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ORIGINAL ARTICLE

Surface integrity of INCONEL 718 turned under cryogenic conditions at high cutting speeds

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Abstract
Nickel alloys such as Inconel 718 have been widely used in the aerospace, oil and gas, and chemical industries, since they have excellent properties that combine high creep resistance and high mechanical strength, fatigue and corrosion. However, these properties make these alloys extremely difficult to machine, due to a high level of heat generation during material removal, causing rapid wear of cutting tools and a detrimental effect on the surface integrity, reducing the fatigue life of the machined component and lowering the productivity. Looking at the literature, it seemed that there is an opportunity to study the surface integrity of Inconel 718, turned under cryogenic conditions at cutting speeds of 250, 275 and 300 m/min. For these reasons, this work aims to evaluate the influence of the cutting parameters on the surface integrity of Inconel 718 turned under cryogenic conditions using liquid nitrogen (LN2) at high cutting speeds. A whisker-reinforced ceramic tool was used in order to provide wear and shock resistance at high cutting speeds; these are factors that are associated with surface integrity in terms of roughness Ra, residual stresses, micro-hardness and cutting forces. A central composite design was chosen as factorial planning for the independent variables including cutting speed, feed rate and depth of cut when carrying out the experiments. Cryogenic cooling resulted in an average cutting force of 267 N, where the penetration force was higher. The roughness Ra was 0.52 μm and was influenced by the feed rate and depth of cut. The highest tensile residual stresses in the circumferential direction with LN2 and under dry conditions were 1394 MPa and 1237 MPa, respectively and were influenced by the depth of cut. Small changes in microhardness occurred at a depth of 0.3 mm from beneath machine surface and the presence of a white layer was not observed. Although tensile residual stresses were slightly higher when using LN2 compared to dry machining on the surface, the use of LN2 caused higher compressive residual stresses at the subsurface, which can improve the fatigue life of machined components at high cutting speeds. The results showed that lower cutting parameters tend to give the best results in terms of the cutting force and surface integrity.

Keywords Turning · Inconel 718 · Surface integrity · Cryogenic cooling · Liquid nitrogen

1 Introduction

According to Thakur and Gangopadhyay [43], nickel-based superalloys have found extensive application, primarily in critical components of aerospace engines and gas turbines. Umbrello [47] studied the use of superalloys in severe environments, and in particular, their ability to maintain high resistance to mechanical stress, corrosion, thermal fatigue, creep and erosion at high temperatures.

Hadia et al. [14] describe the nickel-based superalloys as exhibiting several key characteristics such as excellent mechanical strength, resistance to thermal creep deformation and good surface stability, and show that they are

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widely applied in the oil and gas, aerospace, chemical and petrochemical industries. Additionally, Villares Metals [48] show that nickel-based superalloy has a resistance to corrosion and oxidation and can be applied at cryogenic temperatures below − 250 °C.

Umbrello [47] also comments that Inconel 718, a commercially available nickel-based superalloy, is commonly used for many applications, for example in aircraft, gas turbines, space vehicles, heat-treating equipment, nuclear power plants, the chemical and petrochemical industries and heat exchangers.

There are several manufacturing processes in which Inconel 718 is applied; according to Kaynak [18], machining is one of the most important processes in the manufacture of functional components, for example in the aerospace, oil and gas, and other industries. However, in view of its physical and chemical properties, Ezugwu et al. [11] describe Inconel 718 as hard to machine in comparison to steels. For Olgun and Budak [24], this is due to its low thermal conductivity and high heat resistance, which cause an increase in temperature in the cutting zone and reduce its machinability. Other factors that reduce machinability have also been identified by Thakur et al. [44] as hardening, the presence of abrasive carbide particles and the chemical affinity of the Inconel alloy, which reacts with several types of cutting tool materials.

The effects of the low machinability of the Inconel alloy are mainly seen in the rapid wear of the cutting tool. For Zhu et al. [54], this wear is generally associated with the mechanical properties (mainly abrasion) and chemical properties (thermochemical wear and diffusion) of the interactions between the cutting tool and the material. Due to the large amounts of heat generated during the machining of Inconel, a carbide insert is generally used in low cutting speed. However, a carbide insert has a limited life at low cutting speeds, giving lower productivity. According to Pande and Sambhe [25], a ceramic and CBN insert has more resistance to the heat and wear generated by a high cutting speed, which can be useful in increasing productivity.

Xue and Chen [50] show that tool wear not only affects the integrity of the surface of the machined component but also reduces the life of the cutting tool, affecting the production process. Aramcharoen and Chuan [3] find that when machining materials with a high shear strength and low thermal conductivity, such as nickel-based alloys, conventional oils (mineral and water-soluble oils) are not sufficiently effective in reducing heat generation in the cutting zone. Yildiz and Nalbant [51] show that one of the most suitable methods for the reduction of heat in the cutting zone is cryogenic cooling by liquid nitrogen, finding that this has a considerable capacity to reduce tool wear by reducing the temperature within the workpiece-tool contact area. According to Sivaiah and Chakradhar [34], cryogenic machining effectively reduces the cutting temperatures and it can be applied to machining of difficult-to-cut materials to improve the performance characteristics. Sivaiah and Chakradhar [38] completed that cryogenic machining is an environmental clean machining process and can be successfully applied to different machining processes for improving the machining performance.

The temperature of the cutting zone is one of the main factors that can be used to guarantee the surface integrity and thus increase the fatigue life of the machined component, since thermal effects resulting from high temperatures cause deformations and induce tensile residual stresses that are not beneficial in components operating in regimes of high mechanical stress. In this sense, Sivaiah and Chakradhar [34] concluded that cryogenic machining effectively reduces the cutting temperatures due LN2 characteristics. In relation to surface integrity, Kenda et al. [19], the compressive residual stresses are usually aimed at the machined surface to increase the fatigue life.

Lately there is a great deal of concern with environmentally friendly production processes and operator safety. Sivaiah and Chakradhar [39], while studying the modelling and optimization of sustainable manufacturing process, concluded that cryogenic coolant evaporates quickly after reaching machining zone, hence is a clean production technique.

1.1 Machining of Inconel 718 with ceramic tools

Li et al. [20] compared the use of three coated carbide inserts (TiCN/Al2O3/TiN, TiAlN and TiN/TiCN/TiN) and four Sialon ceramic inserts (SiAlON) from different classes and with different geometries, with cutting optimized using Taylor's equation and dry machining using Inconel 718. They concluded that the relation between the amount of material removed and the life of the tool was optimal for a ceramic tool at high cutting speeds (over 125 m/min), using an insert with round geometry. Amini et al. [2] also performed studies of Inconel machining and compared tools made of alumina-based mixed ceramic (Al_2O_3 + TiN) and a carbide insert with TiAlN-coating, finding a relation that minimized the values of average roughness and shear strength. They therefore concluded that ceramic inserts showed better results under certain machining conditions, even at higher cutting speeds. This relation was defined under two conditions: for an average roughness of 0.894 μm, the parameters found were: vc = 200 m/min; f = 0.08 mm/rev; ap = 0.4 mm, while for a lower cutting force (F = 118.8 N), the cutting parameters were: vc = 150 m/min; f = 0.05 mm/rev; ap = 0.4 mm. Ezugwu et al. [11] used ceramic inserts with silicon carbide whiskers (SiCw) using conventional refrigeration and different types of cooling pressures for Inconel 718 machining. The best result in terms of tool life and lower wear by notching was obtained using a cutting speed of 270 m/min (f = 0.1 mm/rev, ap = 0.5 mm) with a cooling pressure of 15 MPa. This shows that adjustments to the cooling pressure can accentuate notch wear and consequently reduce tool life. Altin et al. [1] studied the effects of cutting rate on the machining of Inconel 718 using two classes of ceramic inserts (Sialon ceramics and whisker-reinforced alumina ceramic, Al_2O_3 + SiCw), two different types of geometry (square, SNGN, and round, RNGN) and conventional cooling. This comparison showed that at a cutting speed of 200 m/min (f = 0.2 mm/rev, ap = 2 mm), all types of inserts showed less than the maximum wear of 0.3 mm according to the ISO3685 standard after removal of the material volume at 273 cm^3. The RNGN inserts showed lower flank wear than the SNGN inserts at higher cutting speeds. With regard to the main wear mechanisms, notch and flank wear were more evident for the round geometry inserts, while for the square insert, crater wear was observed in addition to flank wear.

1.2 Machining of Inconel 718 with liquid nitrogen

According to Yildiz and Nalbant [51], liquid nitrogen is widely used in the cryogenic refrigeration process of metallic parts and is produced industrially by fractional distillation of liquid air. Sharma et al. [33] show that LN2 at around − 196 °C can be applied to reduce the temperature in the cutting zone. Sivaiah and Chakradhar [35] showed that in cryogenic machining, appreciable improvements of the product surface and sub characteristics were observed, which lead to high reliability of the product. Sivaiah and Chakradhar [40] cited that cryogenic machining is a novel eco-friendly as well as efficient cooling techniques. Kenda et al. [19] demonstrated that the use of cryogenic cooling conditions decreases the thermal effect and consequently reduces the tendency for producing tensile stresses. In a study by Aramcharoen and Chuan [3], the application of cryogenic cooling by LN2 reduced the temperature in the cutting zone by 44% compared to dry machining. Fernández et al. [12] also carried out experiments to compare different cooling techniques in Inconel 718 machining. Taking the same criterion as Kaynak [18] for maximum flank wear (ISO 3685), the volume of material removed was larger with the use of cryogenic refrigeration (6 bar) when compared to techniques such as emulsion, cold air and dry machining. Reinforcing this argument, Sivaiah and Chakradhar [36], when conducting an experimental investigation of 17-4 PH stainless steel turning, concluded that the maximum tool flank wear reductions observed in cryogenic machining was 40% compared to dry environment. PVD coated carbide was used in this experiment with a cutting speed of 50 m/min (f = 0.25 mm/rev and ap = 0.3 mm). The predominant wear in Inconel 718 machining was abrasion on the flank of the tool but wear as crater and notch type were also observed, especially at the end of tool life. Sivaiah and Chakradhar [37], when machining of 17-4 PH stainless steel, proved that cryogenic turning improve performance at higher cutting velocities, increasing the productivity with better superior quality.

1.3 Surface roughness in machining of Inconel 718

Bushlya et al. [8] used PCBN inserts with and without TiN coating in the machining of Inconel 718 with different cutting parameters, using semi-synthetic oil-based cooling, and analysed aspects of the surface roughness and surface integrity. They observed a large difference in roughness between the coated and uncoated inserts using the smallest feed rate (0.1 mm/rev). According to Zhou et al. [52], this behaviour can be attributed to the softening of the workpiece material due to the low thermal conductivity of the TiN coating. In addition to the cutting parameters, another factor that influences the roughness is the geometry of the tool. Arunachalam et al. [4] analysed the effects of cutting tool geometry on surface roughness with round and square CBN inserts for Inconel 718 machining. After 25 mm of machining, the higher roughness value using a square insert was found to be due to the occurrence of built-up edge wear, which deposited material on the machined surface; this did not occur for the round insert. Coelho et al. [9] also compared the influence of tool geometry on roughness using two classes of ceramic inserts (mixed ceramic and silicon carbide ceramic) and a CBN insert. The results showed that the round insert gave lower roughness than square and triangular geometries. The cutting data used in this study were the same for the different classes of the tool material as for the different geometries (vc = 500 m/min, f = 0.1 mm/rev and ap = 0.35 mm). In addition to the round geometry, the ceramic insert also gave lower roughness, and was thus a good option for Inconel 718 machining. Pusavec et al. [29] evaluated the roughness under dry machining, and with MQL, LN2, and MQL with LN2, using a carbide cutting tool. Using values of vc = 60 m/min, f = 0.05 mm/rev and ap = 0.63 mm, they showed that the roughness using LN2 was lower than for dry and MQL (Minimum Quantity Lubrication) machining. Zhuang et al. [55] evaluated the surface roughness under different refrigeration conditions (dry, induction preheating and LN2) with the use of a ceramic tool. They noticed that the LN2 gave lower roughness than dry machining, which they ascribed to a reduction in the temperature within the cutting zone. The other cutting parameters used were f = 0.2 mm/rev and ap = 1.5 mm.

1.4 Residual stress in the machining of Inconel 718

Pawade et al. [27] analysed the influence of the CBN tool on surface integrity in the machining of Inconel 718 with different cutting parameters and tool geometry, and without coolant oil. Three cutting speeds (125 m/min, 300 m/min and 475 m/min), feed rates (0.05 mm/rev, 0.10 mm/rev and

0.15 mm/rev) and depths of cut (0.5 mm, 0.75 mm and 1 mm) were used. A change in the cutting speed from 125 m/min to 300 m/min caused the residual stress to increase in the tensile direction, while a cutting speed of 475 m/min changed this from tensile to compressive stress. These authors concluded that lower cutting speeds have lower removal rates (chip generation) and consequently lower heat dissipation, which generates residual tensile stress. When the feed rate is increased, the tensile residual stress tends to be higher. With the depth of cut, the residual stress changed from tensile to compressive due to the increase in the volume of material removal and consequently the dissipation of heat during machining. Kenda et al. [19] analysed the effect of cryogenic machining in residual stress of the Inconel 718 and the results showed that the cryogenic machining process generates larger compressive residual stresses at deeper levels. In addition to the effects of the cutting parameters, Arunachalam et al. [4] analysed the influence of the geometry of the CBN insert on the surface integrity for Inconel 718. A round insert showed lower tensile residual stress compared to a square insert. Bushlya et al. [8] analysed the axial and tangential stresses using round and uncoated cutting tools (vc = 300 m/min and f = 0.1 mm/rev). The use of the CBN insert gave advantageous compression stresses for both coated and uncoated CBN tools, although the uncoated insert exhibited lower tensile stress. Another factor responsible for the generation of compression stresses on the machined surface was the geometry of the tool, and in particular a large radius, which causes greater deformation on the machined surface and increases the mechanical stresses related to compression. Peng et al. [28] evaluated the influence of wear in the whisker-reinforced ceramic tool on the residual stress in Inconel 718 machining. They used values of vc = 200 m/min, f = 0.2 mm/rev and ap = 0.3 mm to show that the tensile residual stress increased considerably in the cutting direction due to tool wear. Arunachalam et al. [4] analysed the effects of ceramic and CBN tools in Inconel machining and showed that a surface machined with ceramic tools showed much higher tensile stresses compared with CBN tools. However, the cutting speeds were different between the types of inserts, meaning that the residual stress condition may have been due to an increase in temperature in the cutting zone. The CBN insert was used at vc = 375 m/min, and the ceramic insert was used at vc = 450 m/min. These authors also concluded that the use of cooling can result in compressive stresses or lower tensile stresses compared to dry machining. Pusavec et al. [29] studied the effects of different cooling approaches on residual stress in Inconel 718 machining using a carbide cutting tool. They observed that the use of LN2 generated higher residual stress on the surface, although they found higher values of compression stress in the subsurface compared with the other types of cooling. In both cases, the residual stress was always greater in the circumferential direction than in the longitudinal direction. Finally, He et al. [15] carried out studies comparing the influence of dry and LN2 machining on the residual stress in the machined surface of Inconel 718, and found that the use of LN2 reduced the residual stress to around 100 MPa, using a carbide tool in the circumferential direction.

1.5 Microhardness in the machining of Inconel 718

Bushlya et al. [8] analysed the effects of the machined surface of Inconel 718 on subsurface deformation and residual stress distribution using a round insert. They observed that the zone of severe deformation was distinct and adjacent to the machined surface, with significant curvature and elongation in the contours of the grains and sliding lines in the cutting direction. According to the researchers, this can be ascribed to an increase in temperature, which can result in a reduce of material strength and increase of plasticity, allowing a more intensive deformation. Another cause of subsurface damage may have been the effect of the size of the cutting edge of the tool (round insert) further contributing to the mechanical action. Devillez et al. [10] also studied the effect of machining on the microstructure of the Inconel 718 alloy, comparing the effects of dry and cooled machining. Under dry machining conditions, a thin layer (10–20 μm) appears below the machined surface with elongation of the grain structure and a directional grain boundary orientation, unlike in cooled machining. Although more damage and deformation occur in the larger microstructure in dry machining than in cooled machining. Ezugwu et al. [11] evaluated the change in microhardness with variation of the cutting speed and high refrigeration pressure (11 MPa). They observed that when using conventional cooling, lower cutting speeds had less effect on the machined area than higher cutting speeds. A reduction was seen in the plastic deformation caused by the thermal effect, which tends to decrease the temperature and minimize the difference in microhardness at different cutting speeds. However, the microhardness values at lower cutting speeds increased with the use of a higher cooling pressure than used in conventional cooling; this can be explained by the exchange of the thermal effect by the mechanical effect in the deformation, which maintained the working in the machined area. Devillez et al. [10] evaluated the influence of cooling on microhardness in Inconel 718 machining using a coated carbide tool (vc = 60 m/min), where the use of conventional coolant reduced the effect on microhardness compared to dry machining. This difference in microhardness is due to the higher plastic deformation and temperature increase with dry machining, which affects the subsurface to a depth of 200 μm (HV0.02). In relation to the influence of cooling on the microhardness, Zhuang et al. [55] compared three cooling conditions (dry machining, plasma induction heating and LN2) using a round ceramic tool and analysed the micro-hardness effect. The value of the microhardness at the subsurface with the use of LN2 cooling was smaller than in dry machining. The effects of the use of LN2 and MQL on the microhardness were also evaluated by Iturbe et al. [16], who showed that the use of conventional cooling (soluble oil) caused a smaller change in the microhardness beneath the surface than the use of LN2 with MQL. This may have been caused by increased wear of the cutting tool with the use of LN2 with MQL, resulting in wear of cutting edge of the tool and making it difficult to remove the material during machining of the Inconel 718. The cutting data applied to the coated carbide used by Iturbe et al. [16] were vc = 70 m/min, f = 0.2 mm/rev and ap = 0.2 mm.

1.6 High-speed turning Inconel

It is recognized that Inconel's industrial turning is performed at low cutting speed, which makes the process uncompetitive. Researchers around the world have devoted themselves to studying turning under high cutting speeds, but few papers have been published in cryogenic cooling conditions at high cutting speeds. The following list deals with papers published under these conditions in recent years: Thamizhmaniia et al. [45] studied the performance evaluation of cryogenically treated worn CBN insert by turning process at cutting speeds of 100, 125, 150, 175 and 200 m/min; Musfirah et al. [22] studied the tool wear and surface integrity of Inconel 718 in dry and cryogenic coolant at high cutting speed at cutting speeds of 140 and 160 m/s; Bagherzadeh and Budak [5] investigated the machinability in turning of Inconel using a new cryogenic cooling at cutting speeds of 100 m/min; Iturbe et al. [16] analysed the machining Inconel 718 with conventional and cryogenic cooling at cutting speed of 70 m/min; Pusavec et al. [29] studied the surface integrity in cryogenic machining of Inconel 718 at cutting speed of 60 m/min; He et al. [15] compared the residual stresses in cryogenic and dry machining of Inconel 718 at cutting speeds of 40, 60 and 80 m/min; Ghosh and Rao [13] evaluated the performance of deep cryogenic processed carbide inserts during dry turning of Nimonic 90 at cutting speeds of 40, 60 and 80 m/min; Patil et al. [26] compared the high speed machining of Inconel 718 in dry condition and by using compressed cold carbon dioxide gas as coolant at cutting speeds of 70, 85, 100, 115 and 130 m/min; Shalaby and Veldhuis [32] studied the effect of the tool wear and chip formation during dry high-speed turning of direct aged Inconel 718 using different ceramic tools at cutting speeds of 150 and 250 m/s; Shalaby and Veldhuis [31] studied the effect of wear and tribological performance of different ceramic tools in dry high-speed machining of Ni-Co-Cr at cutting speeds of 75, 150 and 250 m/min; Nataraj et al. [23] studied the surface integrity of high speed turning of Inconel 718 using cutting speeds of 44, 73 and 102 m/min; Sørby and Vagnorius [42] studied the high-pressure cooling in turning of Inconel 625 with Ceramic Cutting Tools at cutting speeds of 200 and 300 m/min; Behera et al. [6] compared the recent lubri-coolant strategies for turning of Ni-based superalloy at cutting speeds of 40, 60, 80, 100 and 120 m/min; Kadam and Pawade [17] evaluated the surface integrity in high-speed machining of Inconel 718 at cutting speeds of 80, 150 and 220 m/min.

Looking at the literature, it seemed to us that there is an opportunity to study the surface integrity of Inconel 718 turned under cryogenic conditions at cutting speeds of 250, 275 and 300 m/min. So, the purpose of this study is, evaluate the influence of the cutting parameters on the surface integrity of Inconel 718 turned under cryogenic conditions using liquid nitrogen (LN2) at high cutting speeds, with a whisker-reinforced ceramic tool and the results compared with dry cutting condition respectively.

2 Experimental details

2.1 Materials and equipment

The material used in this experiment was solution-treated and aged Inconel 718 (VAT718A), with Ø50.8 mm and length 520 mm. The chemical composition and mechanical properties of the Inconel 718 used in this experiment are shown in Tables 1 and 2, respectively. The workpiece dimensions were defined and illustrates at Fig. 1.

The cutting tool chosen for machining of the Inconel 718 was a round, whisker-reinforced silicon ceramic tool (RNGN120400T - IW7 class) and a toolholder (CRGNR2525M-12CEA) with negative geometry (− 6° angle), manufactured by Iscar.

The cutting experiment was conducted on a Romi CNC lathe (Centur 30D model), with power 7.5 kW and a maximum revolution of 4000 RPM.

Table 1 Chemical composition of the VAT718A alloy used in this experiment (% weight)

Material	Ni	Cr	Fe	Nb	Mo	Ti	Al	C	Nb+Ta
VAT718A	53.1	17.92	19.31	4.99	2.95	0.98	0.46	0.023	5.04
	Si	Mn	Co	Cu	B	Pb	S	P	Mg
	0.05	0.02	0.04	0.01	0.004	0.0002	< 0.001	< 0.005	0.005

Source: Adapted from Villares [48]

Table 2 Mechanical properties of the VAT718A alloy used in this experiment

Material	Yield tensile strength (MPa)	Ultimate tensile trength (MPa)	Hardness (HRc)
VAT718A	934	1227	39

Source: Adapted from Villares [48]

The cryogenic cooling equipment consisted of a pressurized cylinder of LN2, a pressure regulating valve, a pressure gauge, a rigid stainless steel pipe and copper coated with insulating material. The pipe delivering LN2 to the cutting zone was adapted using the tool holder. Figure 2 shows the set up of the cooling system close to the CNC lathe. Cryogenic spraying of LN2 was chosen for these experiments, as it is easier to adapt this to the CNC lathe by applying LN2 directly to the tool–chip interface through nozzles at a pressure of 1.5 bar.

In order to measure the cutting forces during machining, the tool holder was modified by adapting a piezoelectric transducer (model PCB 260A02) previously calibrated by PCB supplier Piezotronics. Data on this force were obtained using Spider8-30 and Catman software, manufactured by HBM. The frequency of data acquisition was 200 Hz. For conditioning of the piezoelectric transducer signal, a PCB-482C model from PCB Piezotronics was used.

The roughness measurements were performed at the centre of the machined path, using a cut-off of 0.8 mm and $n = 5$. Each sample was measured at three positions spaced at 120° from each other using a rugosimeter (Surftest SJ-301), thus giving an average roughness value.

Residual stress analysis of all samples was performed by X-ray diffraction (XRD) using an XRD-7000 diffractometer manufactured by Shimadzu. The parameters used for this residual stress measurement are shown in Table 3.

The residual stress was measured approximately 12 mm after the start of machining, in both the longitudinal (feed rate) and circumferential directions of the workpiece.

In addition to measuring the residual stress by XRD, the blind hole method was used to evaluate the respective stress profiles beneath the surface in some samples. The device used for this was the MTS 3000-SINT model, as shown in Fig. 3. The parameters used for residual stress measurements are shown in Table 4.

2.2 Methodology

The machining experiments involved the conditions and variables to be analysed, adequate statistical planning and preparation of the samples. The conditions and variables involved in the experiment were as follows:

a) Fixed conditions: the geometry and material of the samples, the lathe machine, the cryogenic equipment and parameters, and the geometry and material of the cutting tool.
b) Independent variables: the cutting speed, feed rate, depth of cut, and the use of LN2 or dry machining.
c) Dependent variables: the roughness, residual stress and cutting force.

In order to carry out a statistical analysis of the effects of the cutting parameters on the surface integrity of the machined surface, a central composite design (CCD) with six replicates in the central points was chosen. The cutting parameters defined for the experiment were based on the manufacturer's recommendations for the cutting inserts, and preliminary experimental trials were undertaken as follows:

a) Cutting speed: 250 m/min, 275 m/min and 300 m/min;
b) Feed rate: 0.15 mm/rev, 0.20 mm/rev and 0.25 mm/rev;
c) Depth of cut: 0.2 mm, 0.3 mm and 0.4 mm.

For statistical evaluation, Statistica 13.2 software was used. The treatment number with the information (C) refers to the replica at the central point (a total of six replicates).

The workpiece was fixed to the CNC lathe, as shown in Fig. 4. The LN2 nozzles were fixed to the tool holder to deliver LN2 for cutting area (Fig. 5). A CNC program was designed to allow the individual machining of each section, with cutting parameters calculated using Statistica 13.2 software.

After each sample was machined (18 mm), the position of the ceramic insert was changed by approximately 30° to allow

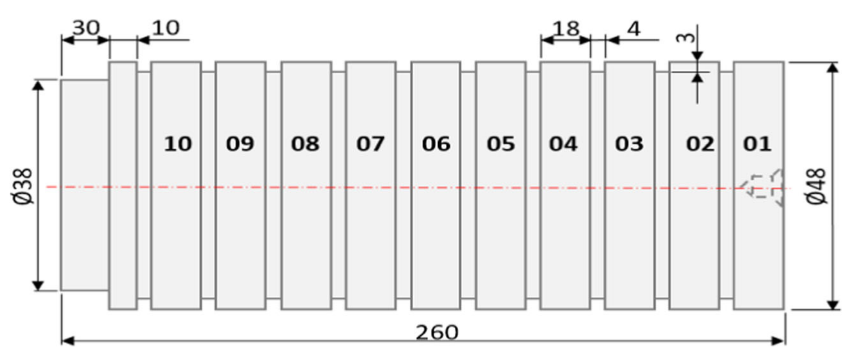

Fig. 1 Inconel bar with ten samples (dimensions in millimeters)

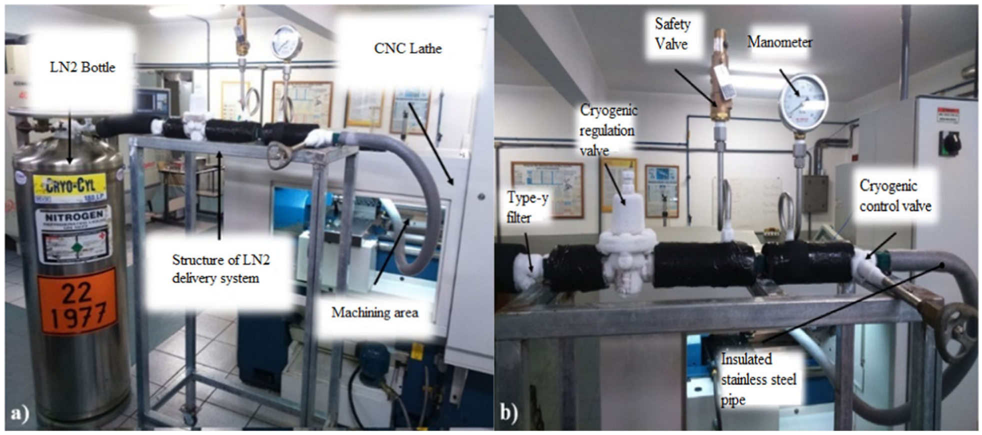

Fig. 2 Set-up of the cryogenic cooling system. **a** Equipment adapted to the CNC lathe and **b** components used in the cooling system

a new cutting edge to be used, to prevent wear from influencing the further analysis of each machined sample.

3 Results and discussion

3.1 Forces during machining

The adaptation of the tool holder to facilitate insertion of the piezoelectric transducer allowed us to obtain the three forces exerted during the machining of samples under dry and LN2 conditions. Table 5 shows the results obtained for these forces during the machining of the samples, showing the feed force (Ff), the cutting force (Fc) and the penetration force (Fp).

As shown in Table 5, the highest values of the cutting forces were obtained for the penetration force component when the highest depth of cut (ap = 0.47 mm) was used. These values were 412 N with the use of LN2 and 273 N in dry machining. The penetration force had a higher value than the cutting and feed forces, and this can be explained by the round geometry of the cutting tool used in the experiment. According to Madariaga et al. [21], a cutting tool with round geometry tends to increase the contact area in the cutting zone, thereby increasing the penetration force. Figure 6 shows the mean values of the force components measured during machining of Inconel 718 at the centre of the experiment (vc = 275 m/min, f = 0.2 mm/rev and ap = 0.3 mm. The average values of the forces under dry machining were smaller than with the use of LN2.

The differences between LN2 and dry machining can be associated with a reduction in the temperature of the cutting zone due to the supply of LN2 at the sample surface; the workpiece is "frozen" before the cut takes place, causing an increase in the shear stress and force, and thus the deformation during machining, as described by Pusavec et al. [30]. Devillez et al. [10] found that the increase in temperature in dry machining leads to a reduction in the mechanical properties, resulting in lower cutting forces.

Pusavec et al. [29] found that the values of the cutting force were higher than the other forces. According to Bordinassi [7], the cutting force is mainly responsible for the power required by the machine and is directly related to the cut section removed from the workpiece. However, the results obtained in this experiment indicate that the penetration force showed the highest values, and this may be due to the round geometry of the cutting tool. Since the values of feed force were much smaller, only the influence of the independent variables on the cutting and penetration forces will be analysed here.

In order to determine which independent variables had the most significant effect on the cutting force using LN2, and analysis of variance was carried out with 95% confidence, an R^2 value of 0.81 and an adjusted value of R^2 of 0.63,

Table 3 Parameters used to measure the residual stress in the XRD

Parameters	Specification
X-ray tube	Cr
Filter	Vanadium
diffraction angle (2)	128.5°
K factor	− 91.4
Incident angle	20°/28°/36°/45°
Source operated	40 kV
	30 mA
Speed	2°/min
Path	127 to 130°

Table 4 Parameters used for measurement of residual stress by the blind hole method

Parameter	Value
Ø milling tool	Ø 1.6 mm
Total depth	0.4 mm
Gauge rosette	Excel PA 062RE-120

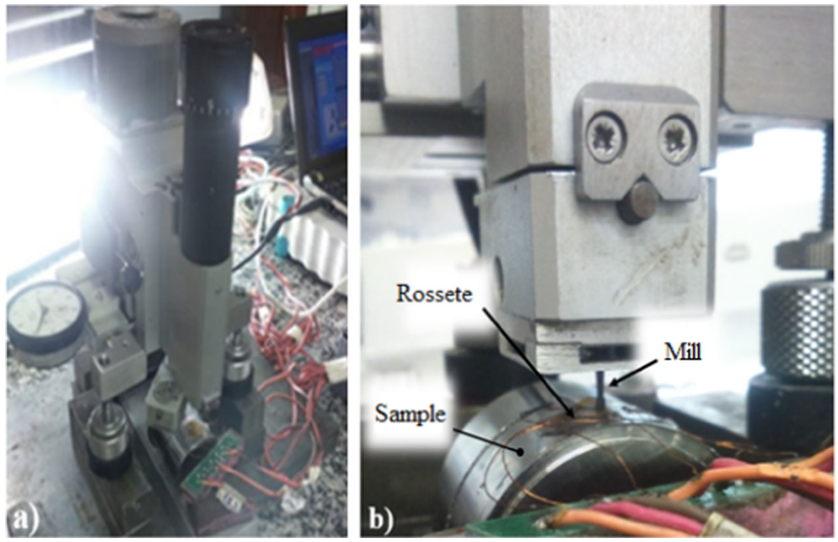

Fig. 3 MTS 3000-SINT equipment: blind hole method. **a** Equipment prepared to measure the residual stress; **b** details of the measurement site

indicating the depth of cut and feed rate. The most significant independent variables affecting the cutting force with the use of LN2 were the depth of cut and the feed rate. In dry machining, the analysis of variance showed 95% confidence, an R^2 value of 0.97 and an adjusted R^2 value of 0.94, indicating that the depth of cut, the feed rate and the interaction between them were the most significant independent variables for the cutting force. The most significant variables for the cutting force with dry machining were also the depth of cut, the feed rate and the interaction between them. Amini et al. [2] reported that the depth of cut and feed rate were the most significant variables and found that these were directly related to cutting forces, meaning that the lower these values were, the lower the forces were during machining. Pusavec et al. [30] also reported results showing that the depth of cut and feed rate were the most significant variables for cutting forces.

For the penetration force, the most significant independent variable using LN2 was the depth of cut, (95% confidence, R^2 value 0.82 and adjusted R^2 value 0.66). Under dry machining, analysis of variance showed that the depth of cut and feed rate were the most significant independent variables for the penetration force (95% confidence, R^2 value 0.94 and adjusted R^2 value 0.88). In a similar way to the cutting forces, the most significant variables for the penetration force were the depth of cut and feed rate, although when using LN2, only the depth of cut had a significance of above 95%. The large radius of the round tool also contributed to the significance of the depth of cut in the variable Fp.

A comparison between the results obtained from this experiment and those reported in the literature shows that the depth of cut and feed rate are the most significant variables for cutting and penetration forces during the machining of Inconel 718. Using LN2, both the cutting forces and the penetration forces were higher, due to the reduction in temperature in the cutting zone; this may have reduced the thermal effect, but increased the mechanical effect of plastic deformation. According to Ulutan and Ozel [46], the plastic deformation caused by the mechanical action tends to generate compressive stresses in the machined surface.

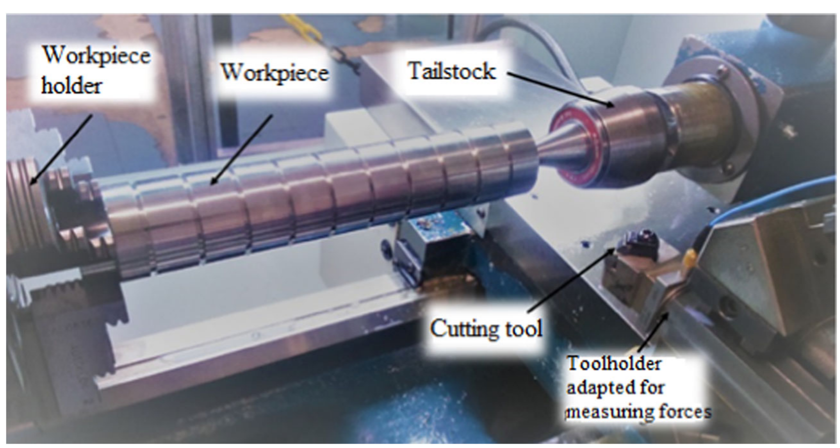

Fig. 4 Inconel 718 bar attached to the CNC lathe in the work area

Fig. 5 Feeding the LN2 into the cutting tool

3.2 Surface roughness

Roughness measurements were performed at a distance of approximately 12 mm after the start of machining at three positions spaced at 120° in the longitudinal direction, from which an average was obtained for each sample. Table 6 shows the average roughness Ra after LN2 and dry machining.

As shown in Table 6, the highest roughness value using LN2 was 0.79 μm, and this was produced when using the highest feed rate (f = 0.28 mm/rev). For dry machining, the highest roughness value was 0.56 μm at one of the central points (f = 0.20 mm/rev). The difference in the roughness results between LN2 and dry machining can be associated with the higher cutting force during machining with LN2, which causes vibrations that influence the roughness.

The average roughness after the machining of Inconel 718 is shown in Fig. 7, where the roughness Ra using LN2 (Ra = 0.52 μm) was slightly higher than for dry machining (Ra = 0.46 μm).

Arunachalam et al. [4] found that the lower roughness under dry conditions can be associated with a slight softening of the material caused by an increase in the temperature during dry machining, which reduces the cutting force and creates less vibration during machining, resulting in a lower effect on the roughness.

Xavier [49] also found a similar difference with the use of LN2, where a higher roughness was associated with increases in the cutting speed and depth of cut. For Savaiah and Chakradhar [41], another reason is that as cutting velocity increases cutting forces decreases which causes for less tool damage resulting in generation of less tool wear marks on the machined surface. However, Pusavec et al. [29] found a lower

Table 5 Forces measured during the experiments

Sample	Vc (mm/min)	f (mm/rot.)	ap (mm)	LN2			DRY		
				Ff(n)	Fc(N)	Fp(N)	Ff(n)	Fc(N)	Fp(N)
17(C)	275.00	0.20	0.30	52	200	255	39	165	178
3	250.00	0.25	0.20	30	137	184	30	142	155
2	250.00	0.15	0.40	66	272	335	52	184	202
11	275.00	0.12	0.30	25	125	154	30	112	142
14	275.00	0.20	0.47	105	321	412	70	254	273
19(C)	275.00	0.20	0.30	51	190	242	43	182	197
5	300.00	0.15	0.20	30	149	196	25	109	131
16(C)	275.00	0.20	0.30	50	160	304	48	194	211
10	317.04	0.20	0.30	69	282	278	48	198	216
18(C)	275.00	0.20	0.30	61	265	267	51	201	225
8	300.00	0.25	0.40	59	283	312	62	257	252
7	300.00	0.25	0.20	48	211	204	28	129	163
20(C)	275.00	0.20	0.30	51	277	308	41	173	191
6	300.00	0.15	0.40	54	169	279	50	183	206
4	250.00	0.25	0.40	69	270	332	70	272	282
9	232.96	0.20	0.30	35	149	175	49	190	220
1	250.00	0.15	0.20	27	99	192	25	108	138
12	275.00	0.28	0.30	59	246	269	57	244	253
15(C)	275.00	0.20	0.30	50	192	225	46	187	213
13	275.00	0.20	0.13	18	91	113	18	91	116

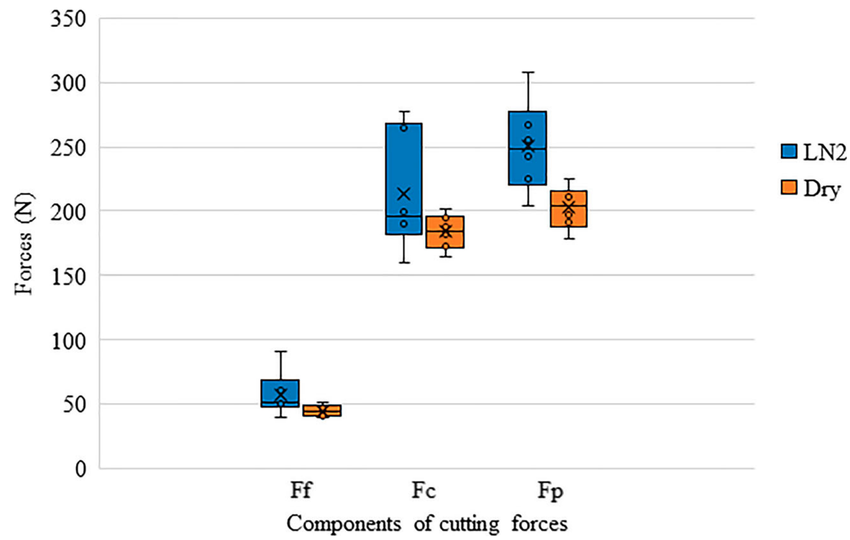

Fig. 6 Components of the cutting forces during machining of Inconel 718 using LN2 and dry machining (vc = 275 m/min, f = 0.2 mm/rev and ap = 0.3 mm)

roughness when using LN2 with MQL in comparison to dry machining, stating that this may be related to rigidity conditions of the equipment and to the lower effects of cryogenic refrigeration on the workpiece.

The feed rate, depth of cut, cutting speed and interaction between the cutting speed and feed rate were the independent variables that were most significant in terms of Ra roughness using LN2 (95% confidence, R^2 value 0.87 and adjusted R^2 value 0.76). Zhuang et al. [55] showed that the cutting speed and feed rate were the most significant variables for roughness, while higher cutting speeds and lower feed rates tended to give lower values for roughness.

In general terms, the surface roughness is related to the feed rate, tool radius and cutting speed, since these parameters create grooves on the machined surface that are uniformly repeated at a distance related to the feed rate. However, the results of the experiment show that the depth of cut is also a significant variable, given the large tool radius (round insert).

3.3 Residual stress

Residual stresses were measured in both the circumferential and longitudinal directions using XRD. Table 7 shows the residual stresses recorded for LN2 and dry machining conditions. The highest values of residual stress were 1394 MPa for LN2 and 1237 MPa for dry machining; these were both in the circumferential direction and were associated with a larger depth of cut (ap = 0.47 mm). The lowest values of residual stress were 756 MPa for LN2 and 664 MPa for dry machining; these were also in the circumferential direction and were associated with a smaller depth of cut (ap = 0.13 mm). Thus, the influence of the depth of cut on the residual stress was found to be significant for the highest and lowest residual stresses.

Another factor associated with the residual stress values was related to the use of LN2, as this technique showed higher tensile stresses than dry machining. Figure 8 presents a comparison between dry and LN2 machining using parameters v = 275 m/min, f = 0.2 mm/rev and ap = 0.3 mm.

Arunachalam et al. [4] reported that the use of coolant to reduce the temperature in the cutting zone (and consequently the thermal effect during machining) tends to generate lower tensile stresses. Pawade et al. [27] also reported that an increase in temperature raises residual stress values; however, the results obtained in some studies have shown the opposite.

Table 6 Roughness Ra after LN2 and dry machining

Sample	vc (mm/min)	f (mm/rot.)	ap (mm)	Roughness Ra (μm)	
				LN2 Average	Dry Average
17 (C)	275.00	0.20	0.30	0.54	0.43
3	250.00	0.25	0.20	0.29	0.26
2	250.00	0.15	0.40	0.41	0.22
11	275.00	0.12	0.30	0.32	0.24
14	275.00	0.20	0.47	0.69	0.23
19 (C)	275.00	0.20	0.30	0.56	0.56
5	300.00	0.15	0.20	0.23	0.20
16 (C)	275.00	0.20	0.30	0.55	0.48
10	317.04	0.20	0.30	0.36	0.32
18 (C)	275.00	0.20	0.30	0.55	0.48
8	300.00	0.25	0.40	0.68	0.38
7	300.00	0.25	0.20	0.61	0.30
20 (C)	275.00	0.20	0.30	0.46	0.42
6	300.00	0.15	0.40	0.34	0.26
4	250.00	0.25	0.40	0.40	0.27
9	232.96	0.20	0.40	0.38	0.24
1	250.00	0.15	0.30	0.22	0.30
12	275.00	0.28	0.30	0.79	0.51
15 (C)	275.00	0.20	0.30	0.42	0.38
13	275.00	0.20	0.13	0.29	0.23

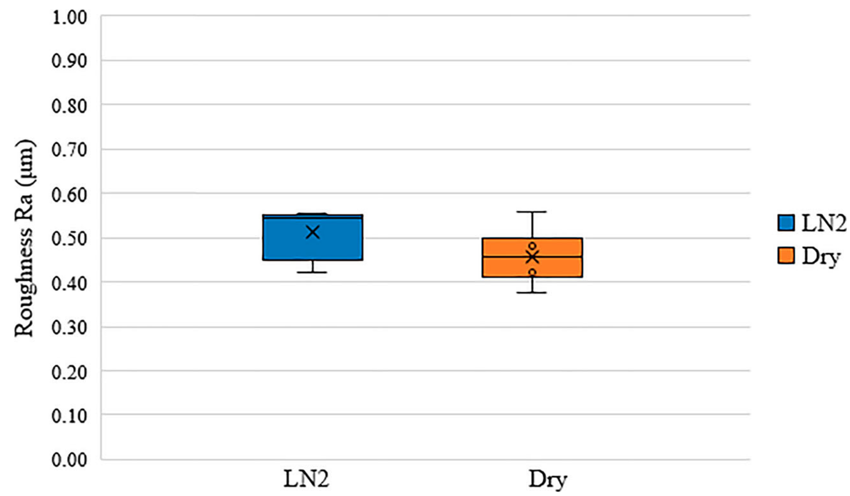

Fig. 7 Average roughness Ra after LN2 and dry machining of Inconel 718 (vc = 275 m/min, f = 0.2 mm/rev and ap = 0.3 mm)

It may be that the thermal effect in plastic deformation has little influence on the residual stress. Thus, a mechanical effect is more likely to increase the tensile residual stress with the use of LN2 (non-homogeneous deformations), and this may be associated with a higher penetration force.

Another factor observed here refers to the results of the residual stresses, which were higher in the circumferential direction than in the longitudinal direction. According to Zhou et al. [53], residual tensile stresses tend to be higher in the circumferential direction due to the influence of the cutting speed and depth of cut. In the longitudinal direction (feed rate direction), lower residual tensile stresses or even compressive stresses are expected. This affirmative also was showed by Kenda et al. [19] where residual tensile stresses are more critical in the circumferential direction than longitudinal direction.

In order to verify the influence of the cutting parameters on the residual stress using LN2, a variance analysis indicated that the depth of cut, speed cutting and interaction between

Table 7 Results of residual stresses under LN2 and dry conditions

Sample	vc (mm/min)	f (mm/rot.)	ap (mm)	LN2		Dry	
				Stress (MPa) Circumferential	Stress (MPa) Longitudinal	Circumferential	Longitudinal
17 (C)	275.00	0.20	0.30	994	524	873	471
3	250.00	0.25	0.20	869	367	858	298
2	250.00	0.15	0.40	1335	1035	1114	598
11	275.00	0.12	0.30	761	529	835	416
14	275.00	0.20	0.47	1394	1123	1237	673
19 (C)	275.00	0.25	0.30	952	549	829	387
5	300.00	0.15	0.47	867	707	751	332
16 (C)	275.00	0.20	0.30	991	465	873	451
10	317.04	0.20	0.20	854	684	1085	697
18 (C)	275.00	0.20	0.30	942	480	855	447
8	300.00	0.20	0.40	920	774	973	813
7	300.00	0.25	0.20	859	523	863	531
20 (C)	275.00	0.20	0.30	966	475	825	493
6	300.00	0.15	0.40	870	778	1041	570
4	250.00	0.25	0.40	1192	872	994	530
9	232.96	0.20	0.30	826	950	790	256
1	250.00	0.15	0.20	1051	752	942	403
12	275.00	0.28	0.30	860	791	838	543
15 (C)	275.00	0.20	0.30	980	543	984	469
13	275.00	0.20	0.13	756	384	664	378

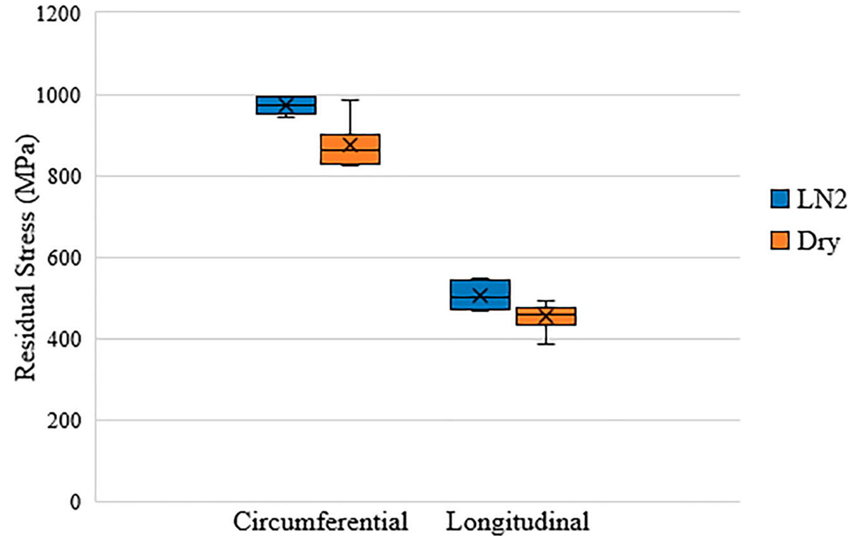

Fig. 8 Mean of the residual stress values in the circumferential and longitudinal direction under LN2 and dry machining (vc = 275 m/min, f = 0.2 mm/rev and ap = 0.3 mm

them were the most significant variables in the circumferential direction (95% confidence, R^2 value 0.84, adjusted R^2 value 0.70). In the longitudinal direction, the significant variables were the depth of cut and the cutting speed (95% confidence, R^2 value 0.85, adjusted R^2 value 0.71).

For dry machining, the same analysis of variance was performed in order to verify which independent variables were most significant in the residual stress. The depth of cut was the most significant variable in the circumferential direction (95% confidence, R^2 value 0.79 and adjusted R^2 value 0.61). In the

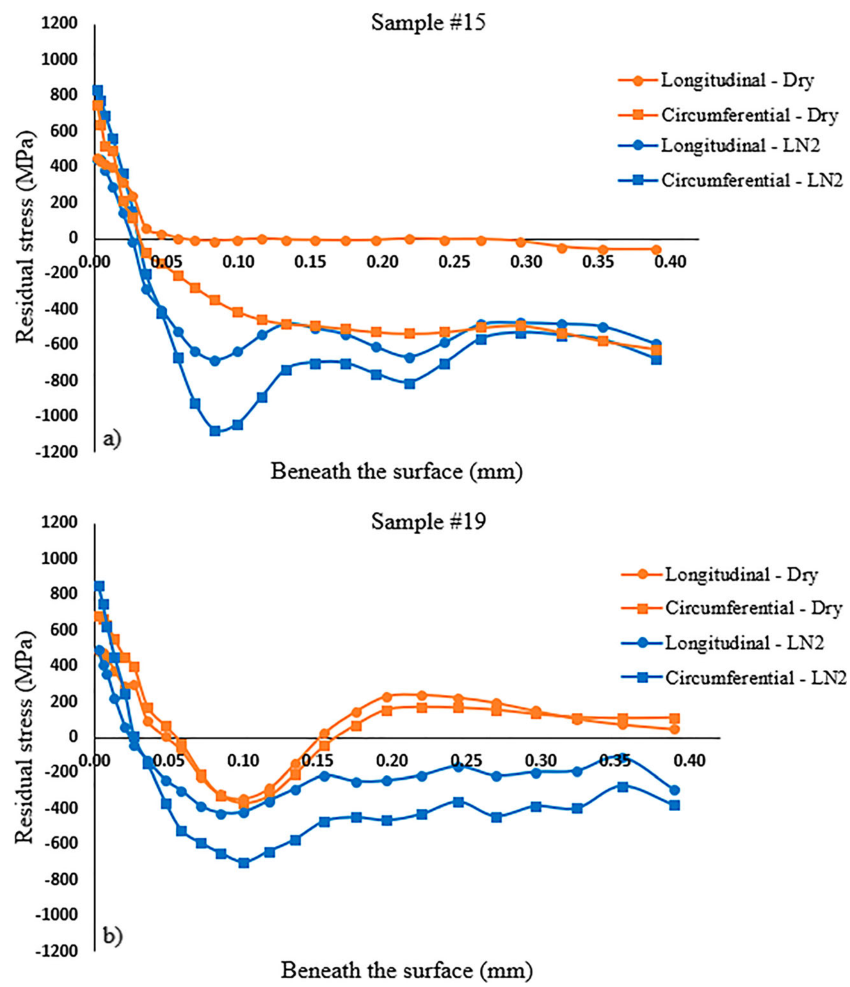

Fig. 9 Residual stresses obtained by the blind hole method, using LN2 and dry machining (vc = 275 m/min, f = 0.20 mm / rev and ap = 0.30 mm). **a** Sample no. 15; **b** sample no. 19

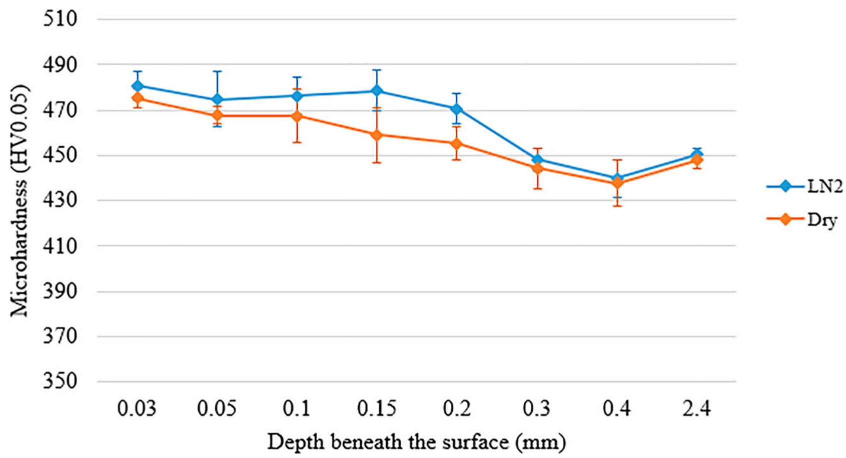

Fig. 10 Average microhardness measurements using LN2 and dry machining (vc = 275 m/min, f = 0.2 mm/rev and ap = 0.3 mm)

longitudinal direction, the most significant variables were the depth of cut, cutting speed and interaction between feed rate and cutting speed (95% confidence, R^2 value 0.88 and adjusted R^2 value 0.77).

Under both cutting conditions (LN2 and dry machining), the depth of cut was the most significant variable. The second most significant variable was the cutting speed, where the increase in cutting speed is associated with the increase of temperature in the cutting zone given by the low thermal conductivity of Inconel 718.

Pawade et al. [27] reported that the cutting speed, the depth of cut and the feed rate were significant in terms of the residual stress; a higher cutting speed with a lower feed rate and higher depth of cut generated residual compressive stresses, which may be associated with high heat dissipation due to the removal of larger amounts material. However, the results obtained in this experiment indicated lower cutting speeds and the depth of cut in dry machining. An indication of a higher cutting speed is given only with the use of LN2, since this has an effect on the temperature in the cutting zone. Although Arunachalam et al. [4] found that residual compression stresses can be induced by the mechanical effect, our results indicate the opposite; the use of LN2 created higher tensile stresses compared to dry machining, and this may be associated with the higher machining forces exerted with the use of LN2.

In order to observe the effects of residual stresses on the subsurface, the blind hole method was used to verify the effect of LN2 and dry machining in the circumferential and longitudinal directions, using the cutting parameters at the central point (Fig. 9).

Although the use of LN2 resulted in higher tensile stresses at the machined surface compared to dry machining, the subsurface showed higher values of compressive stress. Kenda et al. [19] found similar results where machining under cryogenic conditions results in higher compressive stresses beneath the machined surface, as well as generates a thicker compressive zone beneath the machined surface. He et al. [15] also reported that the use of LN2 results in higher compressive stresses in the subsurface than in the dry machining process, and these can increase the fatigue life of machined components. While tensile stresses tend to decrease mechanical resistance to nucleation and consequently to catastrophic failure, compressive stresses tend to increase resistance.

Using LN2 as a cooling method, the lowest depth of cut and parameters of vc = 275 m/min and f = 0.2 mm/rev can be used to obtain lower tensile stress values. The use of dry machining showed a tensile residual stress at the surface that was 92 MPa lower than that obtained using LN2.

3.4 Microhardness

Samples using the central cutting parameters were chosen for the microhardness measuring analysis. The results of the microhardness profile are shown in Fig. 10.

The behaviour of the profile for the use of LN2 showed higher values of microhardness in the subsurface up to 0.3 mm below the surface compared to dry machining. This small difference may be associated with softening occurring in the subsurface, generated by the increase in temperature in the cutting zone with dry machining. Devillez et al. [10] reported that cooling tends to reduce the plastic deformation caused by the thermal effect, and consequently has less impact in terms of changes in the microhardness. Zhuang et al. [55] show that the hardening depth may be related to notch wear, and that there is a critical hardened layer thickness arising from the occurrence of notch wear; furthermore, with an increase in this hardening layer, the groove wear also increases. Kenda et al. [19] also described that cryogenic condition induced the highest hardness on the machined surface, associated to precooling by cryogenic condition which reduces the temperature of the workpiece (as well as the cutting tool), which results in increase of compressive residual stresses as well as in increase of hardness in the finished product.

4 Conclusions

The experiments carried out here allowed us to evaluate the influence of cutting parameters at cutting high speeds on the surface integrity of Inconel 718 alloy, both using LN2 as coolant and under dry machining conditions for comparison. The main conclusions of this study are as follows:

a) The most significant variables affecting all the forces applied during machining under both conditions (LN2 and dry machining) were the cutting speed and the depth of cut. The penetration force was higher than the other forces and was influenced by the larger contact area of the round tool.
b) The components of the forces during the machining of Inconel 718 were slightly larger when using LN2 than under dry machining (Fp = 267 N and 203 N, respectively), a result that may be associated with the surface hardening caused by the machining process involving cryogenic coolant.
c) In terms of the surface roughness, all of the independent variables were significant in both experiments. However, the most significant variable with the use of LN2 was the feed rate, and in dry machining this was the depth of cut.
d) The average roughness Ra was very similar for both LN2 and dry machining (Ra = 0.52 μm and 0.46 μm, respectively); however, the roughness of the samples using LN2 was higher, which may be associated with vibrations during machining caused by an increased machining force.
e) The roughness is lower ($Ra < 0.3$ μm) for a lower feed rate and depth of cut at higher cutting speeds, for both LN2 and dry machining, although a larger tool radius was also an important condition.
f) The main variables affecting the residual stresses after machining with the use of LN2 were the depth of cut and the cutting speed. In order to obtain lower residual stresses, the cutting parameters referring to the most significant variables should be the smallest possible ones. The mean residual stresses measured by XRD at the central point were tensile stresses for both LN2 and dry machining. The use of LN2 gave tensile residual stress values that were slightly higher than those for dry machining. Residual tensile stresses tended to be higher in the circumferential direction than in the longitudinal direction and were affected by the cutting speed and depth of cut.
g) Residual stress measurement using the blind hole method showed that residual compression stresses beneath the surface were higher with the use of LN2.
h) There was a small difference in the average values of microhardness near the surface for both LN2 and dry machining. Dry machining showed less change than the use of LN2, and this may be associated with the softening of the material during machining.
i) The results show that lower cutting parameters tend to give the best results in terms of the cutting force and surface integrity.

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