristics. These systems supply fluids in small amount, in the form of precision-metered droplets, under the support of compressed air. Vegetable-based oils are generally used for minimum quantity lubrication (MQL), due to their high biodegradability [16, 17], and emulsions or water can be applied for minimum quantity cooling (MQC) systems. Many studies highlighted that MQL ensures satisfactory results in practical machining operations [18-20], and that it may allow superior performances in comparison to dry and wet turning on the basis of cutting forces, tool life, cutting temperatures and surface finish [21].

The objective of this paper is to present an integrated analysis of the influence of different lubrication strategies (wet, dry and MQL) on machining performances in milling and turning of gamma titanium aluminides.

2. Experimental procedure

2.1. Workpiece materials

The experimental tests were carried out on gamma titanium aluminides with nominal chemical composition Ti-48Al-2Cr-2Nb (proportions in atomic percentage). A block measuring 120×120×30 mm, provided by AvioProp S.r.l. (Italy), was used for milling. The workpiece was EBM sintered, thermally treated, and squared by grinding prior to the cutting tests [22]. A bar produced by GfE Metalle und Materialien GmbH (Germany) via vacuum arc remelting was used for turning. After the preparatory cast skin removal the bar diameter was 140 mm, and the length was approx. 200 mm.

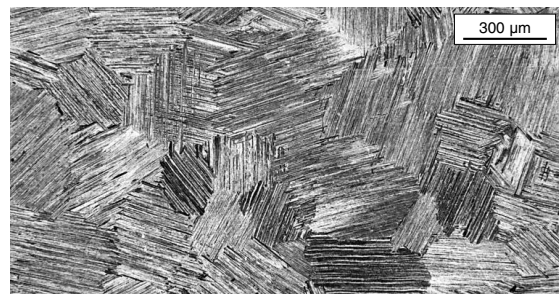


Fig. 1. Workpiece (block) microstructure.

Microstructural analyses were executed by means of a Leica MEF4U inverted optical microscope. Some specimens were randomly extracted from both the workpieces, polished, and etched by the Keller's reagent. Lamellar-type structures were revealed (Figure 1). Few porosities were observed in the EBM sintered block [23], whilst a moderate tendency to the formation of elongated grains in the radial direction of the bar was found.

2.2. Cutting tests and lubrication conditions

Milling tests were performed on a three axis Cortini M500/F1 vertical CNC milling machine, by using 8-mm diameter Silmax TiAlN coated and chamfered end-mills. Process parameters were selected according to former researches [23, 24]. Axial (d_z) and radial (d_r) depth of cut were kept constant and both equal to 0.3 mm, and the feed was fixed to 0.08 mm/tooth. Firstly, standard wet cutting was carried out with a 5% emulsion of Roloil Biotem-AD soluble semi-synthetic oil in water, and process performances were analyzed at varying the cutting speed ($v_c = 25, 50$ and 100 m/min). Then, for the case $v_c = 50$ m/min, three lubrication conditions (dry, wet and MQL) were compared. An Accu-Lube minimum quantity lubrication system fitted out the machine tool, and an aerosol of LB2000 vegetable-based oil conveyed by compressed air (at a pressure of 5.5 bar) was applied to the cutting area. The oil consumption was measured to be 0.3 ml/min.

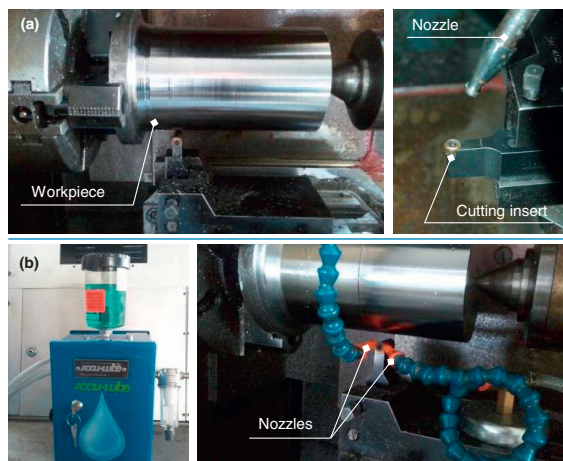


Fig. 2. Experimental set-up for WET (a) and MQL (b) conditions in turning.

Longitudinal external turning operations were carried out by means of a Graziano 101 SAG slant bed CNC lathe. RCMT 08 03 M0-SM S05F and RCMT 12 04 M0-SM S05F round inserts provided by Sandvik Coromant were used. The tungsten carbide inserts were CVD coated with a 4 μm multilayer coating (inner layer: Ti(C,N), intermediate layer: Al_2O_3 , outer layer: TiN). The inserts were clamped on Seco SRDCN 2525 M08 and Microna SRDCN3225-12M tool holders. A factorial plan was designed for dry machining, in order to evaluate the influence of cutting parameters on tool life. The cutting speed v_c ranged from 25 to 50 m/min, the

feed f from 0.1 to 0.3 mm/rev, and the depth of cut a_p from 0.3 to 0.7 mm. Tests were repeated applying both the cutting tool geometries (RCMT 0803 and RCMT 1204). Afterwards, the influence on machinability of wet and MQL cooling and lubrication conditions was studied by using the RCMT 1204 inserts, which had provided the best performances in dry machining. For wet cutting, a water-based emulsion containing 5% of soluble semi-synthetic oil was supplied by the conventional flood cooling system of the machine tool. The emulsion was conveyed through an adjustable external nozzle, with a flow rate of 10 l/min. The angle between the lubricoolant jet and the direction perpendicular to the tool rake face was around 30° (Figure 2a). The Accu-Lube MQL system applied for the milling tests was also used (Figure 2b), maintaining the same equipment setup. For all the lubrication conditions, at fixed feed ($f = 0.1$ mm) and depth of cut ($a_p = 0.3$ mm), the cutting speed v_c was varied in order to draw the curves of Taylor. The range of variation of v_c was specifically chosen for each condition. For each test (milling and turning), at regular time-steps, the tool wear evolution was analysed by measuring the wear of the cutting edges, and the surface roughness parameters were acquired.

3. Results and discussion

3.1. Milling

In milling, for each cutting condition, flank and corner wear were measured on the secondary tool flank surface, by means of a Leica MS5 optical stereo-microscope (with $40\times$ magnification). Unlike previous experiments carried out by the authors with sharp mills [23, 24], the maximum tool wear do not always correspond to the corner wear (Figure 3). A reduction of the chipping of the tool tip was expected, due to the chamfer which strengthens the cutting edge.

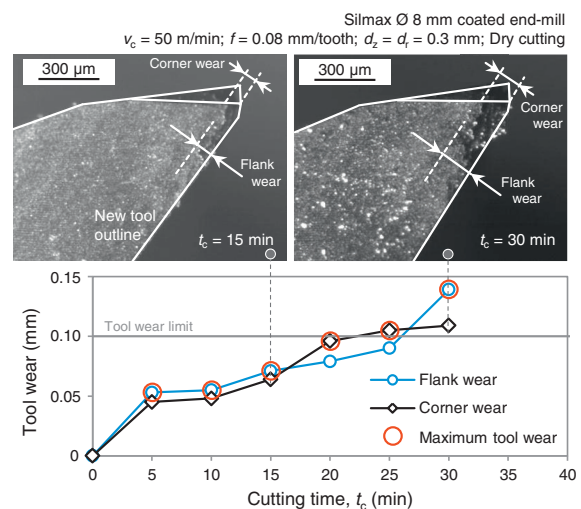


Fig. 3. Tool wear measurement criteria for milling.

The maximum value between flank wear and corner wear was used to plot the tool wear curves. A precautionary wear

limit of 0.1 mm was chosen to estimate the tool life T_L , since the machining of components semi-manufactured via EBM is often limited to finishing operations. Therefore, surface integrity and strict tolerances are critical requirements that must satisfy severe product specifications, whilst high tool wear levels generate poor finishing, surface hardening and residual stresses [23, 24]. Typical tool wear curves are shown in Figures 4 and 5. Each experimental point represents the average value of the measurements acquired on the four edges of the mills: variability of tool wear results was lower than 12% in terms of relative range.

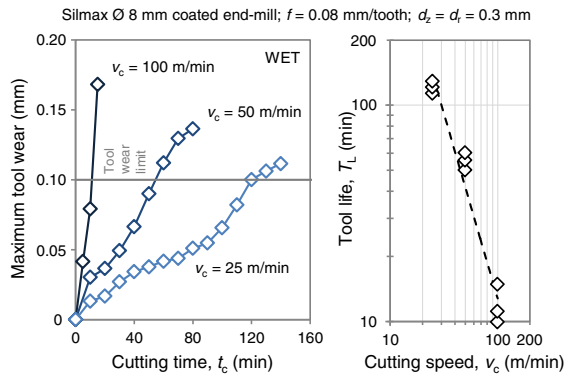


Fig. 4. Tool wear curves for wet milling.

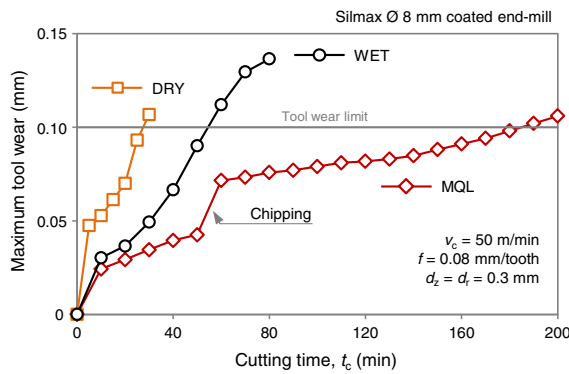


Fig. 5. Effect of lubrication conditions on tool wear for milling.

In wet conditions (Figure 4), tool wear raises by increasing the cutting speed v_c . Calculated tool life (T_L) values as a function of v_c can be interpolated by a Taylor's straight line, the slope of which emphasizes the huge effect of such process parameter. As far as the effects of lubrication conditions are concerned (Figure 5), wet cutting perform better than dry, and MQL appears to be the best strategy to reduce tool wear, although chipping of the tool tip could not be completely avoided. Figure 6 reports the surface roughness results achieved by a Hommelwerke Tester T1000. The average values of all the measurements taken until the wear limit was reached are plotted. Even if variations are small, the arithmetic mean roughness R_a and the maximum roughness profile height R_t decrease with the increase of cutting speed

v_c , and the results for dry cutting are slightly better than for MQL and wet conditions. This evidence could be traced back to the chip detachment mechanism [24]. Moreover, surface hardness analyses confirm the results discussed by the authors when milling with uncoated end-mills [24]: for MQL conditions, the low friction coefficient limits the strain hardening with respect to the other cutting conditions.

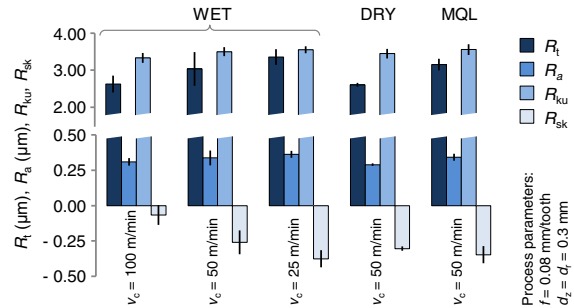


Fig. 6. Roughness results when milling (in feed direction).

3.2. Turning

In turning, tool wear was evaluated in accordance to the ISO 3685 standard, by using a Leitz MM6 Metallorg microscope with 50× magnification.

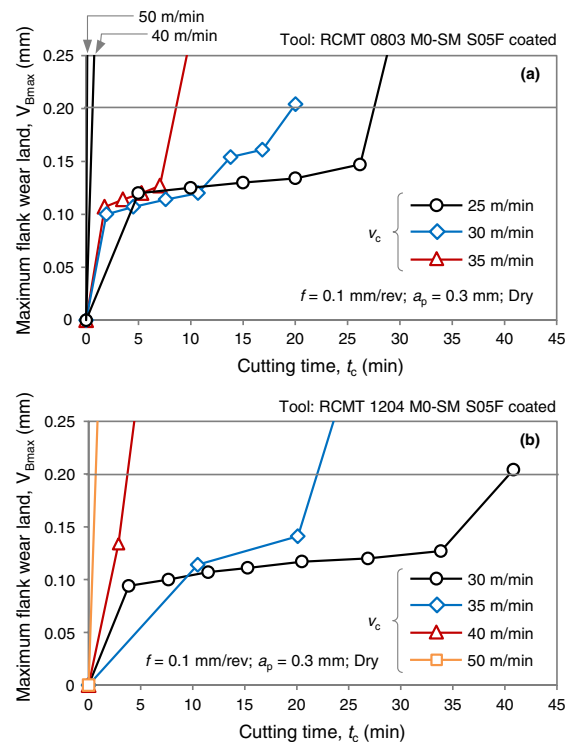


Fig. 7. Tool wear curves for dry turning, when using RCMT 0803 (a) and RCMT 1204 (b) coated inserts.

The wear formation mechanism is mainly abrasive, with a fairly uniform wear scar characterized by the presence of break-outs of the cutting edges. For all the tests, adhesion of the workpiece material on the worn tool surfaces was also detected by SEM analyses carried out with a Zeiss Evo 50 XVP scanning electron microscope equipped with an EDS microprobe [25]. The maximum flank wear land $V_{Bmax} = 0.2$ mm was assumed as tool wear limit. Typical tool wear curves for dry cutting are shown in Figure 7. The wear evolution is quite fast in absence of lubricoolant supply, as a consequence of the lack of lubrication and cooling effects. In particular, as shown by Figure 7a, with the RCMT 0803 insert the tests performed at a cutting speed higher than $v_c = 40$ m/min were interrupted at $t_c < 1$ min. This was due to the tool catastrophic failure. As for the effects of process parameters are concerned, results strictly follow the literature: tool wear increases with the increase of cutting speed, feed, and depth of cut. Moreover, for the same process parameters, process performance considerably improves by using the RCMT 1204 cutting insert (Figure 7b). The larger corner radius of the main cutting edge leads to the increase of tool life, to the decrease of cutting forces and to the decrease of surface roughness indices [26, 27]. More in detail, the 12-mm diameter cutting insert shows a tool life doubled in comparison to that of the 8-mm tool, for $v_c = 30$ and 35 m/min.

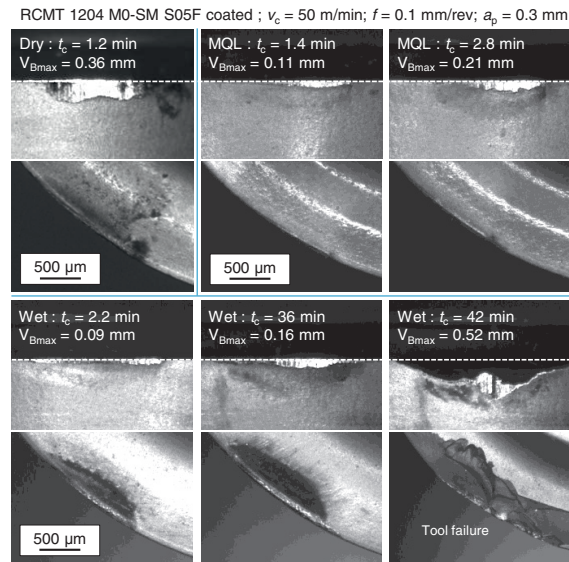


Fig. 8. Tool wear observations as a function of cutting time.

The effects of lubrication conditions (dry, wet and MQL) on tool wear/life are presented in Figures 8 and 9. Under the chosen range of process parameters, better outcomes were obtained by using standard cooling. When applying MQL, intermediate tool life results between dry and wet cutting were achieved. High process temperatures likely require the better cooling effect of the emulsion. Moreover, the sensitivity of machinability to the cutting conditions is revealed by the slope of the Taylor's curves: small variations in cutting speed correspond to significant changes in tool life results.

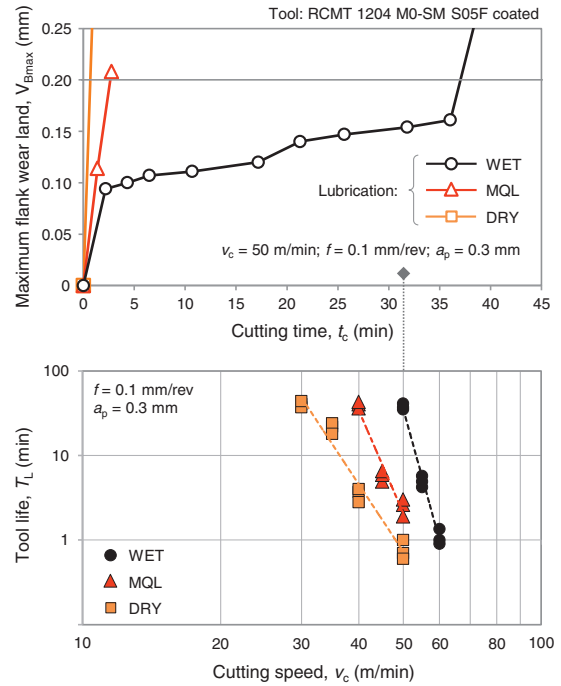


Fig. 9. Effect of lubrication conditions on tool wear for turning.

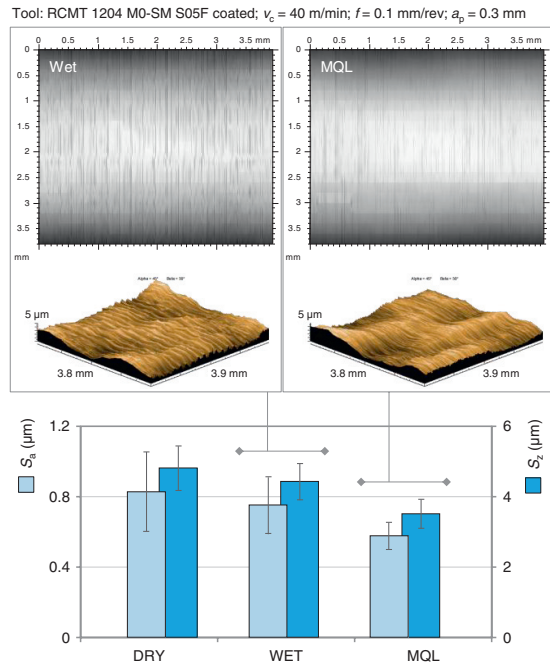


Fig. 10. Roughness results for turning under dry, wet, and MQL conditions.

Figure 10 presents the roughness results acquired with a 3D Form Talysurf 120 profilometer. The measurements refer to surfaces machined with unworn tools. The 3D roughness parameters S_a and S_z were calculated on rectangular areas of

ca. 16 mm² (3.8 × 3.9 mm), after compensating the form error via software. For each lubrication condition, the histograms correspond to the average values of all the repeated measures, and the bars highlight the maximum and the minimum values acquired. Results highlight that, dry conditions lead to the worst surface finish. The adoption of wet cutting results in a benefit in term of S_a and S_z , which decreased by 9.1 % and 8.0 %, respectively. MQL allows to obtain the best surface quality results, with a noticeable decrease of both the indices by approximately 30 % in comparison to dry machining. The S_{sk} (skewness) and S_{ku} (kurtosis) parameters were around 0 and 3, respectively, for all the tests, therefore the roughness profiles had a symmetrical height with a normal distribution of peaks and valleys.

4. Conclusions

Experimental tests were carried out in milling and turning, in order to compare the performances of minimum quantity lubrication (MQL) conditions versus standard flood cooling and dry cutting. The latter one is widely identified as the most sustainable cutting condition. The lubricant consumption is reduced to zero, and the energy consumption is not affected by the use of pumps and apparatus to supply and/or recirculate the lubricant. However, results show that it requires a sensible reduction of process parameters to preserve a stable process. MQL represents an advantageous environmentally-friendly solution, being the oil non-toxic, biodegradable, and manufactured from renewable raw materials. Under the chosen cutting conditions, in milling, the tool life under MQL conditions is improved as a consequence of the friction reduction due to the better lubricating properties of the oil. In turning, wet cutting is the best choice for reducing the tool wear, since the expected higher process temperatures require the higher cooling effect of the emulsion. In other words, the poor cooling capability, due to the low thermal capacity of oil and air and also to the small amount of the mix involved, limits the effectiveness of MQL where excessive heat generation is the main problem. On the other hand, MQL allows to obtain the best surface quality results in turning.

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