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Surface Integrity When Machining Inconel 718 Using Conventional Lubrication and Carbon Dioxide Coolant

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Abstract

Surface integrity induced by machining process affects strongly the performance of functional products, for instance, the fatigue life as well as the resistance to stress corrosion cracking. Consequently, it is relevant to evaluate the induced properties on and beneath the machined surface to ensure the good performance of the mechanical components while operating under either static or cyclic loads. Furthermore, this is even more important when designing critical components that withstand high loads at high temperatures. In this context, many studies have been carried out in order to characterize the surface integrity (residual stresses, surface roughness, micro-hardness of the affected layer) when machining Inconel 718. However, so far, the cryogenic effect on surface integrity of Inconel 718 is not well established although some preliminary works have already been developed. Therefore, this work aimed to point out the performance of cryogenic machining using the carbon dioxide CO2 as a cryogenic cutting fluid, considering as a reference the conventional lubrication. A comparative study has been carried out during turning operations of Inconel 718 using the same cutting parameters and the same tool geometry. Microhardness measurements showed that the CO2 condition induced higher strain hardening near the surface while conventional condition did not generate notable difference compared to the bulk material microhardness. With respect to residual stresses, results showed that conventional lubrication generated higher tensile residual stress near the surface along the cutting direction when using new tools. As for CO2 cryogenic condition, lower tensile residual stresses have been obtained near the surface. In addition, CO2 condition induced the largest compressive peak when using new and semi−worn tools in comparison with conventional lubrication.

Keywords: Carbon dioxide; Inconel 718; Machining; Surface integrity

1. Introduction

Nickel based alloys exhibit high performance over a wide range of temperature such as high strength and good corrosion resistance [1,2]. These superalloys are frequently used in the hot parts of gas turbine engines. However, during the machining process, these alloys are classified as difficult to cut materials due to a low thermal conductivity causing very high temperature at the cutting zone, high chemical reactivity with most of tool materials as well as high strength [3,4]. All these properties induce rapid tool wear and thereby the final surface integrity of the machined parts is adversely impacted. In this context, cryogenic fluids are employed in order to cool down. the cutting zone and hence to decelerate the tool wear mechanisms occurring at high temperature and to enhance the surface integrity of the workpieces [5]. Currently, one of the most employed cryogenic systems is the one based on carbon dioxide (CO2). Compared to conventional lubrication, the carbon dioxide presents advantages with respect to ecological and health issues. CO2 is maintained liquid at room temperature at high pressure holding 57 bars. When delivering CO2 at the cutting area, the fluid changes to snow (dry ice) and

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gas with respect to the Joule Thomson effect [6] as displayed in Figure1.

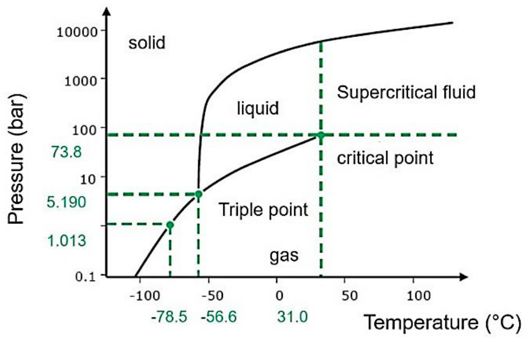

Fig. 1. Illustration of phase diagram of carbon dioxide CO2 [7].

According to literature review, CO2 cooling strategy showed good trend in terms of tool wear decrease when machining titanium alloys [6,8]. Consequently, surface integrity of the workpiece could be favorably improved. Most of previous studies that examined the CO2 effectiveness when cutting Inconel 718 have only investigated the tool wear evolution and cutting forces. For instance, Fernandez et al. [9] have focused on evaluating the cryogenic effect of CO2 strategy in milling operation of several materials including Inconel 718 in comparison with flood emulsion. They have only highlighted the tool wear results without mentioning the consequence on surface integrity. Recently, Vignesh and Mohammed Iqbal [10] have compared the performance of the liquid nitrogen (LN2) and the CO2 in terms of surface roughness when turning a nickel based alloy (Hastelloy C276). Authors found that the LN2 induced better results with respect to the surface roughness but they did not mention the effect of CO2 condition on neither microhardness nor residual stresses.

Patil et al. [11] examined the effect of compressed cold CO2 cooling strategy on the surface finish and the microhardness of the parts when turning Inconel 718. They claimed that the surface finish was improved due to a decrease in tool wear. Authors also found that the microhardness of the machined surfaces and subsurfaces showed a notable gradient of microhardness com- pared to the bulk material hardness reaching 505 HV near the surface against 380 HV in the bulk.

Other studies have identified the relationship between tool wear and microhardness alterations. Sharman et al. [12] investigated the tool wear effect on the microhardness of the workpiece when turning Inconel 718 with conventional cooling. They found that as the tool wear increases, the amount of the plastic deformation increases as well. Indeed, they proved that the depth of plastic deformation and the maximum microhardness are closely related to the cutting forces claiming that the resultant force increase induces higher level of strain hardening.

Nevertheless, residual stresses distribution were just studied in the case of LN2 cryogenic cooling condition when turning Inconel 718 [13,14]. So far, previous studies have not revealed the impact of CO2 cryogenic condition on the residual stress distributions when machining Inconel 718. In this paper, a comparison between conventional lubrication and CO2 cooling condition is conducted to evaluate the efficiency of CO2 cooling condition when turning Inconel 718 in finishing operations in terms of microhardness measurements and residual stresses distribution.

2. Experimental material and methodology

Inconel 718 is a nickel based alloy and its microstructure is composed of the austenitic matrix ’γ’, the phase precipitations γ’(Ni3(Al,Ti)), γ’’(Ni3Nb) and δ (Ni3Nb) besides the carbides particles. The phase precipitations were obtained during a structural hardening heat treatment according to the following cycle: solution treatment at a temperature of 940°C, heating at a temperature from 940 to 1010°C followed by water quenching, heating until 720°C for eight hours, cooling until 620°C with a speed equal to 50°C/h and maintain for eight hours at this temperature followed by air cooling. The mechanical properties of the superalloy are given in Table1.

Table 1. Mechanical properties of Inconel 718

Ultimate Compression Strength (MPa)	1754
Yield strength (MPa)	1150
Young modulus (GPa)	206
Hardness ($HV_{0.1}$)	462
Thermal conductivity coefficient (W/m.K)	11.2

Longitudinal turning operations of Inconel 718 have been conducted under conventional and CO2 cryogenic conditions using the CNC lathe Danumeric 2 (Figure 2).

Fig. 2. Illustration of CO2 experimental set-up

DNMG 150612-MS US905 insert tools were employed during the machining experimental trials. Cutting parameters were fixed namely: the cutting speed Vc = 70 m/min, the feed rate f = 0.2 mm/rev and the depth of cut ap = 0.2 mm. For each cooling strategy, two repetitions were conducted. Tool flank wear measurements was performed using a LEICA Z16 APO stereo-microscope. Microhardness measurements were carried out using the Vickers microhardness testing method applying a load of 50 g and the full load was maintained for 10 s. Two repetitions were conducted for each cooling condition. The microhardness measurements started with 30 µm from the machined surface, followed by five indentations separated of

70 µm and the final four indentations were separated of 100 µm. Residual stresses measurements were conducted employing the blind hole drilling method according to the ASTM standard using the RESTAN MTS300 hole-drilling equipment. The EA-06-031Re-120 strain gauges were employed and the drill bits with a diameter of 0.8 mm. Regard the depth of drilling, the first five increment were of 10 µm, followed by 5 increments of 20 µm and the final seven increments were of 50 µm.

3. Results and discussions

3.1. Tool wear

The experiments were stopped after 15 min of machining where the maximum criterion of tool flank wear defined as V_{BMAX} = 0.3 mm was not reached. Figure 3 gives information of the tool flank wear states measured by the end of the test.

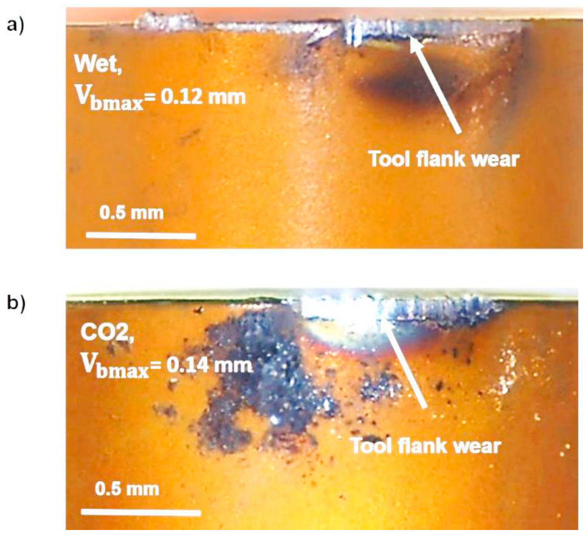

Fig. 3. SEM observations of the tool flank wear states after 15 min of machining under: a) wet; b) CO2 cooling strategies.

During wet condition, the maximum tool flank wear value held 0.12 mm of V_{BMAX} while under CO2 condition, this parameter was equal to 0.14 mm. In this work, these levels of tool flank wear are defined as semi−worn tools.

3.2. Microhardness

This study aims to examine the tool flank wear effect on the microhardness profiles obtained under conventional and CO2 cooling approaches. Figure 4 presents the microhardness evolution below the machined surfaces when cutting using semi−worn tools.

Results show that CO2 cooling strategy induced higher strain hardening than the conventional lubrication beneath the machined surfaces. Indeed, the maximum value was measured very close in the near-surface layer of the machined parts holding 500 HV in CO2 cooling condition against 477 HV in conventional condition while the bulk material exhibits 462 HV. This could be explained by the fact that the low temperature of the fluid generated harder work material as reported in [11].

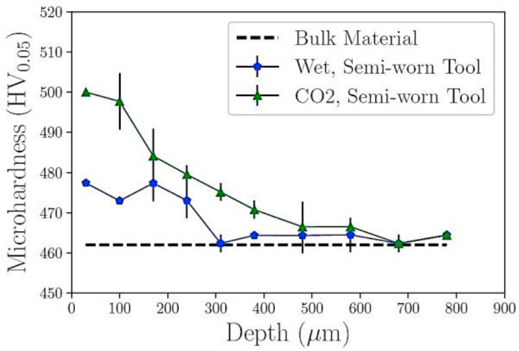

Fig. 4. Illustration of the microhardness evolution below the machined surfaces under wet and CO2 conditions when using semi−worn tools.

Moreover, it is worth mentioning that higher machining forces were found when using CO2, and therefore inducing more severe mechanical deformation [15]. The same trend was obtained in [13] revealing that cryogenic temperature during the machining process caused harder larger work hardened layer was observed in CO2 condition along 380 µm starting from the free machined surface.

3.3. Residual Stresses

Superficial residual stresses generated during the machining process affects significantly the workpiece performance while operating, specifically the fatigue life [16]. According to literature review, it is rather preferred to obtain compressive than tensile residual stresses in the issue of crack initiation [17]. Figure 5 highlights the residual stresses measured near the surface when using new tools under both conditions.

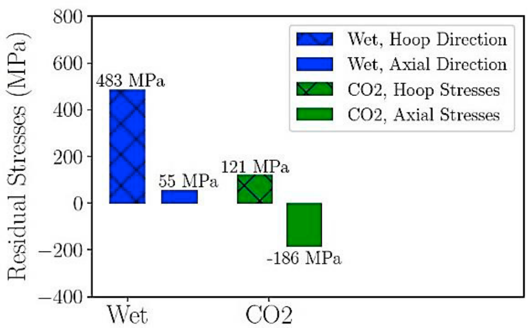

Fig. 5. Residual stresses measured near the surface (10 µm below the surface) under wet and CO2 cooling strategies when machining using new tools.

Results show that CO2 strategy induced lower tensile residual stresses along the hoop direction (cutting direction) holding 121 MPa versus 483 MPa measured in conventional condition. Compressive residual stresses were obtained along the axial direction (feed direction) in CO2 condition while tensile value was obtained in conventional lubrication. Besides, if comparing the compressive peak generating both conditions, CO2 cooling strategy provided larger compressive peak either in hoop or axial directions holding respectively -298 MPa and -247 MPa against -199 MPa and -61 MPa (Figure 6) in conventional lubrication. This result might be beneficial with respect to fatigue resistance.

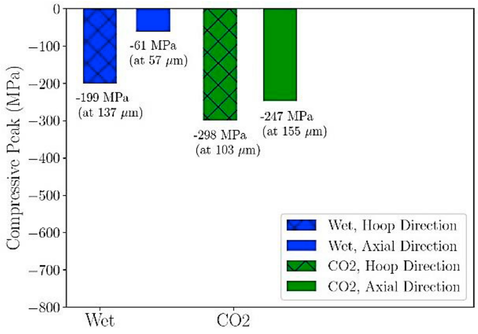

Fig. 6. The corresponding compressive peak obtained under wet and CO2 cooling strategies when machining using new tools.

Figure 7 illustrates a comparison between the wet and the C02 cooling effects on the superficial hoop and axial residual stresses when machining using semi worn tools. Under conventional condition, the near surface residual stress along the hoop direction increased to achieve around 670 MPa versus 405 MPa in CO2 cooling condition. Along the axial direction, more tensile residual stress was observed in conventional lubrication while compressive residual stress were obtained in CO2 condition.

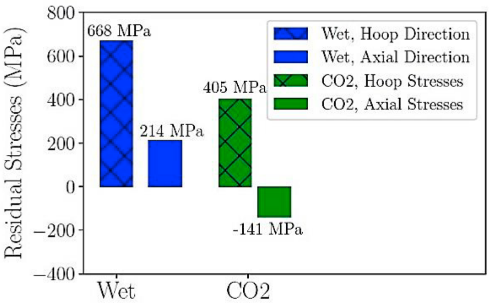

Fig. 7. Residual stresses measured near the surface (10 µm below the surface) under wet and CO2 cooling strategies using semi−worn tools.

Furthermore, the compressive peak was higher in CO2 condition than in conventional lubrication when using semi worn tools (Figure 8). These results may justify the cooling efficiency of the cryogenic fluid CO2 to reduce the thermal load effect and thereby higher compressive stresses are generated knowing that two different mechanisms involved in the residual stresses generation (thermally and mechanically influenced plastic deformation) that control the resulted residual stresses generated in the machined surfaces [18]. It should be also noted that tool wear evolution affects notably the distribution of the residual stress distribution along both directions (hoop and axial) due to the increase of the cutting forces components (especially the radial force) as reported in [12].

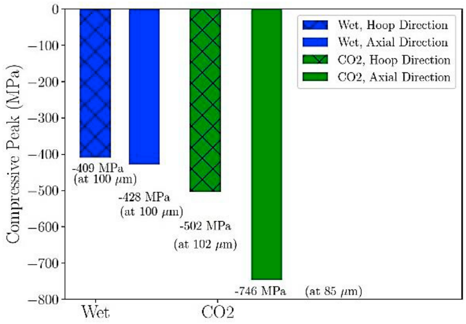

Fig. 8. The corresponding compressive peak obtained under wet and CO2 cooling strategies when machining using semi−worn tools.

Furthermore, if comparing the depth of the compressive peak obtained under both conditions when using new tools, along the hoop direction, the depth of the compressive peak exhibited higher value in conventional lubrication though the compressive peak value was lower. Nevertheless, along the axial direction, the depth of the compressive peak was higher un- der CO2 cryogenic condition as depicted in Figure 6. In the case when tool wear increased (using semi worn tools), no significant difference was revealed under both cooling conditions (Figure 8). Overall, no obvious correlation could be identified in terms of cooling conditions effect regardless the tool wear state with respect to the depth of the compressive peak.

4. Conclusion

In this study, a comparison between conventional lubrication and CO2 cryogenic strategy was carried out in terms of surface integrity of the work material Inconel 718. The main results of this work consist in higher work-hardening of the machined surfaces obtained in CO2 cooling condition. Besides, lower tensile residual stresses near the surface as well as larger compressive peak were observed in CO2 condition when com- paring with the conventional lubrication. Regard tool wear effect, results showed that more tensile residual stresses near the surface and larger compressive peaks were generated along the hoop and the axial directions when using semi worn tools un- der both cooling strategies. Based on the obtained results, CO2 cooling strategy seems to be more appropriate since this cooling approach produces a better surface integrity than conventional lubrication and therefore probably a better fatigue resistance.

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