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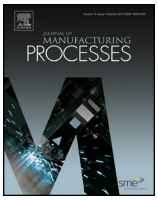

Full length article

Temperature effects on the Ti6Al4V machinability using cooled gaseous nitrogen in semi-finishing turning

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ABSTRACT

More and more stringent environmental concerns and regulations over contamination and pollution are driving the research to alternative cooling strategies that are more environmental friendly but still offer the same advantages of the conventional cutting fluids during machining operations. Even if some solutions, such as Liquid Nitrogen (LN2) or air cooling, have been proved to perform well, they are still rarely used in industrial applications due to their high operating costs, safety issues, and scarce availability of data about their effects on the alloy machinability. In this context, the object of the work is to evaluate the performances of a new cooling method using gaseous Nitrogen (N2) cooled by LN2 in a range of temperature between 0° and $-150\,^\circ$C. The method was applied in semi-finishing turning of the titanium alloy Ti6Al4V. Different tests were conducted in order to evaluate the temperature effects on the Ti6Al4V machinability and identify the cooling condition that guaranteed the best performances in terms of both tool wear and machined surface integrity. The study proved that the coolant temperature influenced the alloy machinability and that a critical temperature existed below which no additional improvements were detected compared to the wet and LN2 cooling strategies used as baseline. The best solution was highlighted using N2 cooled at $-150\,^\circ$C, which induced significant reduction of the rake and flank wear reduction compared to LN2 and wet condition, as well as the improvement of the surface integrity. Furthermore, the coolants cooling capacity was analytically modelled to explain the obtained experimental results.

1. Introduction

In recent years, manufacturing companies are searching solutions to increase their productivity at reasonable production costs and without compromising the component final quality. To this aim, several improvements in the cutting tools, machine controls and innovative lubricating technologies have been already implemented during machining processes. However, a conclusive solution to the environmental issues related to the use of cutting fluids during machining has not been found, yet. Cutting fluid disposal, component cleaning, pollution and human health damage are just few problems that are driving towards more stringent regulations in order to encourage the use of innovative environmental friendly technologies.

Conventional cutting fluids present characteristics of cooling, lubrication and chip assistance; an ideal substitute must guarantee all these functions in addition to the abovementioned environmental and economic sustainability. A candidate showing all these characteristics can be hardly found, however it is desirable to choose a cutting fluid capable to prevent the main mechanisms responsible of both the tool wear and machined surface damage; to this aim, the knowledge of the material machinability when using an alternative cutting fluid results mandatory.

Titanium alloys, and Ti6Al4V in particular, are well-known to be difficult-to-cut metal alloys due to their high chemical reactivity, low thermal conductivity, and relatively high hardness that determine both high cutting forces and significant heat generation in the cutting zone, the latter being the main responsible of rapid tool wear [1,2]. In a previous work [3], the Authors highlighted how the main wear mechanisms occurring in dry cutting semi-finishing turning were diffusion and adhesion, both thermally-activated phenomena, as well as abrasion. In particular, abrasion mainly involved the tool flank face, while adhesive and diffusive wear affected the tool rake face with the formation of the characteristic wear crater. Being the temperature the parameter that mainly influenced the tool wear, the application of the sole cooling technique resulted sufficient in this type of operation to guarantee acceptable tool wear resistance as well as product quality.

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One of the emerging cooling strategies extensively studied and nowadays also industrially available is based on the use of Liquid Nitrogen (LN2): different research works demonstrated its high performances, since to work at cryogenic temperatures (−196 °C) allowed eliminating most of the heat generated during machining difficult-to-cut alloys. Hong et al. [4] reported that the best results were found when cooling simultaneously the tool flank and rake faces and, as observed by Venugobal et al. [5], the beneficial effect increased at increasing depth of cut and feed rate. Bermingham et al. [6] showed how the cryogenic coolant was effective in extending the tool life thanks to the inhibition of the adhesion wear mechanism and reduction of the tool-chip contact length despite the observed increase of the friction coefficient with respect to the wet case.

The use of Carbon Dioxide (CO2) with a working temperature equal to −78.5 °C led to interesting results as well: Machai et al. [7] reported that both the average and maximum flank wear width were reduced compared with those obtained in wet tests, however the chemical reactivity between the workpiece and tool materials still prevailed because the CO2 stream did not have the ability to effectively penetrate the tool-chip interface. Dilip Jerold et al. [8] compared LN2, CO2 and wet strategies with dry cutting finding how the use of CO2 produced the lowest cutting forces and the most reduced flank wear, showing an improvement up to 40% compared to the use of LN2.

Despite the several advantages highlighted hitherto, the industrial application of these cooling technologies is still limited due to their high operating costs in terms of necessary equipment (insulated ranger, vacuum insulated pipe, etc.) and coolant consumes and to their extremely low working temperatures that, especially in the case of LN2, could damage the machine tool components and cause thermal distortions with consequent loss of dimensional accuracy of the machined components. Moreover, the coolant adducted to the cutting zone could induce an excessive cooling of the workpiece material with detrimental effects in terms of both tool wear and machined surface integrity as demonstrated both by Shokrani et al. [9] during Ti6Al4V end milling and by the Authors [10], in semi-finishing turning of the same alloy.

To overcome the aforementioned limitations, this research work presents for the first time an innovative cooling approach based on the use of gaseous Nitrogen (N2) cooled by LN2 in a range of temperature between 0° and −150 °C. The objective of the paper is twofold: (i) to determine the effect of the coolant on the Ti6Al4V machinability finding the best compromise between the working temperature and machinability; (ii) to compare the N2 cooling capacity at different working temperatures with that of the LN2 in order to explain the obtained correlation between the working temperature and machinability.

2. Experimental set-up

2.1. Material

The workpiece material used in this work is the Ti6Al4V ELI alloy [11]. The alloy was supplied by Sandvik^{TM} Bioline in form of bars of 50 mm of diameter in the annealed state. Fig. 1 shows the alloy microstructure analysed by means of optical microscopy and Scanning Electron Microscopy (SEM) with the Back Scatter Electron (BSE) detector: the thermo-mechanical process produced a recrystallized equiaxed structure composed by alpha grains with 8% of beta phase at the grain boundaries. The mechanical properties of the alloy in the as-received state are presented in Table 1: the high values of strength and hardness and reduced elongation at fracture determine a low machinability, thus classifying the Ti6Al4V as a difficult-to-cut alloy.

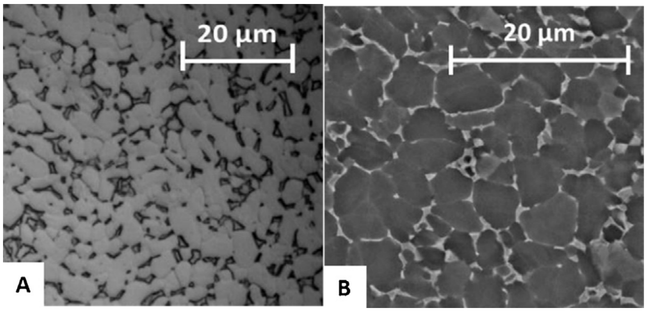

Fig. 1. Ti6Al4V microstructure in the as-received state: A) optical microscopy image, and B) BSE-SEM image.

Table 1
Mechanical properties of the Ti6Al4V in the as-received state (from Sandvik Bioline datasheet [12]).

	E (GPa)	UTS (MPa)	Y_S (MPa)	Elongation (%)
Ti6Al4V	118	940	870	15.0

Table 2
Experimental plan for the turning tests.

Cutting parameters	
Cutting speed (m/min)	80
Feed rate (mm/rev)	0.2
Depth of cut (mm)	0.25

2.2. Turning tests

The semi-finishing turning tests were carried out on a Mori-Seiki^{TM} NL1500 CNC lathe using TiAlN coated tungsten carbide inserts supplied by Sandvik^{TM} (CNMG 120404-SM1105), with a radius of 0.4 mm, rake and clearance angles of 7° and 0°, respectively. The inserts were clamped in a Sandvik^{TM} PCLNR 2020 K 12 tool holder with an approach angle of 95°. In a previous work carried out by the Authors [13], it was highlighted that the best results in terms of tool wear were obtained using the set of cutting parameters reported in Table 2, 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.

The turning tests were carried out using gaseous Nitrogen (N2) as cutting fluid, cooled through an experimental apparatus called Cryofluid^{TM} patented by Air Liquide Service Italy. The N2 was cooled to different temperatures in the range between 0° and −150 °C within an insulated chamber where Liquid Nitrogen (LN2) was mixed with the N2 until reaching the desired temperature. As soon as the desired temperature was reached, it was kept constant for the whole test using an internal PLC controller to manage the flow rates of the two fluids. The output pressure of the cooled N2 was set constant at 2.5 bar. In order to provide the right amount of coolant, a single nozzle with internal diameter of 6 mm was fixed onto the tool holder so as to direct the flow to the tool rake face being this area the most exposed to the thermally-activated wear mechanisms. An overall image of the experimental apparatus with a detail of the cutting zone is shown in Fig. 2.

Two other cooling conditions were used as baseline, namely the wet condition making use of a water emulsion with 5% of semi-synthetic cutting fluid Monroe^{TM} Astro-Cut HD XBP, and the LN2 cryogenic cooling at 15 bar. For the latter case the lathe was provided with a self-designed cooling line to supply the LN2 in the cutting zone; two copper nozzles with internal diameter of 0.9 mm