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Internal cryolubrication approach for Inconel 718 milling

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Abstract

Due to their extremely performant capabilities, super-alloys are gratefully acknowledged by mechanical designers to satisfy the requisites from the combustion chambers and other hot parts from the aircraft turbine. However, the high mechanical resistance and high chemical reactivity of heat resistant super-alloys (HRSA) lead to very aggressive machining operations where the tool life must be conveniently protected with cutting fluids. The novelty in this work lies in the idea of applying cryogenic cooling with MQL lubrication (CryoMQL) with CO2 as internal coolant to favor the integration of more environmental friendly machining systems. To prove the benefits from the novel technique, CryoMQL was compared with other lubri-coolant technologies. In this context, contour milling tests were carried out in Inconel 718.

Keywords: Cryogenic machining; Inconel 718; CryoMQL; CO_2 coolant.

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1. Introduction

The use of heat-resistant alloys in aeronautical turbomachinery industry is growing worldwide. Improving machining processes in this type of alloys is a challenge which has to be faced due to both economic and environmental reasons. On one hand, cutting fluids in difficult-to-cut alloys supposes between 20-30% of manufacturing costs [1]. On the other hand, although some of fluids are recovered, 30% is lost due to system leaks, evaporation or dirty [2].

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Hence, it is needed to explore new lubri-cooling techniques and strategies. Within this context, minimum quantity lubrication (MQL) and cryogenic technologies are positioned as key alternatives for improving both technical and environmental pollution produced by machining processes. MQL lubrication consists in spraying biodegradable micro-oil particles in the cutting zone with an oil flow-rate between 10-100 ml/h. This reduces the environmental and economic impact associated to machining processes. On the other hand, in cryogenic machining, liquid nitrogen (LN2) or carbon dioxide (CO2) is used as cutting fluid. Among other advantages, it does not generate any waste being completely harmless to workers' health. Furthermore, in the case of CO2, it is obtained from a primary process, that is, it is used a second time instead of being directly exhausted to the atmosphere as waste. Thereby, environmental innocuousness associated to conventional cryogenic machining is maintained.

Inconel 718 is the most heat-resistant alloy used in turbomachinery critical components. Properties such as good tensile strength, fatigue or creep resistance combined with a high corrosion resistance at high temperature makes it the best choice. However, these properties during machining processes lead to high cutting forces, low material removal rates, adhesion, welding and other problems that cause premature tool breakage. Furthermore, surface integrity shall be damaged by both thermal and mechanical effects [3]. Therefore, during machining there is a dual need of lubricating and cooling the cutting zone. From the literature, predominant wear effects are produced by chipping, adhesive, abrasive or diffusion wear [4-8]. So, the combination of cryogenic technology with MQL lubrication could be an advantageous alternative. This combination, also known as CryoMQL, was explored and studied in several researches either for roughing operations or in finishing operations, to enhance surface integrity in comparison with other lubri-cooling technologies [9-11]. However, CryoMQL applied to contour milling using end mills with internal channels was not tested. This is a common operation in the manufacturing of turbine cases and so, tooling costs (end mills and fluids) could be significantly reduced. In this case, MQL is injected in the cutting zone externally and CO2 is injected through the tool. Thus, the tool works as a heat exchanger and the material is not hardened by CO2 resulting in relatively lower and stable shear stress during the machining.

Under this perspective, in order to prove the benefits from the novel technique, CryoMQL with internal CO2 setup was compared against conventional CryoMQL with external CO2 for milling Inconel 718 between other techniques as wet machining or MQL lubrication. The experimental procedure included the recording of cutting forces and wear measurements at different tool life stages to choose the best performance.

2. Experimental setup

Experimental tests were performed in a Kondia A6 three axis-machining center under wet machining, MQL lubrication and CryoMQL machining. The oil emulsion flow-rate was 7 l/min. The oil flow-rate used during MQL and CryoMQL machining was 100 ml/h. In the case of CryoMQL machining, CO2 was injected with 14 bars and -78ºC. Besides, when it was needed, CO2 was injected through the internal tool channels, as shown in Fig. 1.

Fig. 1. CO2 injected as external and internal coolant.

The work material was aged nickel-based superalloy (Inconel 718), which is hardened by precipitation of secondary phases into the metal matrix (45 HRc). The chemical composition is shown in Table 1.

Table 1. Inconel 718 percentage.

Ni	Cr	Co	Fe	Nb	Mo	Ti	Al	B	C	Mn	Si	Others
52.5%	19%	1%	17%	5%	3%	1%	0.6%	0.01%	0.08%	0.35%	0.35%	1.79

The cutting tools used were carbide end mills with D=10 mm, 6 flutes, helix angle β=45º and coated with TiAlN. Cutting conditions were Vc=60 m/min, fz=0.02 mm/tooth, ap=10 mm and ae=0.2 mm. As wear criterion, the tests were stopped at a flank wear of VB=0.2 mm, because higher values (from previous experiences) demonstrated the surface integrity can be affected.

In this research, several ways to apply the different lubricooling techniques were used, respectively. To inject conventional oil emulsions, convergent nozzles were used. In the case of MQL spray, it was injected using a double-channel nozzle to make Venturi's effect and pulverize the oil. Finally, to apply CryoMQL techniques two ways were used. In this case, despite MQL spray was used as external coolant, CO2 was injected as internal and external coolant, respectively. When CO2 is used as external coolant, a convergent nozzle was used. However, to be able using CO2 as internal cutting fluid, high pressure tools with internal channels were needed. These tools are provided with holes matrix in each rake face.

During the process, cutting forces were recorded using a triaxial Kistler 9255 piezoelectric dynamometer and an OROS® OR35 real-time multi-analyzer with a sample frequency of 16,384 samples/s. Besides, Tool wear VB was progressively measured by pausing the passes at different stages (Nikon SMZ-2T microscope).

The experimental setup is shown in Fig. 2. The cutting tests were planned as successive passes of contour (peripheral) down-milling of 200 mm length. The tool entrance and exit is done tangentially with a radius of 15 mm.

forces and wear measurements at different tool life stages to choose the best performance.

3. Test results and discussion

In this research, the main aim is to compare internal CryoMQL with other near-to-dry and conventional techniques during Inconel 718 machining. Measuring the cutting forces along the process is a good indicator to decide between the different alternatives. The procedure was doing short cutting passes to continuously track tool wear, what is critical for superalloys.

Fig. 3 shows a view of the average cutting forces at different tool wear stages. In the first stage, when the tool is new, tool wear influence in the cutting forces can be neglected. In this case, the differences obtained in the cutting forces are mainly caused by the lubricooling techniques used in each test. Taking MQL cutting forces as reference, the other one values are lower. This is due to MQL spray lubricates but does not cool the cutting zone. However, cooling the cutting zone also can harden the material and makes the cutting process more aggressive. This behavior is shown by the difference presented in the cutting forces between external CryoMQL and internal one. On the other hand, it should be noted the slight differences between internal CryoMQL and wet machining cutting forces. These values along the tests are below 10%, what supposes similar behavior between both techniques.

Together with force measurements, machined length was also analyzed. From the wear rates for each of the studied techniques, it is possible to describe the most performant process by summation of the machining passes (length) until the specified wear limit (VB=0.2 mm). In Fig. 4, the machined length reached with each lubricooling technique is shown.

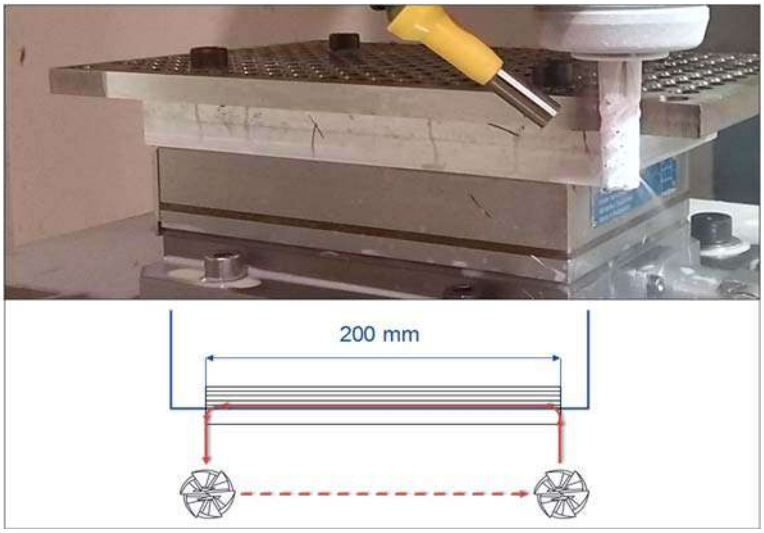

Fig. 2. Experimental setup.

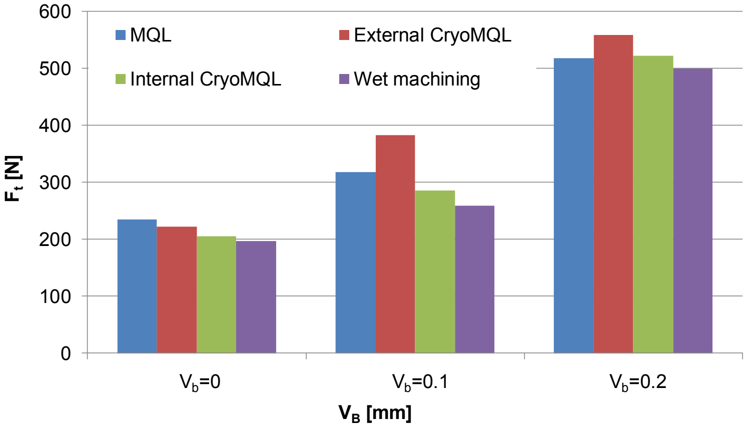

Fig. 3. Average Cutting forces at different stages.

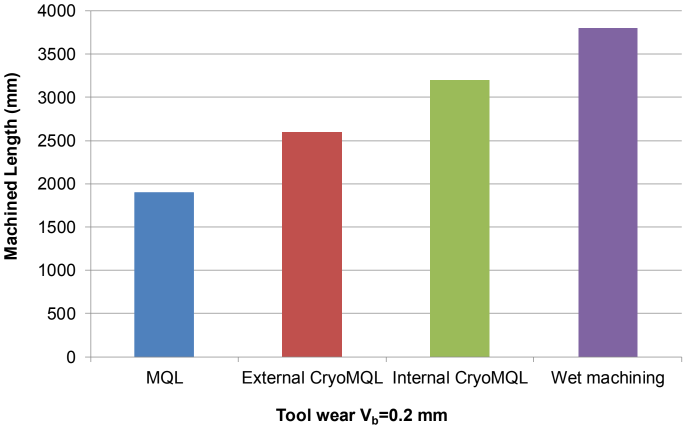

Fig. 4. Machined length by the different lubricooling techniques.

Using MQL, the lubrication effect of the oil spray injected in the cutting zone implies a machined length of 1900 mm. However, if the cutting zone is both lubricated and cooled with external CryoMQL technique this value increases until 2600 mm. However, if these values are compared with the obtained with wet machining, they are not enough to obtain a feasible process. In this situation, internal CryoMQL is presented as a solution which presents a balance between ecological and technical issues. In fact, with this technique the machined length reaches 3200 mm, what supposes only a difference of 16% in comparison with wet machining technique. This is possible because instead of cooling the material, the tool is used as heat exchanger what reduces the tool wear due to 2 reasons. The first one is which in comparison with MQL lubrication, the tool is not exposed to so high temperatures. The second reason is related with the way in which CO2 is used and thus, makes the difference between internal and external CryoMQL: In this case, the CO2 cools the tool but not the material. Then, the material is not hardened by the CO2 and the shear stress is maintained relatively lower. Thus, with internal CryoMQL technique the benefits of both green technologies are combined.

4. Conclusions

In this paper a new CryoMQL performance is presented. The advantage of this setup is which not only combines the benefits of MQL and cryogenic technology but also reduces CO2 consumption.

To test its technical viability, this technology was compared with MQL, external CryoMQL and wet machining during Inconel 718 contour end milling. The experimental results obtained shown that the use of internal CryoMQL performance implies an improvement in comparison with other green technologies as external CryoMQL or MQL in "stand alone" mode. Besides, if it is compared with wet machining, slight technical differences are obtained. In particular, cutting forces values are below 10% and machined length 16%, what supposes a great approach to obtain an industrial feasible process.

Therefore, taking into account these experimental results, internal CryoMQL is the most suitable alternative in a medium-short term to substitute oil emulsions in workshops, presenting a balance between technical and environmental issues.

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