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Hybrid lubricating/cooling strategies to reduce the tool wear in finishing turning of difficult-to-cut alloys

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ABSTRACT

The increasing use of Difficult-To-Cut (DTC) alloys for high performance components has recently pushed the implementation of different lubricating/cooling strategies during machining operations in order to improve the machinability of these alloys as well as increase the tool life.

Whereas one lubricating/cooling strategy at a time is commonly implemented, the use of two strategies simultaneously, one devoted mainly to lubrication and the other mainly to cooling, hasn't been applied yet to finishing machining operations. To this aim, the objective of the paper is to evaluate the effect of hybrid lubricating/cooling strategies to reduce the tool wear when finishing machining the wrought Ti6Al4V titanium alloy, commonly regarded as a DTC alloy. A commercial Minimum Quantity Lubrication (MQL) system was implemented together with Liquid Nitrogen (LN_2) and Carbon Dioxide (CO_2) distribution systems designing the position of the nozzles to optimize the lubrication and cooling effects. The tool wear mechanisms were identified and quantified by means of Scanning Electron Microscope (SEM) and optical profiler, respectively. The experimental results showed that the crater wear was predominant when the sole MQL technique was implemented, whereas the use of LN_2 and CO_2 reduced it, with the most evident advantages highlighted when adopting CO_2 that drastically reduced the thermally activated tool wear mechanisms, but still preserving the lubricating effect of the MQL.

It was proved that the adoption of hybrid lubricating/cooling strategies is a viable alternative to the conventional ones, leading to a drastic reduction of the crater wear as well as good surface integrity given an optimized positioning of the lubricant/coolant nozzles.

1. Introduction

The demand of titanium alloys in different sectors has increased in recent years thanks to their outstanding properties, such as high strength-to-weight ratio, ability to retain high strength at elevated temperatures, resistance to chemical degradation, excellent biocompatibility and wear resistance. These advanced alloys are especially used in manufacturing components for aerospace, chemical and biomedical devices [1,2]. However, the titanium alloys are classified as Difficult-To-Cut (DTC) materials because of their low thermal conductivity, high thermal reactivity and low Young's modulus; these characteristics cause high temperature increases during the cutting processes that negatively affect the tool life and result in a poor quality of the machined surface [3].

The conventional strategies used to improve the machinability and reduce the process costs consist in adopting appropriate cutting fluids that, penetrating at the chip-tool and workpiece-tool contact areas, are able to effectively remove the generated heat (cooling effect), reduce the friction coefficient (lubrication effect), and assist in the chip flowing (flushing effect). However, the extensive use of large quantities of synthetic emulsions made of mineral oils raises important environmental issues in terms of their recovery and disposal, and forces to carry out costly and time-consuming cleaning steps of the machined surfaces, especially in the case of biomedical parts [4]. In the recent years, the concept of environmental sustainability has driven the manufacturing companies towards the adoption of more environmental friendly cutting fluids that allow both the minimization of the process chain costs and the improvement of the material machinability. The easiest solution would be the conduction of dry machining processes, which would eliminate the environmental costs related to the cutting fluids, but it is well known that they lead to an unacceptable decrease of the tool life with the consequent increase of the production costs ascribable to the machine downtimes required for the tool change. An alternative strategy, nowadays widely accepted thanks to its economical

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competitiveness, is represented by the Minimum Quantitative Lubrication (MQL), which consists in spraying an aerosol made of biodegradable oil micro-particles to the cutting zone. The supply and disposal costs are reduced because the flow rate is between 50 ml/h and 250 ml/h, which is several order of magnitude lower than the traditional lubrication that has a flow rate of tens of litres per hour [5,6]. Although the MQL has adequate lubricating characteristics, it has a poor cooling capacity that does not allow reducing significantly the generated temperatures and, therefore, the thermally activated tool wear mechanisms. This drawback is particularly relevant in hard turning where most of the oil micro-particles evaporate before reaching the cutting zone, whereas the MQL technique can represent a good solution in case of semi-finishing/finishing operations where the temperature increase due to the cutting process is lower.

Another approach to enhance the machining performance is to reduce the cutting temperature using high-pressure air, liquid coolants or through the application of low-temperature fluids. The use of Liquid Nitrogen (LN2) and Carbon Dioxide (CO2) as low-temperature coolants is becoming particularly attractive because they are clean, safe and non-toxic, and do not present any environmental issue [7]. The two gases differ considerably with respect to the mechanism of refrigeration: the CO2 is stored as a liquid in a medium pressure tank (about 57 bar) at room temperature, and, when it expands at the exit of the nozzle, a transformation into a mixture of gaseous and solid phases occurs lowering the temperature to about -78.5 °C. On the contrary, the LN2 is stored in an insulated tank at pressure of about 20 bar and at the exit of the cooling channel it reaches the temperature of -196 °C [8]. Several studies investigated the use of both the LN2 and CO2 in machining titanium alloys, showing significant improvements in the tool life compared to the dry cutting, which, in turn, allows using higher Material Removal Rates (MRR) [9,10]. Most of the research works about the LN2 analysed the influence of the cutting parameters (depth of cut, feed rate and cutting speed), nozzles position and size, insert geometries and type of insert coating [11–13] on the tool wear mechanisms and machined surface integrity. The same experimental approach was applied for the CO2, showing that its use induced lower cutting forces and better surfaces finish when compared to other gases [14]. Overall, the cooling solutions adopting low-temperature coolants determine significant improvements in terms of both the tool wear and surface integrity, but their lubricating capacity is not comparable yet with the one obtainable in case of adoption of conventional cutting fluids [15].

To overcome the MQL and low-temperature coolants disadvantages above described, the research work here presented is aimed at proposing new approaches, based on hybrid lubricating/cooling strategies, capable to improve the Ti6Al4V titanium alloy machinability in case of semi-finishing machining operations. A few literature works demonstrated the feasibility of these methods reporting important improvements with respect to pure cooling and pure lubricating strategies in case of hard machining of titanium and nickel alloys [16,17], but no evidences about their advantages in case of semi-finishing/finishing operations can be found. Hybrid techniques using LN2/MQL and CO2/MQL were compared to dry cutting, wet cutting using a conventional cutting fluid, MQL and pure cooling methods using LN2 and CO2 as low-temperature coolants, evaluating both the tool wear and the machined surface integrity in terms of surface roughness, topography and deformed layer.

A preliminary analysis of the tool wear mechanisms that occur in semi-finishing operations was conducted, highlighting how the predominant wear mechanisms were diffusion, adhesion and abrasion. In particular, the abrasion mainly involved the tool flank face, while the adhesive and diffusive wear the tool rake face with the formation of the characteristic crater wear [18]. Based on these findings, the experimental set-up for the adduction of the cutting fluids and low-temperature coolants was designed and implemented in order to maximize the obtainable advantages, using for the different tool areas different either cutting fluids or low-temperature coolants as a function of the detected wear mechanisms. In particular, the tool rake face, being mainly interested by the temperature increase due to the cutting process, was cooled by means of low-temperature coolants (LN2 or CO2), while the flank face, more prone to the abrasion, was lubricated using the MQL technique.

2. Experimental

2.1. Material

The Ti6Al4V ELI titanium alloy was used in the experimental investigation. This alloy was supplied in the annealed condition with a microstructure composed by equiaxed α grains with 8% of β phase, shown in Fig. 1 at different magnifications by means of optical microscopy and Scanning Electron Microscopy (SEM) using the Back Scatter Electron Detector (BSED).

The Ti6Al4V mechanical properties in the as-received condition are reported in Table 1.

2.2. Turning tests

The machining experiments were carried out on a Mori Seiki™ NL1500 CNC lathe adopting Sandvik™ WC inserts with a TiAlN coating (CNMG 120404-SM1105), cutting radius of 0.4 mm, and rake and clearance angles of 7° and 0°, respectively. The used tool holder was a PCLNR 2020K 12 with an approach angle of 95°. In a previous work carried out by the Authors [18] it was highlighted that the best results in terms of tool wear were obtained using the following cutting parameter set, which were used in the present study, namely depth of cut equal to 0.25 mm to reproduce semi-finishing turning conditions, feed rate equal to 0.2 mm/rev, and cutting speed equal to 80 mm/min. The turning tests were conducted at a fixed time length of 15 min, using a fresh cutting edge for each trial in order to evaluate the efficiency of the lubricating/cooling condition on the tool utilization; moreover, each cutting condition was repeated twice to assure the repeatability of the results. The whole experimental plan is reported in Table 2, with indication of the applied lubricating/cooling strategies.

Fig. 2 shows the distribution systems used for the different applied lubricating/cooling strategies. In case of cooling using the LN2 and the CO2, the same distribution system made of plates mounted on the lathe turret was used; the cutting zone was cooled using two external copper nozzles with an internal diameter of 1 mm directed onto the insert rake and flank faces (Fig. 2A). The LN2 was supplied at 15 bar with flow rate of 4 l/min

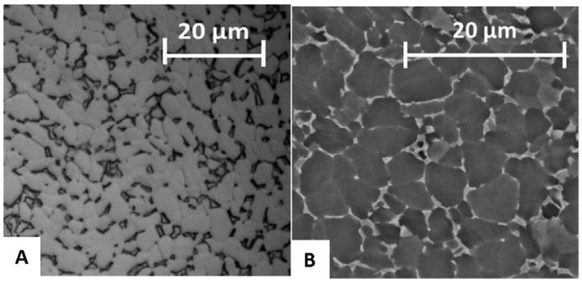

Fig. 1. Ti6Al4V microstructure in the as-received condition analysed by means of: A) optical microscopy and B) BSED SEM.