

An experimental investigation on machining-induced surface/subsurface characteristics of nickel based Inc-718 alloy: A novel hybrid approach in milling process

Musa Bilgin^a, Şener Karabulut^a, Halil Karakoç^a, Yunus Kayır^b, Murat Sarıkaya^{c,*}

^a Department of Mechanical Program, Hacettepe University, 06930 Ankara, Türkiye

^b Department of Manufacturing Engineering, Faculty of Technology, Gazi University, Ankara, Türkiye

^c Department of Mechanical Engineering, Sinop University, Sinop, Türkiye

ARTICLE INFO

Keywords:

Inconel-718
Heat assisted machining
Nanofluids
Tool wear
Microstructural behaviors
EBSD analysis

ABSTRACT

Nickel-based superalloy Inc-718 has become an indispensable alloy in critical sectors, especially in the aerospace industry, thanks to its unique characteristics. However, some properties of the alloy (especially low thermal conductivity and hot hardness) cause difficulties in its machinability. For this reason, comprehensive studies to improve the machinability of Inc-718 alloy by considering the microstructural properties are guiding. In this context, the present study uses various methods to increase the machinability efficiency of Inc-718, while also investigating their effect on microstructural properties. Firstly, the effect of the pre-heating process (hot), pure-MQL (PMQL), nanofluid-MQL (NMQL), and hybrid methods (hot+PMQL and hot-NMQL) on the surface roughness, cutting forces, tool wear, vibration, and temperature was investigated while milling Inc-718 surfaces. Then the utilization of Electron Backscatter Diffraction (EBSD) facilitated a comprehensive examination of microstructural behavior, with a specific focus on Euler-colored maps and phase distribution maps, providing valuable insights into the material's behavior under distinct milling conditions. As a result, hot+PMQL, hot+SiC-NMQL, and hot+Al₂O₃-NMQL provided an important contribution to the improvement of machinability characteristics. Also, it was seen that in EBSD analysis, a limited area is affected by heat in the hot machining environment. The crystal orientations of the pre-heated and hybrid machined Inc-718 alloy are highly similar to that of the dry-machined alloy. This similarity indicates that the removal of the heated layer from the workpiece during the milling process contributes to the preservation of the microstructure.

1. Introduction

Heat resistant super alloys (HRSA) have been developed that can offer the mechanical and thermal properties required for high safety and performance, low fuel consumption and emissions, especially desired in the aerospace industry. According to the kind of major alloying element, superalloys are categorized into four groups. These are nickel-based, iron-based, cobalt-based, and titanium-based alloys. Superalloys are extremely attractive for both high and low temperature applications because to their special characteristics. One of the best prospective options for high temperature applications up to 1000 °C is nickel-based superalloys due to their great oxidation resistance. The outstanding properties of nickel-based alloys, such as long-term retention of chemical and mechanical properties at elevated temperatures, allow for high

corrosion resistance, fatigue resistance, thermal shock, erosion and creep resistance. Due to its excellent weldability and processability with a variety of manufacturing processes, Inconel 718 (Inc-718) is the most popular alloy in the nickel-based superalloy family [1]. The intense demand of Ni-based Inc-718 in the industry has made it necessary to work on improving its machinability both in terms of productivity and part quality. The machinability index of Inc-718 is 12 out of 100 compared to the reference material (low carbon steel-AISI 1018) [2]. Therefore, the specific properties of the alloy i.e., 1) good strength and hardness even at high temperatures, 2) high susceptibility to strain hardening in all conditions, 3) high heat generation in the cutting zone due to its low thermal conductivity, 4) chemical affinity of the alloy to cutting tools, 5) high adhesion tendency of the alloy, 6) built-up edge (BUE) formation, and 7) notch formation on the cutting edge have led it

* Corresponding author.

E-mail address: msarikaya@sinop.edu.tr (M. Sarıkaya).

<https://doi.org/10.1016/j.triboint.2023.109120>

Received 28 October 2023; Received in revised form 12 November 2023; Accepted 17 November 2023

Available online 20 November 2023

0301-679X/© 2023 Elsevier Ltd. All rights reserved.

to be called a difficult-to-cut material. The restricted heat dissipation in the cutting zone is seen as the main factor that impoverishes the machinability of the alloy. To overcome these difficulties, researchers have made several attempts, directly (such as optimizing the cutting parameters and properties of the cutting tool) and indirectly, i.e., cooling, lubrication, hot machining, etc. Among the indirect methods used to increase the machining efficiency and part quality, the use of cutting fluid is frequently preferred. Cutting fluids not only reduce the cutting temperature, but also provide various benefits such as reducing friction at the interfaces, removing chips from the cutting zone, protecting the machined surface from corrosion and oxidation, reducing adhesion, improving surface quality and reducing cutting forces [3]. In this way, it is possible to increase tool life, decrease cutting power and energy usage, and enhance surface integrity. For chip removal operations, emulsion and soluble type cutting fluids with flood cooling system are commonly employed. However, there are now a number of limitations on the usage of this kind of cooling system due to rising environmental concerns [4]. For this reason, tremendous efforts are made to use and develop methods such as MQL (Minimum Quantity Lubrication), compressed air, cryogenic cooling, in order to minimize the use of lubricants, taking into account the cost and human health problems as well as ecological problems. In particular, MQL, which is an environmentally friendly machining method, is widely used in the machining of materials due to its easy application and cost-effective.

Heat-assisted machining (HAM) (or hot machining) is another useful technique to increase the machinability performance of nickel-base alloys. The HAM method involves heating the workpiece with outside heat sources such as gas flame, induction, laser, plasma, etc., to improve the alloy's ductility and, as a result, decrease the yield and shear strength of the workpiece. In this way, it can be easier to remove chips from the material compared to traditional machining. Researchers have carried out various studies to observe changes in the machinability performance of nickel alloys using different heat sources. For example, Parida and Maity [5] used the HAM technique for turning the Inc-718 to observe the effect of gas-flame torch heating on machining responses, namely material removal rate, cutting force, power consumption, tool life, and cutting energy. In another study conducted by Parida and Maity [6], Ni-based Monel 400 superalloy was machined by exposure to heat source and the effect of workpiece temperature on tool life, chip-tool contact length and chip morphology was investigated. In their findings, the authors reported that as a result of heating, the workpiece, the tool life was improved by 85% compared to ambient temperature. Navas et al. [7] investigated the factors involved in improving the machinability of Inc-718 with laser assisted machining. They attributed the improvement of machinability performance with laser-heating to the reduction of material yield strength and hardness, and to the limitation of work hardening. Tadavani et al. [8] studied the machinability reactions in cutting Inc-718 with laser assisted. The researchers found that as the temperature exceeded 500 °C near the cutting zone, there was a 35% reduction in specific cutting energy and a more than 20% reduction in tool wear and surface roughness compared to conventional machining. Moreover, it is also possible to mention other studies [9–17] reporting the increased machinability efficiency of nickel-based superalloys with the help of heat source.

In summary, it is clear that machinability outputs have improved in cutting hard-to-machine alloys both with heat source and under cooling/lubrication. So, it is a matter of curiosity how the simultaneous application of both methods (heating the material and cooling the cutting tool) will affect the machinability outputs. In the literature, very few studies have been found on this subject. Karabulut et al. [18] applied a hybrid process (heating of the material and MQL application) to the Ti6Al4V alloy to overcome the machining difficulties in milling. The authors found significant reductions in vibration and power consumption in hybrid milling compared to dry milling, while slightly worsening in surface quality was observed. In another work published by Karabulut et. [19], investigations were done into the impact of heat assisted hybrid

techniques on the machining behavior of Ti6Al4V alloy. As a result, up to 65% reduction in energy consumption was detected, while surface roughness increased due to adhesion. Luan et al. [20] examined the machinability outputs of Ti6Al4V alloy in heat assisted cutting under MQL. Consequently, heat assisted machining under MQL has dramatically reduced tool wear and enhanced surface finish.

When the findings obtained from the literature are evaluated, the machinability characteristics have been improved by preheating the material and lubricating the tool-chip interface with MQL. However, there is insufficient evidence for the results when both methods are used together in machining superalloys like Inc-718. In addition, to the authors' knowledge, no studies have been found examining a hybrid technique that involves heating the Ni-based superalloy Inc-718 as well as lubricating/cooling the tool-chip-workpiece interface using the MQL method. Therefore, present study aims to investigate the effect of pre-heating process (hot), pure-MQL (PMQL), nanofluid-MQL (NMQL) and hybrid methods (hot+PMQL and hot-NMQL) on the surface roughness, cutting forces, tool wear, vibration, and temperature. In addition, this paper conducted a comprehensive investigation into the microstructural behavior of Inconel 718 alloy machined under different cutting environments. The utilization of Electron Backscatter Diffraction (EBSD) facilitated a comprehensive examination of microstructural responses, with a specific focus on Euler-colored maps and phase distribution maps, providing valuable insights into the material's behavior under distinct milling conditions.

2. Experimental procedure

2.1. Equipment

The machining behavior of the Inc-718 superalloy was studied using a Frontier MCV-866 CNC milling machine, which had a maximum spindle speed of 10,000 rpm. The workpiece had dimensions of 100 mm × 40 mm × 40 mm).

Spectral analysis measurements were performed on Inc-718 using a Bruker Q4 Tasman device at three different locations. Afterward, the obtained data were used to calculate the respective averages. Table 1 presents the chemical composition of Inc-718, and the results of the chemical analysis confirmed that the alloy's composition aligns with the chemical composition of commercially available Inc-718 alloy.

To accurately determine the vibration and peak points in the cutting forces, a single Mitsubishi AOMT123608PEER-M VP15TF grade PVD-coated carbide insert with a 90° entry angle was used in the experiments. The insert was mounted on a standard BBT 40 tool holder, and a new cutting edge was used in each experiment.

A total of 10 milling tests were conducted, encompassing a range of machining environments. These environments included dry cutting at room temperature, pure-MQL, nanoparticle-reinforced MQL, hot cutting, and hybrid milling. The experimental details are illustrated in Table 2. In addition, the experimental setup is shown in Fig. 1.

2.2. Nano-fluid preparation

During the preparation of nano-fluids, three distinct nano-fluids were obtained by incorporating weight percentages of Al₂O₃, SiC, and MWCNT (1 wt%) nanoparticles into the commercially obtained Cuttex 32 R oil. The selection of nanoparticle weight ratios for the mixture was determined based on preliminary experiments and existing literature [21]. In order to mitigate agglomeration within the nano-fluids and enhance the stability of the resulting suspensions, pH adjustment, and ultrasonic vibration techniques were employed. In this process, an HSD180 hot plate magnetic stirrer device was utilized for the mixing process. During mixing, the nanoparticle additives were gradually introduced into the base liquid, and the process was sustained for 30 min. To remove small-sized contaminant particles, a Kudos SK2210HP HP Series 53 kHz heated ultrasonic bath with a power output

Table 1
Chemical composition of Inconel 718 alloy (wt%).

C	Mn	P	Si	Cu	Co	Al	Ti	Mo	W	Nb	Fe	Cr	Ni
0.120	0.110	0.036	0.592	0.072	1.008	0.960	3.000	3.194	0.934	7.200	11.880	23.21	47.58

Table 2
Experimental details.

Milling parameters	Remarks
Cutting environments	Dry PMQL (Pure MQL) Hot (Pre-heating of the material with external heat source) Hot + PMQL Al ₂ O ₃ – NMQL (Al ₂ O ₃ based nanofluid -MQL) SiC – NMQL (SiC based nanofluid -MQL) MWCNT – NMQL (MWCNT based nanofluid -MQL) Hot + Al ₂ O ₃ – NMQL (Hybrid environment) Hot + SiC – NMQL (Hybrid environment) Hot + MWCNT – NMQL (Hybrid environment)
Cutting insert	PVD coated AOMT123608PEER-M VP15TF, nose radius: 0.8 mm
Cutting parameters	V _c : 60 m/min, f _z : 0.06 mm/tooth, a _p : 1 mm, a _c : 12 mm (Constant in each experiment)
Tool holder diameter	16 mm
Number of the cutting insert	1
Nanoparticles	Al ₂ O ₃ (Purity: 99%, size: 40 nm, density: 3.95 g/cm ³ , morphology: nearly spherical) SiC (Purity: 99 + %, size: 40 nm, density: 3.216 g/cm ³ , morphology: nearly spherical) Multi Walled Carbon Nanotubes, MWCNT (Purity: 92%, outside diameter: 8–10 nm, density: 2.4 g/cm ³)

of 90 W and a frequency of 53 kHz was used for 30 min. In the final stage of the nano-fluid preparation process, the resulting mixture was stirred for 60 min at 1500 revolutions per minute using the HSD180 Hot Plate Magnetic Stirrer. The preparation procedure of nanofluids is also shown in Fig. 2.

2.3. Pre-heating process and MQL setup

Before hot and hybrid milling, a preheating process was conducted

using an external heat source, and the specimen was heated up to 300 °C for 40 s using an open flame, oxygen gas, and a torch. Throughout the preheating process, the surface temperature of the Inc-718 was continuously audited using both an MI3 pyrometer and a Testo 872 thermal camera. Once the surface temperature of 300 °C was reached, the open flame was deactivated, and the milling process was then initiated. In the case of hybrid milling, after reaching the desired temperature level, the MQL system was activated to provide lubrication and cooling to the cutting tool during the milling process.

The milling variables such as cutting speed and feed rate used in the experiments were determined based on pilot tests and catalog data provided by the cutting tool manufacturer. In the MQL and hybrid milling environments, a biodegradable cutting oil called Cuttex 32 R was utilized. The kinematic viscosity of this cutting oil is 32–37 cSt at 40 °C, and its density is 0.868 g/cm³ at 15 °C. The oil has a flash point above 232 °C. To achieve effective lubrication and cooling directly at the cutting zone, the Werte STN40 MQL system was utilized, and the MQL nozzle was precisely positioned 20 mm away from the cutting point and at a 20° angle relative to the machine's XY plane. The oil flow rate was continuously adjusted to 10 ml/min.

2.4. Measurements

A Brookfield viscometer (model DV-1) was utilized to measure the viscosities of base fluid, and Al₂O₃ and SiC based nanofluids. In addition, the pH values of these fluids were identified with a pH meter (HANNA).

During the experiments, the cutting forces were measured using a Kistler 9272 dynamometer, with a sampling frequency of 20,000 Hz.

The QM42VT2 vibration measurement sensor was used to record the milling machine's vibration and acceleration. The device was attached to the vise, linked to the polytrace smart box, and the data was synchronously saved and stored on the polytrace website.

After the milling processes, the image of the worn tools was obtained with the help of Tescan Maia3 xmu scanning electron microscope (SEM).

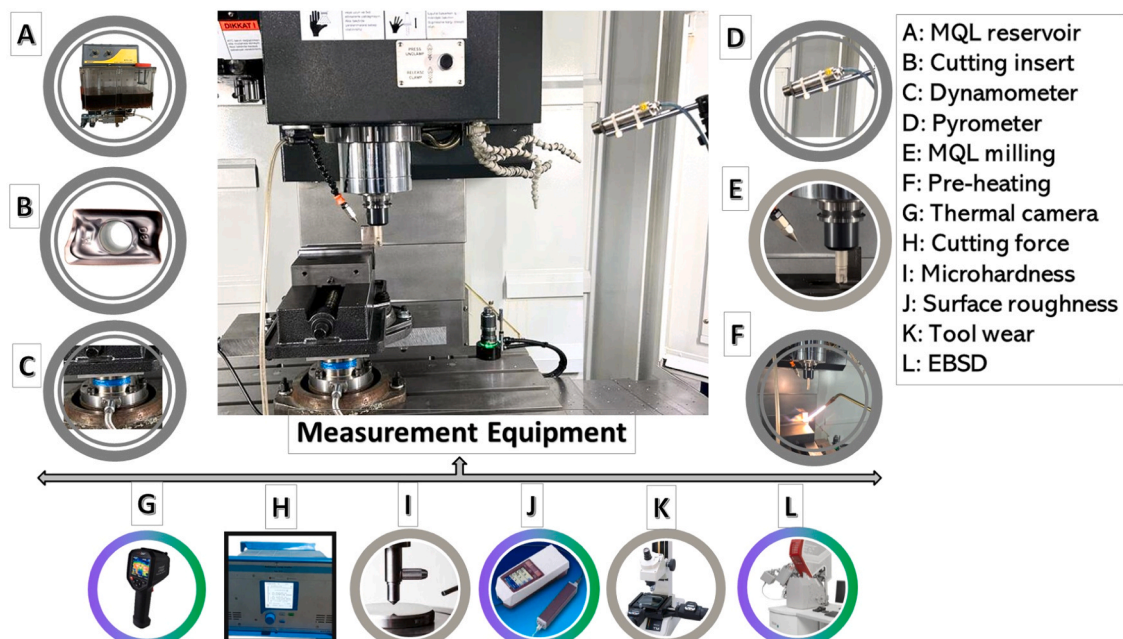


Fig. 1. Experimental setup.

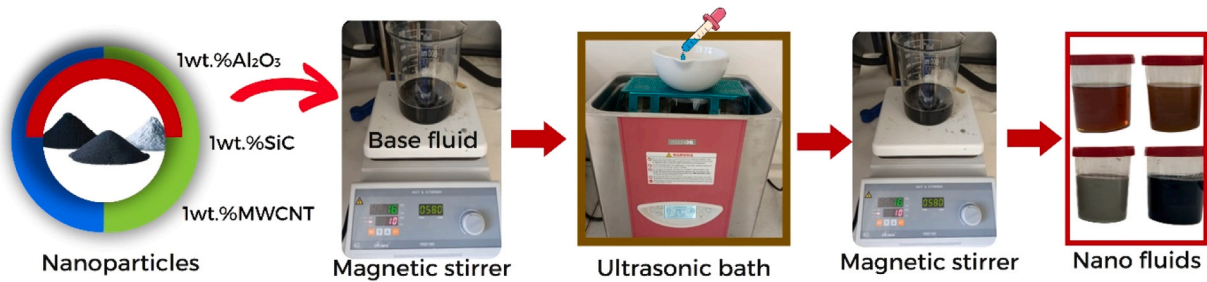


Fig. 2. Procedures followed in the preparation of nanofluids.

Surface roughness measurements were conducted at four different locations along the cutting direction using a Mitutoyo SJ-210 measurement device, and average Ra values were calculated by eliminating the unsuitable values. Hardness measurements were carried out at three different points from the machined surface to the base material, using an Emctest DuraScan 70 G5 device according to the Hv1 scale of the ASTM E384 standard.

After the milling process, the machined surfaces were examined using a Leica DMI 5000 M optical microscope, capable of magnifications ranging from $50\times$ to $1000\times$, in order to observe the changes in the microstructure. The machined Inc-718 was cut by wire electric discharge machining for microstructural analysis, then embedded in bakelite casting resin. Following that, an automated sanding process was employed using silicon carbide sandpapers with grit sizes of 800, 1000, 1200, and 1500 consecutively. Subsequently, polishing was carried out using diamond suspensions with particle sizes of 6, 3, and 1 micrometer, followed by the application of a 0.002 nm colloidal silica solution. For etching purposes, the Kroll reagent was utilized in accordance with the ASTM E407 standard.

The effects of preheating on the machined surface were examined using a Tescan Maia3 xmu scanning electron microscope. The microstructural behavior of the hot-machined Inc-718 was investigated using a high-performance symmetrical Electron Backscatter Diffraction (EBSD) detector produced by Oxford Instruments, to determine whether temperature and milling parameters have any detrimental effect on phase fraction and microstructural changes. The EBSD scanning parameters were set to an acceleration voltage of 20.00 kV, a hit rate of 91.18%, and an acquisition rate of 22.43 Hz. To investigate the microstructural behavior changes of Inc-718, EBSD scanning was conducted on a $240\mu\text{m} \times 300\mu\text{m}$ area. A step size of $0.6\mu\text{m}$ was employed for each loading step, and the scanning process, which took approximately 115 min, acquired EBSD patterns within the frequency range of 300–400 Hz.

3. Results and discussion

3.1. Ph and viscosity

Nanofluids are referred as complex fluids that have emerged mainly to increase the performance of thermal and thermo-mechanical components. However, the low stability caused by the aggregation and/or precipitation of nanoparticles in the fluid over time is one of the most critical challenges for their practical applications. The well-known method used to enhance the dispersion of nanoparticles in base fluid is to provide electrostatic stabilization, which changes the surface charge of nanoparticles by using surfactants or changing the pH [22]. However, surfactants' impacts on nanofluids are complicated since they have various effects on them. Moreover, surface modification methods are also costly and difficult, which makes them impractical for applications in industry. Since the pH of nanofluids can be easily changed, it is simpler and more economical to produce pH-treated nanofluids with better features [23]. For this purpose, the pH values of the base liquid and nanofluids prepared with different types of nanoparticles were

measured and the responses are provided in Fig. 3. Here, a slight decrease was observed in the Ph values of SiC and MWCNT-based nanofluids compared to the pH value of the base fluid, while the pH value of the Al₂O₃-based nanofluid increased more significantly. Since agglomerated structures may develop when the pH is lower than 7, this may lead to rapid sedimentation [24]. As previously reported by [24, 25], richer pH produces substantial surface charges on nanoparticles and inhibits aggregation and therefore improves stability.

The physical and chemical features of nanoparticles and their concentration in the nanofluid have a significant effect on dynamic viscosity and density, and their high values increase power consumption in pumping systems, which becomes a disadvantage for nanofluid use [22]. In MQL systems, on the other hand, high viscosity may cause clogging of the hoses and failure of the pump [26]. Moreover, in terms of cutting performance, the extremely high viscosity of the fluid may also prevent the penetration of cutting fluids into the cutting zone. As can be seen in Fig. 3, while there was a slight increase in the viscosity of the Al₂O₃-based nanofluid compared to the base fluid, there was a sharp increase in the SiC and MWCNT-based nanofluids. Compared to the base fluid, the viscosity of the Al₂O₃, SiC and MWCNT-based nanofluids increased by 8.3%, 350% and 903%, respectively. In this respect, the more reasonable dynamic viscosity of Al₂O₃-based nanofluid compared to others means that it will offer more effective results in industrial use.

3.2. Surface roughness

The use of nickel-based Inc-718 superalloy in the production of critical parts, especially in the aerospace industry, leads to greater attention to its surface and sub-surface characteristics. The reason for this care is that a low surface roughness is one of the most basic indicators of surface quality and it directly affects the service performance

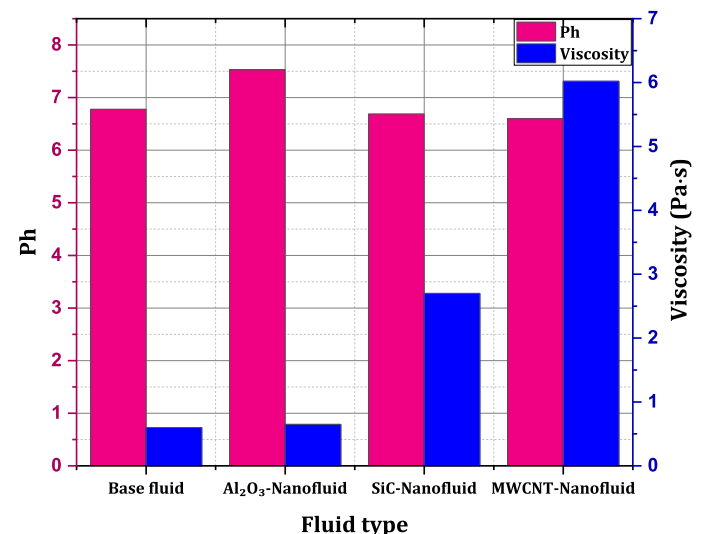


Fig. 3. pH and viscosity values versus fluid type.

of the alloy (strength, fatigue, impact resistance, fracture, etc.) [27]. In this study, surface roughness results were measured in 10 different cutting environments at constant cutting parameters and these were compared with the results obtained in dry conditions as presented in Fig. 4. As expected, the poorest surface quality turned out to be 0.549 μm under dry cutting. Thanks to the applied heating, lubricating and heating+lubricating (Hybrid) agents, the surface roughness has been significantly reduced. Compared to dry cutting, reductions in surface roughness of 37.5–62.8% have been achieved with cooling/lubrication agencies. To put it more clearly, 37.5%, 45.4%, 49%, 51.2%, 51.7%, 56.3%, 56.5%, 58.5% and 62.8% improvements were achieved in (1) PMQL, (2) MWCNT-NMQL, (3) hot+MWCNT-NMQL, (4) SiC-NMQL, (5) hot, (6) hot+SiC-NMQL, (7) Al_2O_3 -NMQL, (8) hot+PMQL, and (9) hot+ Al_2O_3 -NMQL environments, respectively. Although the surface roughness was reduced under all applied conditions, the reductions were more remarkable especially in hot, hot+PMQL and Al_2O_3 -NMQL and hot+ Al_2O_3 -NMQL environments. Heating the workpiece prior to cutting with the aid of an external heat torch results in a reduction in the yield, ultimate tensile and shear strength of the Inc-718 alloy, resulting in a tangible reduction in cutting resistance and cutting forces. Furthermore, due to the weakening of the structural strength of the preheated material and the reduced cutting resistance, the vibration amplitudes of the tool-workpiece pair are also reduced, resulting in a better surface finish. When machining only under PMQL, the surface roughness was reduced compared to dry cutting, but remained above the Ra values obtained by machining under preheating with torch. This situation proves that single cooling-lubrication agency to the cutting zone will be insufficient in cutting of difficult-to-machine alloys such as Inc-718. Luan et al., [20] who reached a similar finding, claimed that under pure-MQL, the roughness of the chip and the wide adiabatic slip band increased the negative effect of the chip on the machined surface of the workpiece, increasing the surface roughness value compared to heat assisted cutting.

Further improvement in surface roughness with hot+ Al_2O_3 -NMQL hybrid agencies is associated with both a decrease in the structural strength of the workpiece with preheating and a reduction in friction with effective lubrication at the tool-chip interface. Moreover, it can be mentioned that possible reductions in cutting forces and tool wear are among the other important reasons for this, thanks to the synergy effect that occurs with the workpiece preheating and lubrication of the cutting zone with nanofluids especially Al_2O_3 -NMQL. On the contrary, there is a poorer surface quality in milling under SiC and MWCNT-based

nanofluids compared to Al_2O_3 -based nanofluid. Al_2O_3 nanoparticles have a spherical shape, a richer specific surface area and adsorption. Al_2O_3 is capable of having high strength and high chemical stability due to the strong polarity of the chemical bonds between Al^{3+} and O^{2-} and the high lattice energy [28]. Zhang et al. [28] claimed that Al_2O_3 nanoparticles exhibits strong surface adsorption and strongly adheres to the base oil, thus forming a thin oil film at the interface. On the other hand, the fact that SiC nanoparticles exhibit irregular shapes and contain multiple edges is not sufficient for oil film formation and "ball effect" at the interface [28]. In addition, the extremely high viscosities of MWCNT and SiC based nanofluids are thought to restrict them from effectively dispersing and forming a thin film at the tool/chip/workpiece interfaces. Likewise, the low pH values of these two nanofluids were also evaluated as an indication of their poor performance due to stability problems.

3.3. Cutting force

Information about the magnitude and direction of the resulting cutting force F and its components is vital for many actions such as designing machine tools, determining cutting parameters, designing cutting tools, interpreting the achievable accuracy of the part and the phenomena occurring at the point of contact, calculating power consumption, etc., in metal cutting operations. As higher forces are generated when cutting more difficult-to-machine materials, more care is required when machining such materials. In this study, the three components of the cutting force F in the x (F_x), y (F_y) and z (F_z) directions were measured with a dynamometer and the resultant cutting force (Fr) was calculated as presented in Eq. (1):

$$Fr = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

The resultant cutting force results under each cutting environment are shown in Fig. 5. Accordingly, the cutting forces under PMQL decreased compared to dry cutting, this alone was while, dramatic decreases in cutting forces were observed with the inclusion of heat source and/or nanofluids in the cutting process. Compared to dry cutting, the resulting cutting force was reduced through PMQL¹, hot², MWCNT-NMQL³, SiC-NMQL⁴, hot+MWCNT-NMQL⁵, Al_2O_3 -NMQL⁶, hot+PMQL⁷, hot+SiC-NMQL⁸, hot+ Al_2O_3 -NMQL⁹ by (1) 23.51%, (2) 50.9%, (3) 51.1%, (4) 52.9%, (5) 54.7%, (6) 54.8%, (7) 57.6%, (8) 57.7% and (9) 61.1%. With the inclusion of the MQL system in dry machining, a very small amount of oil sent to the cutting area in a pulverized manner has reduced the friction between the tool-chip and

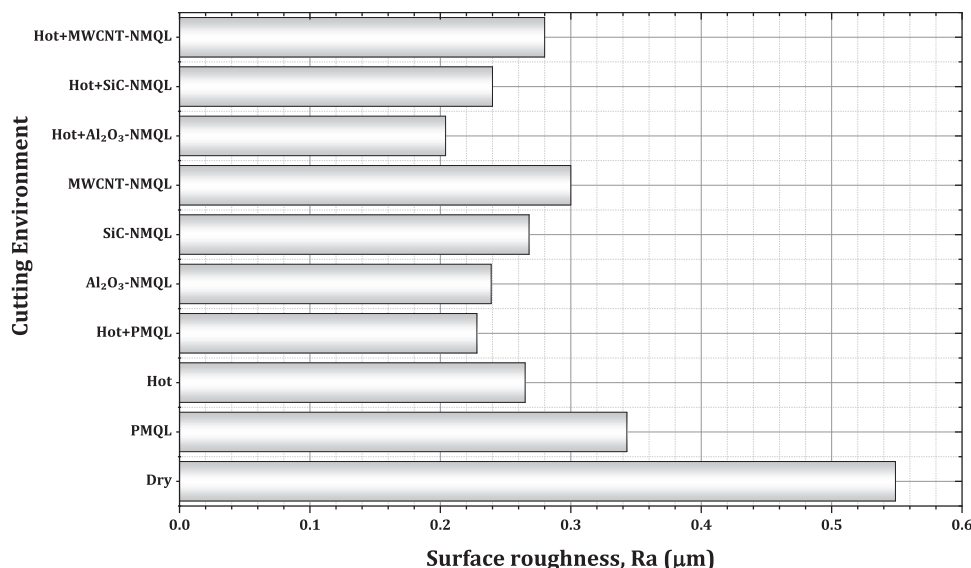


Fig. 4. Surface roughness vs cutting environment.

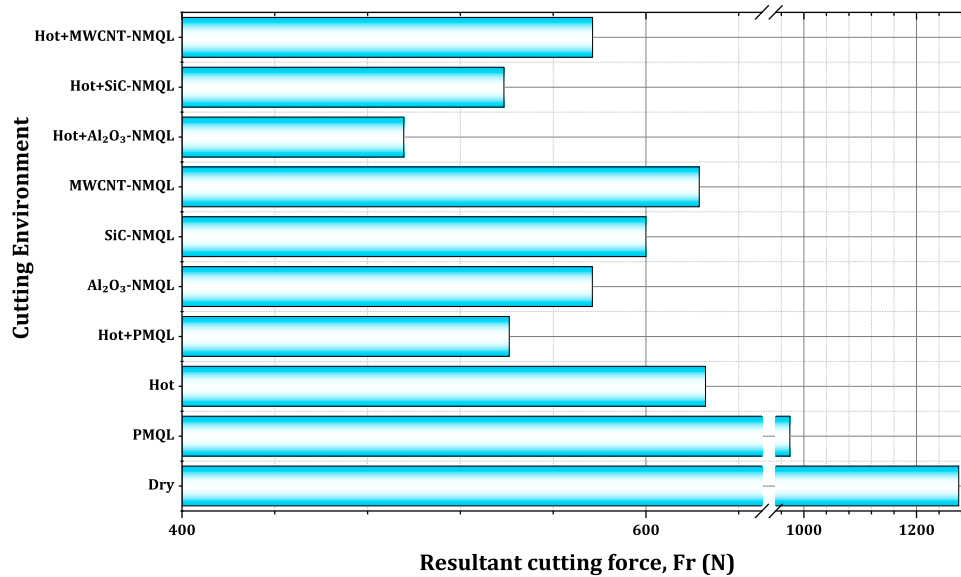


Fig. 5. Resultant cutting force vs cutting environment.

the tool-workpiece, and thus, significant reductions in cutting forces have been observed. Similarly, preheating the Inc-718 workpiece before machining was also very effective in reducing the cutting forces. This important effect is principally caused by a decrease in the yield strength of the machined workpiece material, which results in a reduction in the production of cutting force. In particular, the hybrid use of Al₂O₃ based nanofluids with pre-heating support during machining of Inc-718 further improved the reduction in cutting forces. This situation is attributed to the fact that Al₂O₃ nanoparticles act as a ball between the tool-chip-workpiece and contribute to the reduction of the contact surface areas. It can be said that a similar effect is achieved by SiC based nanofluids in terms of cutting forces. As can be seen from the findings in Section 3.1, the lower viscosity and higher Ph values of Al₂O₃ based nanofluids are considered as a result of the effective penetration of the fluids into the cutting zone. As a matter of fact, the very high viscosity of the MWCNT-based nanofluid limited the penetration of the liquid in the cutting zone, and this had a negative effect on the cutting force, as in other results.

3.4. Tool wear

The term "tool wear" describes the cutting tool failure due to friction at the tool-workpiece or chip contact. One important factor in determining a material's machinability is tool wear. In metal cutting processes, the tool wear has a considerable impact on the surface/subsurface damages, cutting forces, chip morphologies, machining cost, etc. Thus, to understand and reduce tool wear when milling Inc-718, it is essential to investigate tool damages and the responsible wear mechanisms. In this subsection, the damage to the cutting tools during the milling of Inc-718 alloy under different cutting environments was analyzed with SEM images as provided in Fig. 6. When the cutting tool damages in each cutting environment are compared, it is seen that the tool has become unusable by taking serious damage in the dry cutting environment where there is no cooling agency. The size of the damaged area under dry milling is larger than that of the others. Here, built-up layer (BUL) caused by adhesion and chipping are the observed wear mechanisms. In the interrupted cutting process inherent in milling, chipping of the cutting edge is an expected phenomenon. Moreover, it is thought that after a certain milling time, the strength of the cutting tool decreases due to the thermal softening, abrasive, and adhesive wear, leading to a serious failure with chipping of cutting edge. In fact, if the cutting process had continued further, it is highly likely that the crack

seen in Fig. 6(a) would have progressed and caused more serious destructive damage on the cutting tool. It has been emphasized in previous studies that BUE, BUL, adhesion, chipping, catastrophic failure are the mechanisms frequently seen in machining nickel-based superalloys with carbide cutting tools [24,29,30]. In Fig. 6(b), It has been noticed that the damage of the tool is more prominent in the machining performed under PMQL compared to other environments (except in dry environment). It is thought that this situation arises with the chipping mechanism due to the insufficient lubricating ability of PMQL [31]. As seen in Fig. 6(c-j), BUL and BUE formations were formed on the cutting tool due to the adhesion mechanism in the milling operations performed under other environments i.e., hot, NMQLs and hybrid modes. However, it was determined from these SEM images that BUE and BUL formations were more dominant especially in hot (Fig. 6(c)) and hot+MWCNT-NMQL (Fig. 6(j)) environments. This situation was associated with the increased adhesion tendency of the workpiece material loosened by preheating. Moreover, the inability of the MWCNT-based cutting fluid to penetrate the cutting zone allowed this situation. Although the adhesion mechanism of the material was observed in hot+SiC-NMQL and hot+Al₂O₃-NMQL hybrid environments, the formation of BUE and BUL was limited due to the more effective cooling and lubrication application of nanofluids to the tool.

3.5. Vibration

In the milling process, rigidity and tool vibrations are significant issues to take into account. The characteristic features of the milling process, such as intermittent cutting, machining area, high spindle speed, cause more cutting vibration to be produced. The broad vibration phenomena known as "machining chatter" is brought on by the machine tool and the machining conditions. Chatter is a relative structurally generated vibration that occurs in the cutting zone between the workpiece and the cutting tool. It has an impact on the workpiece's surface quality and dimensional accuracy, while vibration has an impact on tool life and machine tool spindle during cutting [32]. In this study, the vibration velocity was measured in units of millimeters/second (mm/s) in the X and Z axes of the machine tool table and results are given in Fig. 7. As seen in Fig. 7, vibration velocities in the X and Z axes of the machine tool vise showed similar trends. Due to the rotation speed of the machine spindle and the cutting forces produced, the vibration speeds occurring in the X axis are higher than those of the Z axis. As seen in Fig. 7, the maximum vibration velocity was observed under dry cutting, while the

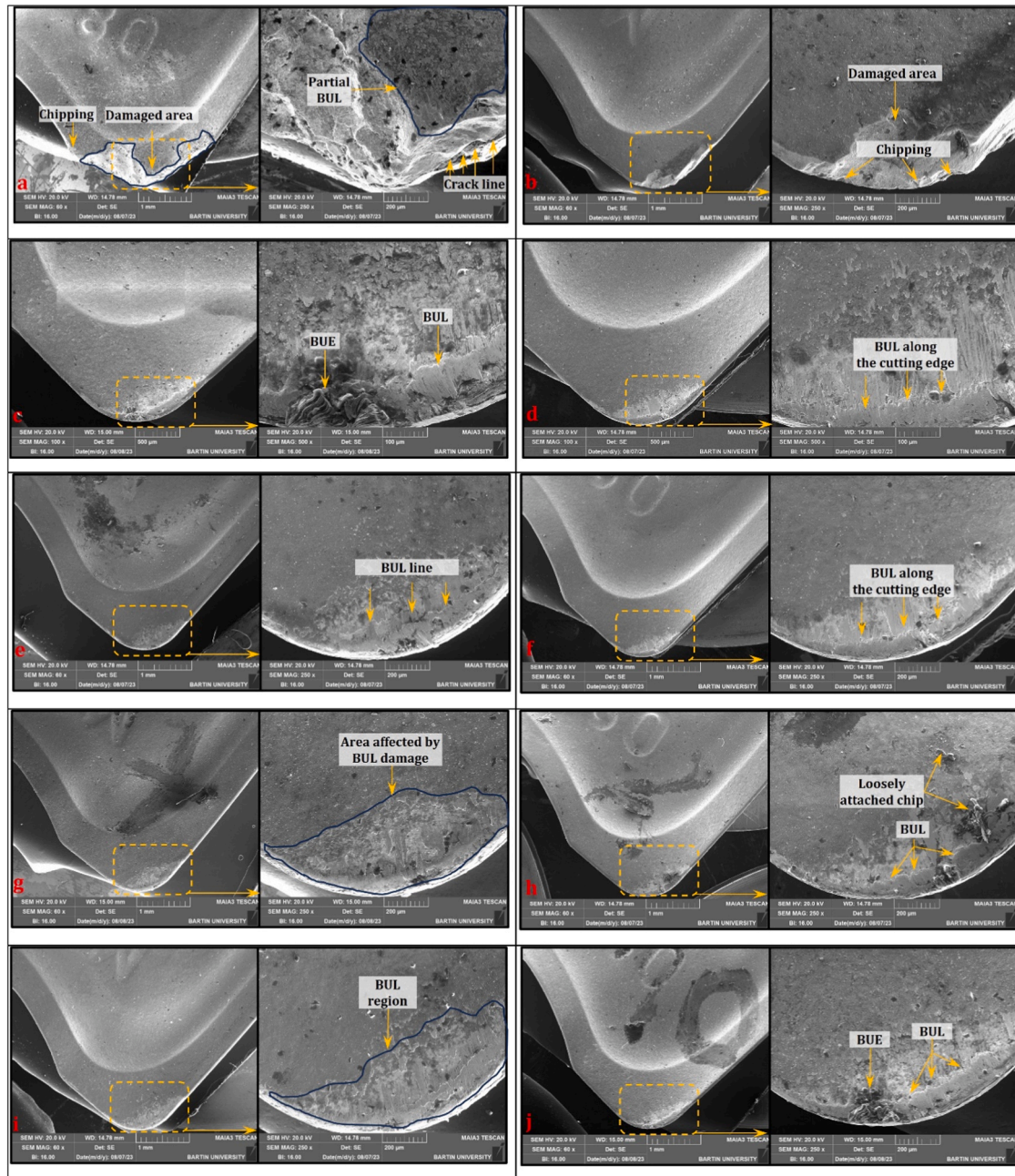


Fig. 6. SEM images of worn cutting tools under different environment a) dry, b) MQL, c) hot, d) hot+PMQL, e) Al_2O_3 -NMQL, f) SiC-NMQL, g) MWCNT-NMQL, h) hot+ Al_2O_3 -NMQL, i) hot+SiC-NMQL, j) hot+MWCNT-NMQL.

minimum vibration occurred in hot+ Al_2O_3 -NMQL. In addition, gradual decreases in vibration rates were obtained under PMQL, hot and NMQL, hot+PMQL and hot+NMQL conditions compared to dry cutting. It is thought that the cutting fluid delivered to the cutting zone with the MQL method contributes to the reduction of friction coefficient, cutting force and tool wear, and thus, significant decreases in vibration speed occur. Possible mechanisms (tribofilm formation and rolling effect) thought to occur on the contact surfaces have been further developed thanks to Al_2O_3 and SiC based nanofluids and have led to a further decrease in the vibration velocity. Moreover, as a result of preheating with the external heat source provided in the hot and hybrid cutting process (hot+PMQL and hot+NMQL), the strength of the material has loosened, thus reducing the cutting forces and consequently the vibration velocity. However, the fact that the vibration reduction capability of MWCNT-based nanofluids was worse than that of Al_2O_3 and SiC-based

nanofluids was attributed to the higher viscosity of the MWCNT-based nanofluid.

3.6. Temperature

One of the key elements in determining the mechanism of the cutting process is the cutting temperature. High cutting temperatures are produced at the tool/chip/workpiece interfaces as a result of the progressive conversion of mechanical energy to thermal energy [33]. Fig. 8 depicts the areas of heat production that are created throughout the machining process. The primary shear zone (zone '1' in Fig. 8) undergoes thermo-mechanical deformation, which contributes significantly to the heat production. Other locations responsible for heat generation are the tool-chip friction zone (zone '2') and the contact zone between the tool and the newly formed surface (zone '3'). The heat

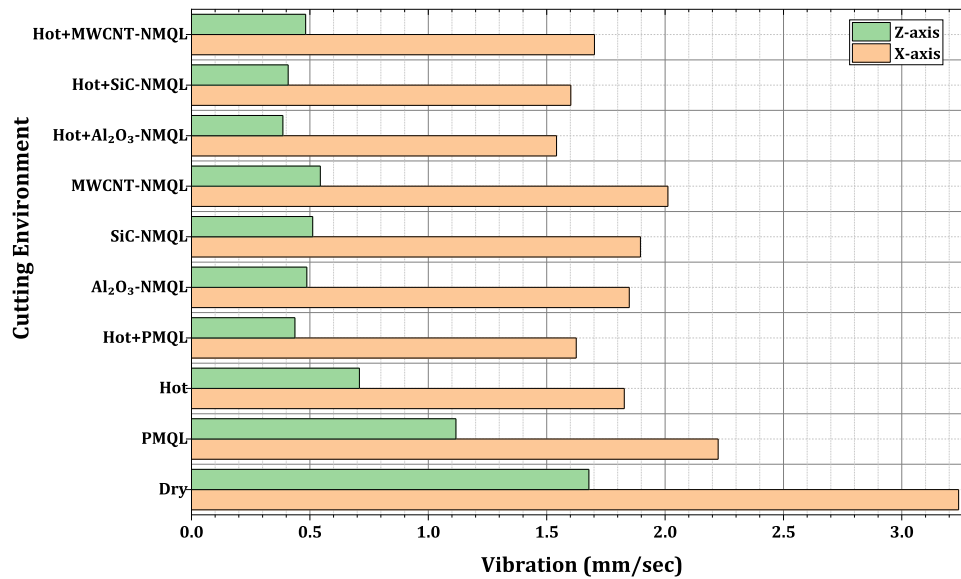


Fig. 7. Vibration values versus cutting environment.

generated is transmitted via cutting tool, workpiece and chips. Heat transfer varies depending on the thermal and physical properties of the workpiece and tool material as well as the machining conditions. The main reason for the increase in cutting region temperature is the poor thermal conductivity of Inc-718 (11.4 W/m-K) [34]. Although a significant portion of the heat is discharged along with the chips, the cutting temperature can rise significantly [35].

In this study, during the milling of the Inc-718 an image of the temperatures formed in the cutting zone by means of a thermal camera is given in Fig. 9. Moreover, the maximum temperatures occurring under each cutting environment are presented in Fig. 10. Accordingly, the order of the environments responsible for the temperatures occurring in the cutting zone from the highest to the lowest is hot¹, hot+MWCNT-NMQL², hot+SiC-NMQL³, hot+PMQL⁴, dry⁵, hot+Al₂O₃-NMQL⁶, MWCNT-NMQL⁷, SiC-NMQL⁸, PMQL⁹ and Al₂O₃-NMQL¹⁰, respectively. The absence of any cooling/lubrication agency and even the increase of the material temperature up to a certain point by preheating caused the cutting zone temperature to rise. However, it was observed that the temperature was still above the dry cutting temperatures even if the MWCNT-NMQL, SiC-NMQL and PMQL cooling/lubrication tools were used with the preheating of the material. Thus, it can be said that after the preheating of the material, the cooling of the cutting tool with these

methods is insufficient. On the other hand, although there is preheating in the cooling of the cutting tool, a lower temperature than dry cutting was obtained only in the Al₂O₃-NMQL condition. Compared to SiC and MWCNT doped nanofluids, the high pH value and lower viscosity of the Al₂O₃ based nanofluid played a critical role in penetrating the tool-chip interface and reducing both friction and cutting temperature. Thanks to Al₂O₃-based nanofluid agency without preheating process, the lowest cutting temperature once again demonstrated the effectiveness of Al₂O₃-NMQL compared to all other conditions. Through preheating process, thermal softening of the Inc-718 is provided on the one hand, and the temperature of the cutting zone increases on the other hand. However, if the cutting tools are chemically stable and able to withstand thermal and mechanically induced stresses, this makes a significant contribution to the reduction of cutting forces, surface roughness and tool wear. Therefore, the perfect planning of hybrid methods offers a balance between the material temperature and the cutting tool temperature, thus increasing the machining efficiency.

3.7. Microstructural analysis by EBSD

In this section, the effect of preheating on the microstructure of the alloy is investigated in detail. For this, hot, hot+MQL (hybrid) environments were taken and compared with the dry environment. Accordingly, Fig. 11 shows the microstructure of the machined Inc-718 under these environments i.e., dry, hot and hot+PMQL. The white regions observed correspond to the α phase, while the dark regions correspond to the β phase, and additionally, a co-axial microstructure is evident. The optical images demonstrate a superficial material particle flow in the cutting direction on the machined surfaces of the samples in different cutting environments. This is due to the surface deformation that occurs during milling. It can be observed that milling performed in hot and hybrid environments did not result in any damage or recrystallization in the machined surface and grain structures of the material.

Inc-718 alloy retains its physical behaviors at high temperatures. However, the microstructural stability of Inc-718 alloy machined in thermal-assisted machining environments is of great importance. The preheating can induce several effects on the surface of workpiece materials, including thermal softening, grain refinement, and strain hardening. These effects can have a negative impact on the microstructural stability and compromise the superior properties of the material [18, 19]. Hence, it is of great importance to determine the effects of high processing temperatures on the physical behaviors and microstructural

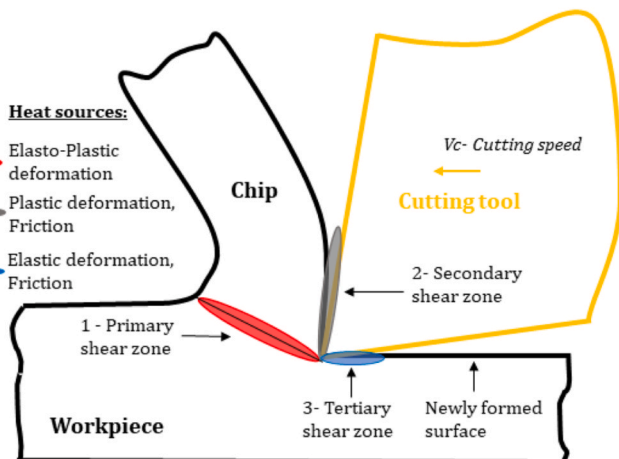


Fig. 8. Heat generation sources in metal cutting. Reproduced from [27] and [36].

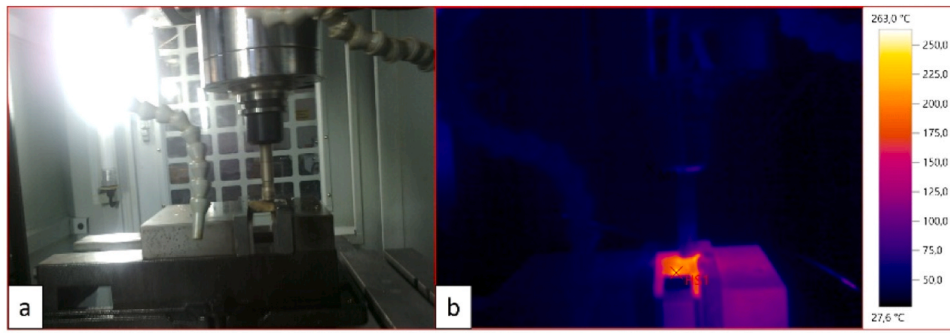


Fig. 9. a) A snapshot of milling and b) its thermal camera view.

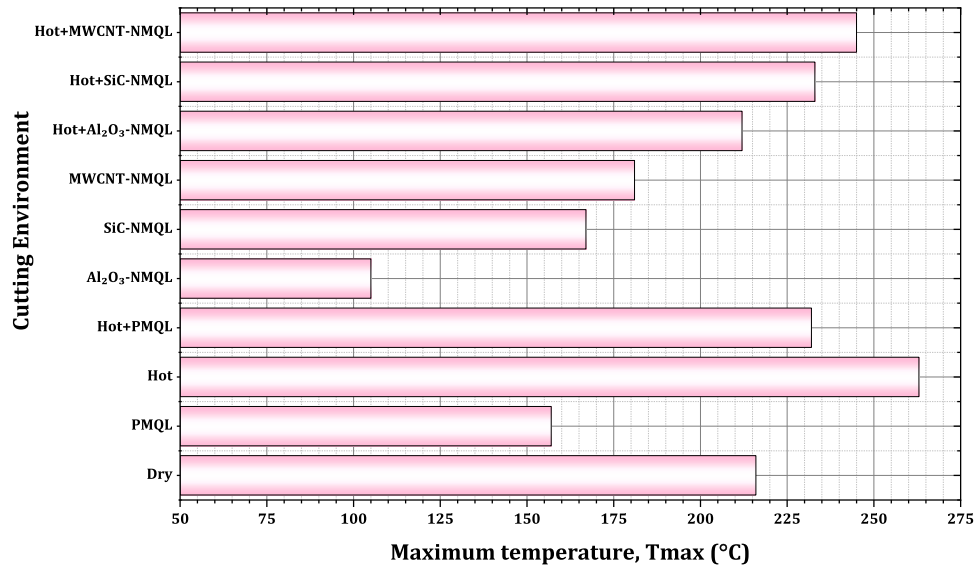


Fig. 10. Maximum temperature values versus cutting environment.

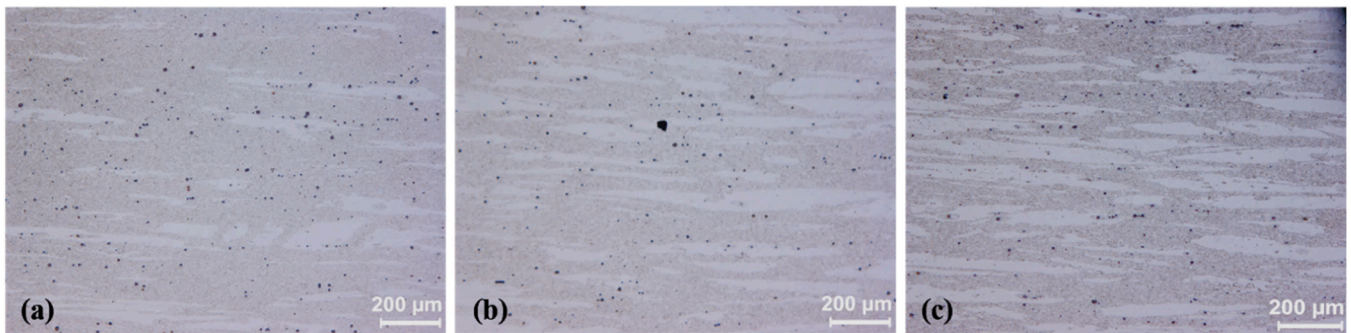


Fig. 11. Microstructure of Inconel 718 alloy machined in a) Dry, b) Hot, c) Hybrid condition (hot+PMQL).

stability of pre-heated Inc-718. In order to thoroughly evaluate the effects of hot machining on the microstructural behavior of the subsurface of the machined Inc-718, an EBSD analysis was conducted. For this analysis, Fig. 12 shows the scanned area.

Fig. 13 presents Euler-colored maps and phase distribution maps, which provide a visual representation of the microstructure state in different milling environments, namely dry, hot, and hot+PMQL. These maps provide a fundamental overview of the scanned area. Euler angles used in EBSD models are employed to characterize a crystal orientation and cover the following ranges: $0 \leq \phi_1\alpha < 360$, $0 \leq \Phi\alpha \leq 180$, and $0 \leq \phi_2\alpha < 360$. For each map, the coloring is based on the

determination of the crystal orientation and the selection of the orientation of the reference samples. The analysis of the Euler color distribution reveals that the hot milling process had an unnoticeable impact on a specific region, extending from the surface of the workpiece to a depth of approximately 14.47 μm into the main material.

Fig. 14 illustrates the phase maps of samples subjected to dry, pre-heated, and hybrid machining conditions. In the phase color maps, the regions displaying phase distribution and those affected by temperature during the hot and hybrid milling processes are indicated by the color black.

Fig. 15 showcases in-situ IPF (Inverse Pole Figure) orientation maps,

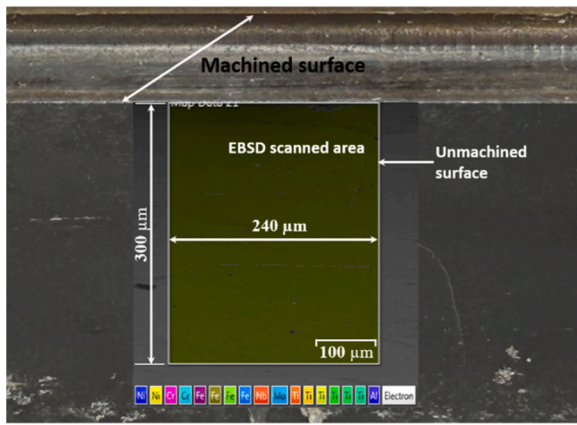


Fig. 12. Scanned area for EBSD analysis.

which display the crystal orientation of machined Inc-718 under dry, pre-heated, and hybrid milling conditions. The IPF color scheme is employed to facilitate the interpretation of color changes, disregarding minor directional variations. Different colors within the map represent distinct crystal orientations, while the uniformity of color within a grain indicates well-aligned grains. This information can be used to understand the mechanical properties of materials and to optimize the machining process. In the case of dry milling, the uniform color formation indicates that the grains are well-aligned and unaffected by unfavorable milling parameters.

The IPF maps clearly demonstrate that each grain exhibits a consistent color and uniform orientation, indicating a well-aligned microstructure. Consequently, upon comparing dry milling with hot and hybrid milling conditions, it becomes evident that the impact of heat is limited and insignificant, affecting only a small region of the material.

The distance between the machined surface and the main material, which is affected by heat, was measured as 14.47 μm. As can be seen in Figs. 13–15, a limited area is affected by heat in the hot machining environment, while the rest of the material has the normal structure of

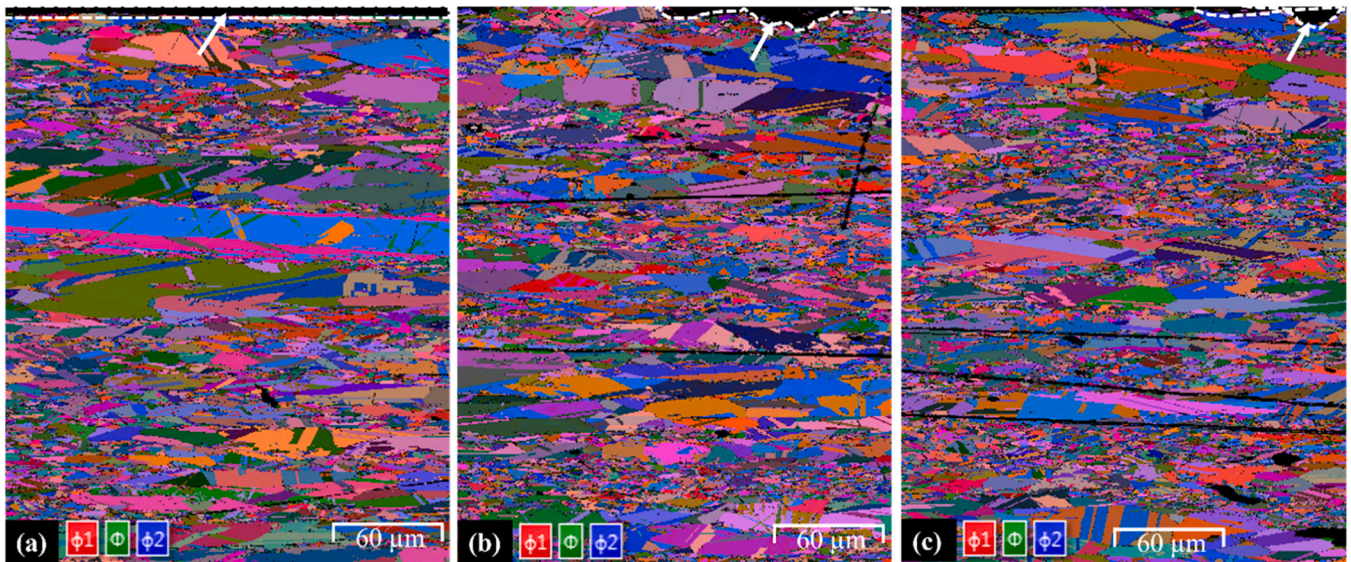


Fig. 13. Euler color maps in the machining of a) Dry, b) pre-heated, and c) hot+PMQL.

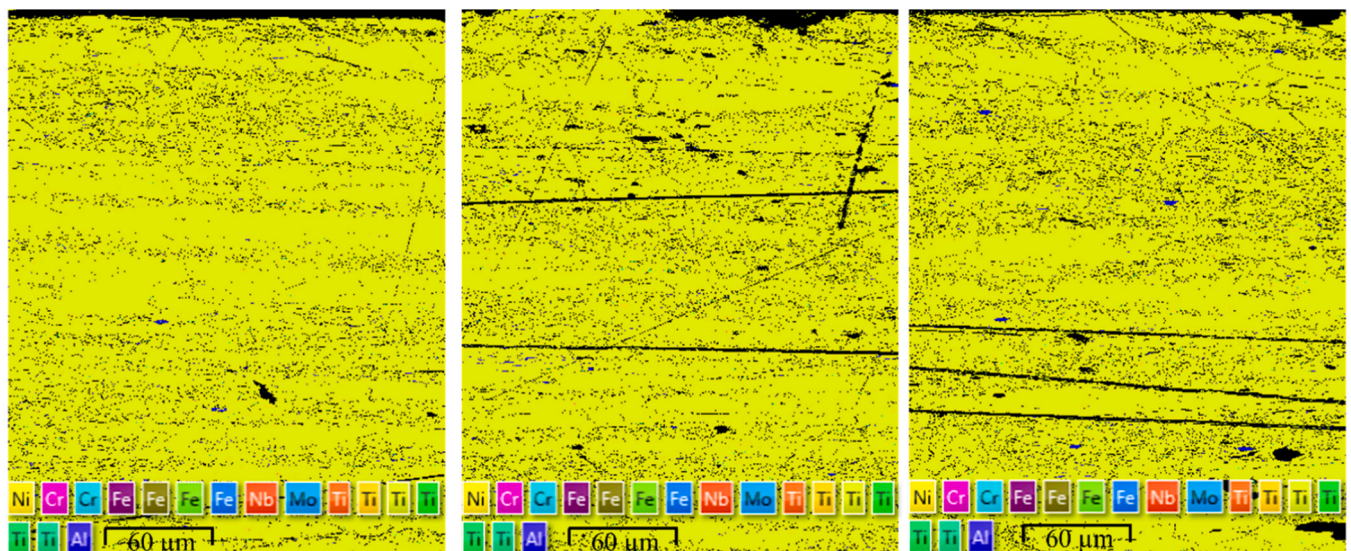


Fig. 14. Phase color distribution maps in the machining of a) Dry, b) pre-heated, and c) hot+PMQL.

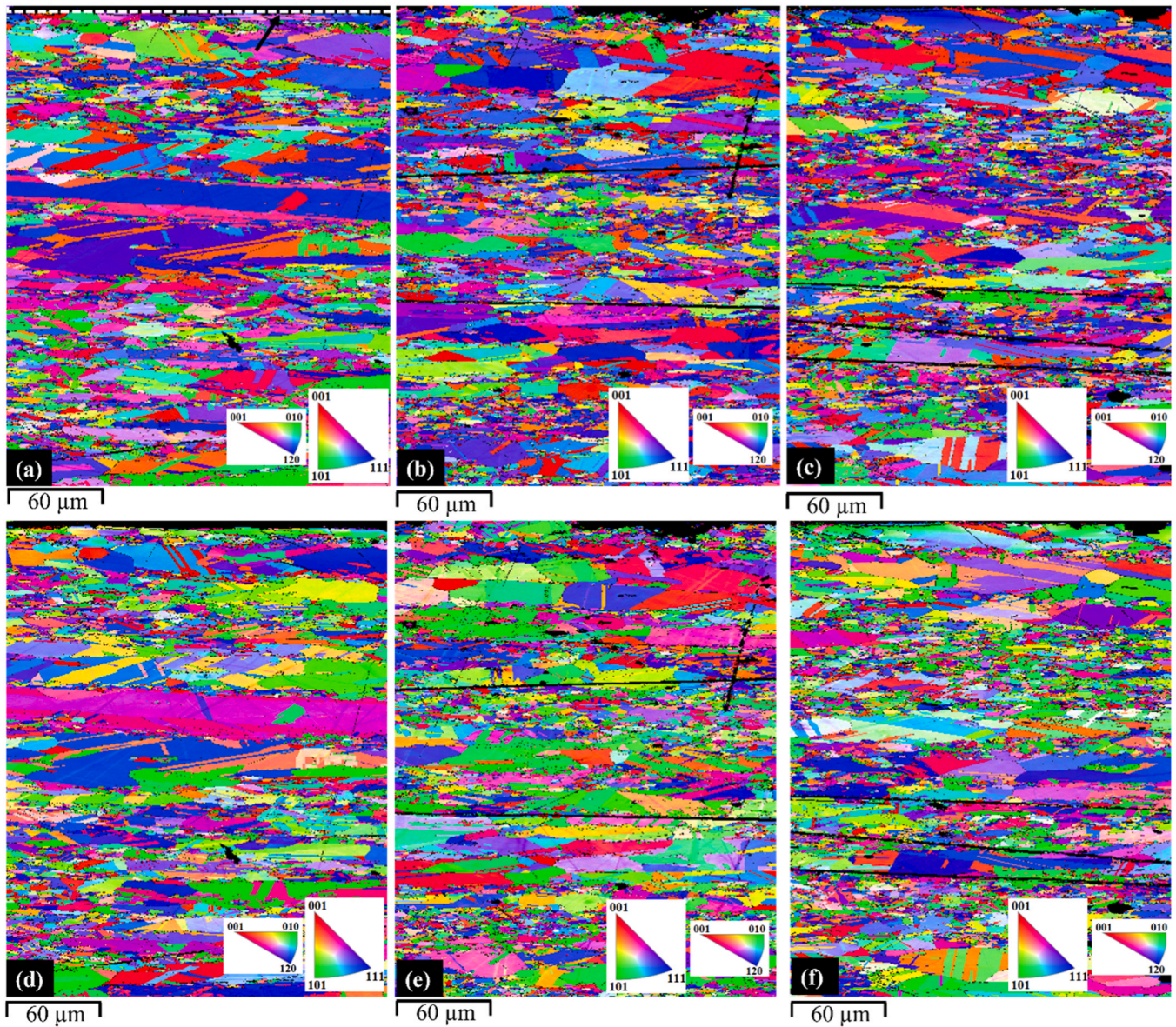


Fig. 15. The crystal orientation maps for the different machining conditions, (a-c) X, (d-e)-Y.

the base material. The IPF maps obtained from the hybrid machined surface revealed the presence of a recrystallized grain structure. This recrystallized grain structure had a depth of 8.39 μm and a length of 21.55 μm . The crystal orientations of the pre-heated and hybrid machined Inc-718 alloy are highly similar to that of the dry-machined alloy. This similarity indicates that the removal of the heated layer from the workpiece during the milling process contributes to the preservation of the microstructure. Furthermore, it was observed that the implementation of the MQL system in the hybrid milling process offered an additional enhancement compared to pre-heated milling. This improvement is attributed to the lubrication and cooling effect provided by the MQL, resulting in improved machining conditions and potentially better outcomes.

3.8. Microhardness

At elevated temperatures, the grain size on the machined surface tends to increase due to the influence of machining temperatures. Simultaneously, the hardness of the material tends to decrease. During chip removal, the cutting tool applies a force on the workpiece surface,

which has the potential to cause damage to the grain structure. However, rapid cooling of the workpiece material can lead to a decrease in grain size, resulting in grain refinement and an increase in the machined surface hardness. As a result, the choice of machining conditions is crucial to avoid any detrimental effect on the mechanical behaviors of the workpiece. When analyzing the grain structures, it becomes apparent that the microstructures achieved in pre-heated and hybrid machining environments exhibit similar behaviors to the workpieces machined at room temperature. This shows that the selected cutting environments, especially pre-heated and hybrid machining, can preserve the desirable microstructural characteristics of the material without compromising its mechanical properties. However, EBSD analysis reveals grain refinement in a region approximately 5.2 μm deep between the surface of the material machined under dry conditions and the main material resulting in higher hardness on the machined surface. Therefore, in addition to EBSD analysis, surface, and sub-surface hardness measurements were conducted to compare the influence of the cutting environments on the machined workpiece.

Fig. 16 depicts the average hardness values measured from the machined surface. The highest hardness values were recorded in the

experiments conducted at room temperature for dry, MQL, and ceramic particle reinforced MQL milling processes, respectively. However, in the case of pre-heated, hybrid, and pre-heated ceramic particle-reinforced hybrid machining agencies, the hardness values of the machined surface decreased compared to the hardness of the unmachined material because of preheating. Consequently, the preheating process caused a decrease in the hardness of the machined surface, while it caused an increase in the milling tests performed in dry conditions. The optical images and hardness values provide evidence that the preheating process did not negatively impact the physical behavior of the Inc-718 alloy. These findings align with the EBSD analysis and can be stated as the removal of the material layer exposed to heat during the milling process, along with the chip.

4. Conclusion

The results obtained in the study can be drawn as follows:

- A slight decrease was observed in the Ph values of SiC and MWCNT-based nanofluids compared to the pH value of the base fluid, while the pH value of the Al_2O_3 -based nanofluid increased more significantly. Compared to the base fluid, the viscosity of the Al_2O_3 , SiC and MWCNT-based nanofluids increased by 8.3%, 350% and 903%, respectively. Therefore, the more reasonable dynamic viscosity with Al_2O_3 -based nanofluid was obtained compared to others.
- Thanks to the applied heating, lubricating, and heating+lubricating (hybrid) agents, the surface roughness has been significantly reduced. Compared to dry cutting, reductions in surface roughness of 37.5–62.8% have been achieved. Maximum improvement in surface roughness was occurred under hot+ Al_2O_3 -NMQL environments.
- Preheating the Inc-718 workpiece before machining was also very effective in reducing the cutting forces. In particular, the hybrid use of Al_2O_3 based nanofluids with pre-heating support during machining of Inc-718 further improved the reduction in cutting forces.
- From the SEM observations, the BUE and BUL formations on the cutting tools proved that the adhesion wear mechanism was quite dominant. Preheating of the material in the hot milling process has led to an increased tendency to adhere. Although BUE and BUL formations were also observed in hot+SiC-NMQL and hot+ Al_2O_3 -NMQL hybrid environments, their size was limited due to the more effective penetration of nanofluids into the tool-chip-workpiece interface.
- The maximum vibration velocity was observed under dry cutting, while the minimum vibration occurred in hot+ Al_2O_3 -NMQL. In

addition, considerable decreases in vibration rates were formed under hot, hot+PMQL and hot+NMQL conditions compared to dry cutting.

- The maximum cutting temperature was found in the hot cutting environment, and the minimum temperature was recorded under the Al_2O_3 based nanofluid.
- The analysis revealed well-defined α and β phases alongside an evident co-axial microstructure within the material. Particle flow observed on the machined surfaces indicated surface deformation resulting from milling, yet notably, no damage or recrystallization occurred in the hot and hybrid machining environments.
- EBSD analysis and phase distribution maps showed that localized heat effects occurred on a limited material region.
- In-situ IPF orientation maps demonstrated consistent crystal orientations and well-aligned microstructures across various machining scenarios. The influence of the pre-heating process was confined to a localized region of the material, attesting to the effectiveness of certain machining environments in preserving material integrity.
- The consequential relationship between hardness and microstructure showed that the preheating process had a limited effect on the hardness of Inc-718. Cutting environment choice influenced hardness and microstructure; preheating process decreased hardness but preserved mechanical properties. The removal of heat-affected layers during milling contributed to the maintenance of desirable material attributes.

Statement of originality

As the corresponding author, I hereby confirm on behalf of all authors that:

- 1) The paper has not been published previously, that it is not under consideration for publication elsewhere, and that if accepted it will not be published elsewhere in the same form, in English or in any other language, without the written consent of the publisher.
- 2) The paper does not contain material which has been published previously, by the current authors or by others, of which the source is not explicitly cited in the paper.

Declaration of Competing Interest

The work presented in this paper is, to the best of my knowledge and belief, original, except as acknowledged in the text, and the material has not been submitted, either in whole or in part, for a degree at this or any other university. There is no conflict of interest to declare.

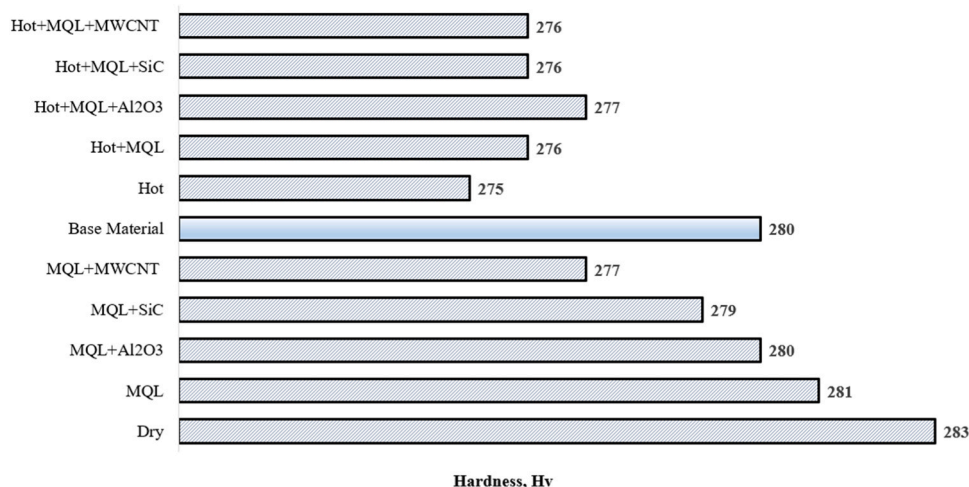


Fig. 16. Average machined surface and subsurface hardness values of Inconel 718.

Data availability

Data will be made available on request.

References

- [1] Soffel F, Eisenbarth D, Hosseini E, Wegener K. Interface strength and mechanical properties of Inconel 718 processed sequentially by casting, milling, and direct metal deposition. *J Mater Process Technol* 2021;291:117021. <https://doi.org/10.1016/j.jmatprotec.2020.117021>.
- [2] Mohsan AUH, Liu Z, Padhy GK. A review on the progress towards improvement in surface integrity of Inconel 718 under high pressure and flood cooling conditions. *Int J Adv Manuf Technol* 2017;91:107–25. <https://doi.org/10.1007/s00170-016-9737-3>.
- [3] Agrawal C, Khanna N, Pimenov DY, Wojciechowski S, Giasin K, Sarikaya M, et al. Experimental investigation on the effect of dry and multi-jet cryogenic cooling on the machinability and hole accuracy of CFRP composites. *J Mater Res Technol* 2022;18:1772–83. <https://doi.org/10.1016/j.jmrt.2022.03.096>.
- [4] Kshittij G, Khanna N, Yıldırım ÇV, Dağlı S, Sarikaya M. Resource conservation and sustainable development in the metal cutting industry within the framework of the green economy concept: an overview and case study. *Sustain Mater Technol* 2022;34:e00507. <https://doi.org/10.1016/j.susmat.2022.e00507>.
- [5] Parida AK, Maity K. Study of machinability in heat-assisted machining of nickel-base alloy. *Measurement* 2021;170:108682. <https://doi.org/10.1016/j.measurement.2020.108682>.
- [6] Parida AK, Maity K. Experimental investigation on tool life and chip morphology in hot machining of Monel-400. *Eng Sci Technol Int J* 2018;21:371–9. <https://doi.org/10.1016/j.jestech.2018.04.003>.
- [7] García Navas V, Arriola I, Gonzalo O, Leunda J. Mechanisms involved in the improvement of Inconel 718 machinability by laser assisted machining (LAM). *Int J Mach Tools Manuf* 2013;74:19–28. <https://doi.org/10.1016/j.ijmachtools.2013.06.009>.
- [8] Azhdari Tadavani S, Shoja Razavi R, Vafaei R. Pulsed laser-assisted machining of Inconel 718 superalloy. *Opt Laser Technol* 2017;87:72–8. <https://doi.org/10.1016/j.optlastec.2016.07.020>.
- [9] Shi B, Attia H, Vargas R, Tavakoli S. Numerical and experimental investigation of laser-assisted machining of Inconel 718. *Mach Sci Technol* 2008;12:498–513. <https://doi.org/10.1080/10910340802523314>.
- [10] Parida AK. Analysis of chip geometry in hot machining of Inconel 718 alloy. *Iran J Sci Technol Trans Mech Eng* 2019;43:155–64. <https://doi.org/10.1007/s40997-018-0146-0>.
- [11] Kiran Kumar A, Venkataramaiah P. Heat assisted machining of Inconel 718 Alloy using Abaqus/Explicit. *Mater Today Proc* 2019;18:4531–6. <https://doi.org/10.1016/j.matpr.2019.07.424>.
- [12] Venkatesan K, Ramanujam R. Statistical approach for optimization of influencing parameters in laser assisted machining (LAM) of Inconel alloy. *Measurement* 2016;89:97–108. <https://doi.org/10.1016/j.measurement.2016.04.021>.
- [13] Anderson M, Patwa R, Shin YC. Laser-assisted machining of Inconel 718 with an economic analysis. *Int J Mach Tools Manuf* 2006;46:1879–91. <https://doi.org/10.1016/j.ijmachtools.2005.11.005>.
- [14] Kim EJ, Lee CM. A study on the optimal machining parameters of the induction assisted milling with Inconel 718. *Materials* 2019;12. <https://doi.org/10.3390/ma12020233>.
- [15] Venkatesan K, Ramanujam R, Kuppan P. Investigation of machinability characteristics and chip morphology study in laser-assisted machining of Inconel 718. *Int J Adv Manuf Technol* 2017;91:3807–21. <https://doi.org/10.1007/s00170-017-9987-8>.
- [16] Pan Z, Feng Y, Hung T-P, Jiang Y-C, Hsu F-C, Wu L-T, et al. Heat affected zone in the laser-assisted milling of Inconel 718. *J Manuf Process* 2017;30:141–7. <https://doi.org/10.1016/j.jmapro.2017.09.021>.
- [17] Venkatesan K. The study on force, surface integrity, tool life and chip on laser assisted machining of inconel 718 using Nd:YAG laser source. *J Adv Res* 2017;8:407–23. <https://doi.org/10.1016/j.jare.2017.05.004>.
- [18] Karabulut Ş, Bilgin M, Karakoç H, Skondras Gioussios D, Markopoulos AP. Study of the heat-assisted milling of Ti–6Al–4V under dry and minimum-quantity-lubrication. *Arab J Sci Eng* 2022. <https://doi.org/10.1007/s13369-022-06878-3>.
- [19] Karabulut Ş, Bilgin M, Karakoç H, Khanna N, Sarikaya M. A study on the influence of thermally assisted novel hybrid methods on the drilling behavior of Ti6Al4V alloy. *Tribol Int* 2022;175:107852. <https://doi.org/10.1016/j.triboint.2022.107852>.
- [20] Luan X, Meng J, Huang B, Dong X, Hu Y, Zhao Y, et al. Machining characteristics of Ti6Al4V alloy in laser-assisted machining under minimum quantity lubricant. *Int J Adv Manuf Technol* 2021;112:775–85. <https://doi.org/10.1007/s00170-020-06333-3>.
- [21] Virdi RL, Chatha SS, Singh H. Experiment evaluation of grinding properties under Al2O3 nanofluids in minimum quantity lubrication. *Mater Res Express* 2019;6:96574. <https://doi.org/10.1088/2053-1591/ab301f>.
- [22] Cacia K, Ordoñez F, Zapata C, Herrera B, Pabón E, Buitrago-Sierra R. Surfactant concentration and pH effects on the zeta potential values of alumina nanofluids to inspect stability. *Colloids Surf A Physicochem Eng Asp* 2019;583:123960. <https://doi.org/10.1016/j.colsurfa.2019.123960>.
- [23] Zhang H, Qing S, Zhai Y, Zhang X, Zhang A. The changes induced by pH in TiO2/water nanofluids: stability, thermophysical properties and thermal performance. *Powder Technol* 2021;377:748–59. <https://doi.org/10.1016/j.powtec.2020.09.004>.
- [24] Yıldırım ÇV, Şirin Ş, Kivak T, Ercan H, Sarikaya M. An attempt towards green machining of Ni-based Hastelloy C4 alloy: effect of vegetable oils and their combination with TiO2 and SiO2 nanoparticles on outputs. *Sustain Mater Technol* 2023;37:e00668. <https://doi.org/10.1016/j.susmat.2023.e00668>.
- [25] Zawrah MF, Khattab RM, Girgis LG, El Daidamony H, Abdel Aziz RE. Stability and electrical conductivity of water-base Al2O3 nanofluids for different applications. *HBRC J* 2016;12:227–34. <https://doi.org/10.1016/j.hbrj.2014.12.001>.
- [26] Maddamasetty A, Bodduru K, Bevara S, Revuru RS, Kumar S. Performance evaluation of graphene added nanofluids and self-lubricating tools in machining Inconel 718. *World J Eng* 2022;19:583–93. <https://doi.org/10.1108/WJE-02-2021-0074>.
- [27] Şirin Ş, Sarikaya M, Yıldırım ÇV, Kivak T. Machinability performance of nickel alloy X-750 with SiAlON ceramic cutting tool under dry, MQL and hBN mixed nanofluid-MQL. *Tribol Int* 2021;153:106673. <https://doi.org/10.1016/j.triboint.2020.106673>.
- [28] Zhang X, Li C, Zhang Y, Wang Y, Li B, Yang M, et al. Lubricating property of MQL grinding of Al2O3/SiC mixed nanofluid with different particle sizes and microtopography analysis by cross-correlation. *Precis Eng* 2017;47:532–45. <https://doi.org/10.1016/j.precisioneng.2016.09.016>.
- [29] Akhtar W, Sun J, Sun P, Chen W, Saleem Z. Tool wear mechanisms in the machining of Nickel based super-alloys: a review. *Front Mech Eng* 2014;9:106–19. <https://doi.org/10.1007/s11465-014-0301-2>.
- [30] Singh A, Ghosh S, Aravindan S. Flank wear and rake wear studies for arc enhanced HiPIMS coated AlTiN tools during high speed machining of nickel-based superalloy. *Surf Coat Technol* 2020;381:125190. <https://doi.org/10.1016/j.surfcoat.2019.125190>.
- [31] Yıldırım ÇV, Şirin Ş, Kivak T, Sarikaya M. A comparative study on the tribological behavior of mono&proportional hybrid nanofluids for sustainable turning of AISI 420 hardened steel with cermet tools. *J Manuf Process* 2022;73:695–714. <https://doi.org/10.1016/j.jmapro.2021.11.044>.
- [32] shihan M, Chandradass J, Kannan TTM. Investigation of vibration analysis during end milling process of monel alloy. *Mater Today Proc* 2021;39:695–9. <https://doi.org/10.1016/j.matpr.2020.09.193>.
- [33] Mahesh K, Philip JT, Joshi SN, Kuriachen B. Machinability of Inconel 718: a critical review on the impact of cutting temperatures. *Mater Manuf Process* 2021;36:753–91. <https://doi.org/10.1080/10426914.2020.1843671>.
- [34] Jafarian F, Imaz Ciaran M, Umbrello D, Arrazola PJ, Filice L, Amirabadi H. Finite element simulation of machining Inconel 718 alloy including microstructure changes. *Int J Mech Sci* 2014;88:110–21. <https://doi.org/10.1016/j.ijmecsci.2014.08.007>.
- [35] Ueda T. Cutting temperature. In: Laperrière L, Reinhart G, editors. *CIRP Encyclopedia of Production Engineering*. Berlin, Heidelberg: Springer Berlin Heidelberg; 2014. p. 334–45. https://doi.org/10.1007/978-3-642-20617-7_6412.
- [36] Abukhshim NA, Mativenga PT, Sheikh MA. Heat generation and temperature prediction in metal cutting: a review and implications for high speed machining. *Int J Mach Tools Manuf* 2006;46:782–800. <https://doi.org/10.1016/J.IJMACTOOLS.2005.07.024>.