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ORIGINAL ARTICLE

Sustainability assessment of cutting fluids for flooded approach through a comparative surface integrity evaluation of IN718

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Abstract

The surface integrity (SI) of IN718 is affected by the excessive heat generation during the machining operation. While milling of Ni-based superalloys, use of traditional flooded strategy is encouraged though, due to its superior heat dissipating capacity. However, the cutting lubricants that have been conventionally employed during this approach are subjected to several concerns in regard to sustainability. Instead, vegetable ester-based biodegradable oil, as eco-friendly cutting oil, is one of the suggested choices formerly employed with minimum quantity lubrication (MQL). Therefore, this experimental investigation tries to combine the advantages of flooded cooling method with sustainable cutting fluid to review its impact on the SI of IN718 at first. It then focuses on establishing a comparison with conventional wet and dry approaches to characterize the machinability and the SI. The milling was carried out under the 450 Mecagreen vegetable ester-based biodegradable oil-assisted flooded condition, the Hocut WS8065 mineral oil-assisted flooded condition, and the dry condition. The three process variables, cutting speed (ν_c), feed per flute (f_z), and axial depth of cut (a_p) were considered for all the three environments. The SI characteristics such as surface roughness (SR), surface topography, microhardness, microstructural alterations, white layer formation, grain refinement, and residual stresses were considered as the response variables. The experimental exploration is complemented with scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and X-ray diffraction analysis (XRD).

Keywords IN718 · Cooling strategies · Surface integrity · Vegetable ester-based biodegradable oil · Milling process · SEM · EDS · XRD

1 Introduction

The rapid increasing demand of precision manufacturing in aerospace and bioimplant applications necessitates improvement of the machining processes for better surface integrity (SI). The SI of the machined components influences their in-service performance; therefore, inferior SI may lead to component failure. Failure investigations in these sectors reveal that the majority of catastrophes occurred due to the poor SI [1]. The surface integrity mainly relates to the three different attributes of a machined part, i.e., (i) surface texture (surface roughness and surface topography), (ii) subsurface metallurgical layer (microhardness and microstructure), and (iii) residual stresses.

Ni-based superalloy IN718 is the best candidate material for the above-cited applications because of its broader range of operational temperatures, exceptional resistance to thermal fatigue, corrosion and erosion, high melting point, and high creep strength [2–4]. Drawbacks of IN718 include poor thermal characteristics, high resistance to deformation, and strain hardening. As a result, high cutting forces and high heat production are experienced in the machining zone which are responsible for the excessive tool wear and deteriorated SI. It is also considered that the major part of this heat generation is due to the friction at the tool rake face-chip interface. Therefore, the use of cooling methods during cutting is indispensable. Traditionally, flooded cooling was the widely employed strategy due to its exceptional lubrication and cooling effects [5–7]. For example, Sadat et al. [5] employ a flood approach during the machining of Inconel 718 at high cutting speed values (0.2, 0.35, 0.63, 1.25, 1.61 m/s). The experimental results show no significant impact of coolant

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on the SI of machined part. It is attributed to the low coolant penetration into the tool-workpiece interaction point. Similarly, Imran et al. [6] evaluate the SI of Inconel 718 subjected to wet and dry machining conditions. The study shows that the cutting temperature and the use of coolant play a significant role in the microstructure alterations.

In pursuit of sustainable manufacturing, strict environmental legislations and policies have shifted the experimental research towards the use of more eco-friendly and economic methods of cooling which can reduce the consumption of cutting oils. The cutting fluids (mineral/synthetic) used with the conventional flooded approach contain various chemical additives like chlorine, sulfates, and biocides as their integral elements. It is believed that these contents are harmful for the workers, environment, as well as for the machining operation [8, 9]. Moreover, high cost of purchase and disposal (lack of renewability and biodegradability) are associated with these conventional fluids [10–12]. The green alternatives include dry, minimum quantity lubrication (MQL), cryogenic, high pressure cooling, ultrasonic machining, etc. In this regards, several investigations have attempted to improve the SI of Ni-based alloys through the application of these cutting environments. For example, Umbrello et al. [13] investigate the SI during the dry turning of Inconel 718 at very low feed rates 0.05–0.100 mm/rev using coated tools. The work shows the grain size refinement and presence of γ” phase at 70 m/min cutting speed and 0.1 mm/rev feed rate. In an effort to support dry environment as a sustainable option, Thakur et al. [14] compare the surface quality of Ni-based super alloy (Incoloy 825) under dry, flood, and MQL conditions. The turning tests are carried out using titanium nitride/titanium aluminum nitride (TiN/TiALN) multilayer-coated tools at constant levels of cutting speed 124 m/min, feed rate 0.08 mm/rev, and depth of cut 0.5 mm. The study reveals that the coated tools are able to reduce the cutting forces under the dry environment, but no efficient reduction of heat within the machining zone is observed compared with the flood and MQL approaches. Furthermore, a minimum temperature results in the case of MQL. Lastly, the study concludes that dry machining can be considered as an eco-friendly alternative to improve the machined surface quality only with the coated tools. Since coated tools are more expensive, productivity is decreased when pursuing the dry environment option in the sustainable domain. To explore the potential of MQL for SI improvements of Ni-based alloys, Touazine et al. [15] perform turning of Inconel 718 at 49, 58, and 83 m/min cutting speed; 0.142, 0.186, and 0.020 mm/rev feed rate, and 0.265, 0.30, and 0.230 mm depth of cut. The experimental results indicate the presence of soft layer after machined surface and large deformation around carbides and twin boundaries instead at the effected layer. Similarly, Musfirah et al. [16] compare the results of cryogenic milling of Inconel 718 with the dry conditions. Three cutting parameters: cutting speed 140–160 m/min, feed per tooth 0.15–0.20 mm, and radial depth of cut 0.2–0.4 mm are employed during the cutting. The results show that the cryogenic cooling reduced the cutting forces by 23% and improved the surface roughness by 88%. Working on Inconel 625 hard-to-cut alloy, Margi et al. [17] attempt to improve the SI through employing high pressure coolant at constant 65 m/min cutting speed, 0.08 mm/rev feed rate, and 1 mm depth of cut. It is concluded that the surface quality and tool wear is improved when coolant is applied towards the tool flank face at 70 bars pressure and 80 l/min flow rate. In contrast, Sharman et al. [18] evaluate the high-pressure coolant effects during the machining of Inconel 718. The study concludes that fluid impinged to the flank face at a pressure of 150 bars has no effect on SI and tool wear. Working on the similar material, Hafiz et al. [19] perform ultrasonic machining at 27 KHz and find no noteworthy effects on the SI enhancement.

In addition to the abovementioned studies, literature can be found supporting the inference that performance of contemporary eco-friendly methods is not comparable with the flood technique. Of the work, Kaynak et al. [20] present a comparative SI evaluation under wet, dry, MQL, and cryogenic methods. The study adds that the improvement in the SI is seen in case of cryogenic cooling compared with dry and MQL but is not the case for the flooded lubrication. Likewise, Fernandez et al. [21] give an SI comparison of Inconel 718 for dry, wet, and cold air MQL. The experimental results show that cold air MQL performs better than a dry condition but no more efficient than the wet environment. After performing surface integrity analysis of Inconel 718 under conventional and cryogenic cooling environments, Iturbe et al. [22] support the claim that conventional cooling method is the best option for both the machinability and SI. The study obtains three times smaller tool life in case of cryoMQL compared with conventional wet approach.

In pursuit of improving the cutting environment with respect to cutting fluids, the biodegradable oils, vegetable-based oils in particular being a green alternative, appear as a top preference in the machining community. A 7–10% annual rise in their consumption indicates that these lubricants are gradually replacing the mineral fluids [10, 11]. Their readily safe integration in the natural carbon cycle, excellent lubricity, and renewable characteristics make them a sustainable choice [23, 24]. It is further reported that the vegetable-based synthetic esters are 100% biodegradable than mineral oil (20–30%) [25] which provides a motivation for this experimental investigation.

During the attempts to replacing the traditional lubricants with biodegradable oil, the literature skews towards the MQL application method. In this context, Fontanive et al. [26] evaluate the SI of Inconel 718 under dry and MQL integrated with biodegradable oil conditions. The experimental work reveals that the MQL strategy is capable of producing better SI compared with dry conditions at 40 m/min cutting speed, 0.009 mm/tooth feed, and 0.4-mm axial depth of cut.

Sharma and Sing [27] employ biodegradable lubricant during the machining of a hard-to-cut material under MQL strategy. The study concludes that SI has been improved after the 50% reduction of cutting temperature. Kuram et al. [12] achieve improved SI and tool life during the milling operation when employing various vegetable-based lubricants integrated with MQL. Similarly, Zhang et al. [28] present a comparative study for the SI evaluation under dry, traditional wet, and soybean-based biodegradable oil applied in flood conditions. The L_9 Taguchi array is selected for the design of turning experimentation using 91.44, 103.6, and 115.8 m/min cutting speed; 0.20, 0.30, and 0.40 mm/rev feed rate; and 1, 1.27, and 1.52-mm depth of cut. The study finds that the soybean oil integrated wet approach is the most efficient among all the three. Debnath et al. [29] and Mohsan et al. [1] in their review articles recommend the biodegradable lubricants as an eco-friendly sustainable substitute of mineral-/petroleum-based fluids. Moreover, the authors are skeptical for the viability of MQL and cryogenic techniques regarding their usage control in industries.

The above-stated literature suggests that the research has been tending towards the use of eco-friendly advanced cutting fluids integrated with non-conventional lubrication techniques mainly focusing on turning operations. It is also revealed through the published research that the advanced application techniques proved less efficient compared with the conventional flooded strategy for the machining of difficult-to-cut alloy IN718 and, thus, limit the advantages of biodegradable fluids. It provides a strong motive to conduct a thorough comparative evaluation under different cutting conditions with the aim to improve surface integrity of IN718 during the milling. Hence, this research work considers three process variables: cutting speed (ν_c), feed per flute (f_z), and axial depth of cut (a_p), and three machining environments: dry (A), flooded approach + mineral oil (B), and flooded approach + vegetable-based synthetic esters biodegradable oil (C). The SI in terms of surface (surface roughness (SR), surface topography), subsurface alterations (microhardness, microstructural deformation, grain refinement, white layer formation), and residual stresses is considered as the response attribute. The experimental findings are supplemented with SEM and EDS results.

2 Experimental details

A comparative analysis of SI (surface and subsurface alterations, residual stresses) of IN718 was evaluated for three different cutting environments. The experimental details such as material, equipment, cutting tool, and experimental design used during the present study are described in the subsequent paragraphs.

Considering the extensive utilization in aerospace, automotive, biomedical, and marine applications, IN718 was selected as a workpiece material for this research work, and its elemental composition is given in Table 1. The key physical and mechanical properties of the alloy with respect to its machinability and industrial applications are given in Table 2 and are considered during the analysis presented in the Section 3.

The slot milling was carried out on 190 × 63 × 24 mm rectangular bars of nickel alloy using LG-800 Hartford machining center. Micro-grained carbide cutting inserts with wiper geometry clamped on a specially designed 2-flute-holder were used for the slot milling. The lower affinity of these inserts with IN718, high resistance to wear, and effective chip ejection due to wiper geometry are the main reasons for their selection [30]. The input machining variables defined from the published literature [15, 16] and the pilot experimental runs are listed in Table 3. A hybrid experimental scheme was employed during this investigative research. At first, a Taguchi L_9 array was selected for the experimentation considering three input variables at three different levels. In addition, for the surface and subsurface alteration comparison, few more test runs were performed under constant cutting parameters for all three cutting methods (see Table 4). A 63 × 9.7 × 3 mm slot was milled using new inserts in each experimental run under three different cutting environments: (A) dry, (B) flooded approach + conventional mineral cutting fluid, and (C) flooded approach + synthetic vegetable ester-based biodegradable oil as shown in Fig. 1a–b. Table 5 lists the specifications employed during the flooded lubrication strategies. The SI of IN718 was investigated in terms of surface (surface roughness (SR), surface topography), subsurface alterations (microhardness, microstructural deformation, grain refinement, white layer formation), and residual stresses. Quantitative observations of SR in terms of arithmetic mean R_a were taken at three different positions using surface profilometer (WYKO NY 1100), and their average value is used in the following section for the sake of statistical analysis. The qualitative assessment of surface topography was done through scanning electron microscope (FEI Quanta 200F).

For microhardness and microstructural analyses, the samples were obtained at the end of the milled slot using wire cut electric discharge machining (WEDM) with the consideration that the effects of tool wear would be more aggressive when

Table 1 Elemental composition of IN718

Element	C	Mn	S	Cu	Ni	Mo	Cr	Al	Ti	Nb	Si	Co	Fe
Weight (%)	0.03	0.08	0.00001	0.06	53.51	3.00	18.23	0.52	1.01	5.10	0.11	0.14	Balanced

Table 2 Physical and mechanical properties of IN718

Density	Yield strength	Breaking stress	Hardness	Melting point	Thermal conductivity
0.297 lb./in.^{3}	959 MPa	1264 MPa	36 HRC	1260–1336 °C	11.2 Wm^{-1} K^{-1}

its leaves the workpiece. The microhardness under the machined surface was calculated with the help of vicker hardness tester (Buehler Micromet-II) at 500 g test force and 12 s of measuring time. Five indentations for microhardness perpendicular to machined surface were made with 30-μm distance interval as shown in Fig. 1c. The microscopy and energy-dispersive spectroscopy were employed for the subsurface alteration measurements including microstructural deformation, grain refinement, and white layer formation via SEM (FEI Quanta 200F), whereas the residual stresses under the machined subsurface were measured through X-ray diffraction (XRD) method. The XRD analysis was carried out using X-ray diffractometer (EQUINOX 2000, Inel Inc., USA) with Co Kα source at a 111° diffraction angle.

3 Experimental results and discussion

With the purpose of comparing the behavior of machining characteristics of IN718 under different cutting environments, three replicate sets consisting of 27 test runs of slot milling were performed to rule out any dispersion in the data. Surface roughness (in terms of R_a), surface topography, microhardness, microstructural alterations, and residual stresses were carefully measured, and results are presented in the following sections.

3.1 Surface roughness

The surface quality plays a paramount role to ensure the performance of machined parts and can be measured in both ways, i.e., quantitatively and qualitatively. Table 6 presents the quantitative results of average SR as per L_9 orthogonal array.

To assess the parametric effects on the SR, the main effects plots are drawn and shown in Fig. 2.

From Fig. 2, it is observable that the cutting environment exhibits a decreasing linear trend for the SR, while the cutting speed (ν_c) and the feed/flute (f_z) show a non-linear behavior. In case of cutting methods, surface finish has improved with the use of lubrication, and its effects are more profound for Mecagreen 450 biodegradable oil-assisted cooling technique. As can be seen from Table 6 and Fig. 2, minimum SR (0.45 μm) is obtained with the use of biodegradable oil integrated with the flooded approach at 65 m/min ν_c, whereas the higher SR (2.50 μm) is reported in case of dry environment at the same ν_c. It is attributed to the brilliant cooling and lubricating characteristics of flooded cooling approach which become more pronounced when integrated with vegetable ester-based biodegradable oil as a cutting fluid.

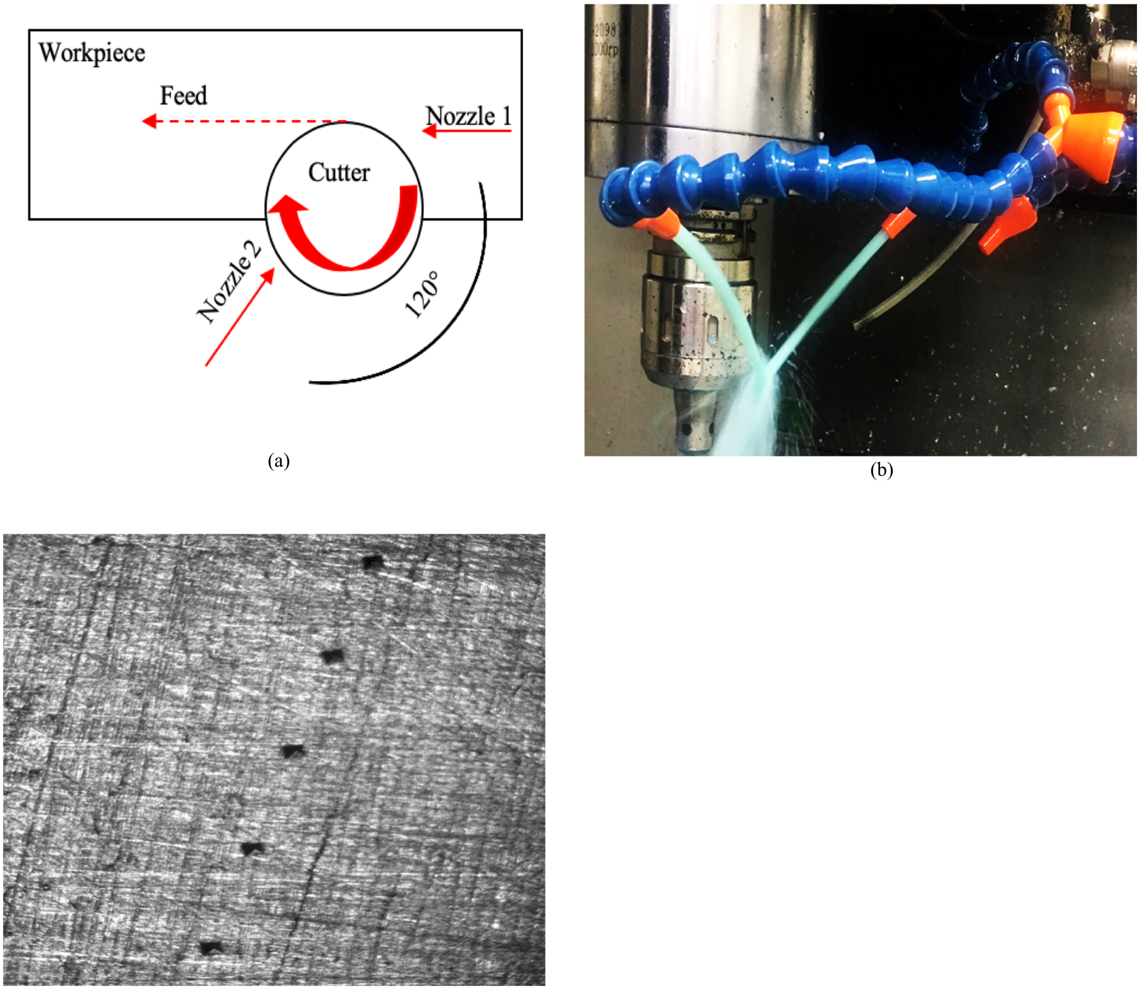
Traditionally, the machining of IN718 is associated with excessive temperature production within the shear zone due to its high strength and low thermal conductivity. As a result, severe tool wear and surface damage occurred if the generated heat could not flush away from the zone. The abundant amount of heat causes formation of built-up layer (BUL) on the machined surface and built-up edges (BUE) on the cutting tool, thus contributing towards the poor surface integrity. These results are supported by the published research [20], wherein Kaynak et al. [20] analyze the effects of different cooling environment on the SI of Inconel 718 and conclude that the high temperature in the machining zone significantly affects the SR. The study further adds that the use of cooling methods can reduce the tool wear and BUL formation. Additionally, friction at the tool-workpiece point of contact is also considered a main

Table 3 Input variables for the slot milling of IN718

Parameters	Specifications
Cutting environment	Dry (A), mineral oil-assisted flooded method (B), biodegradable oil-assisted flooded method (C)
Cutting speed, (v_s), m/min	65, 80, 95
Feed/flute, (f_z), mm/flute	0.1, 0.15, 0.20
Axial depth of cut, (a_p), mm	0.4 (constant)
Radial depth of cut (a_r), mm	9.7 (constant)
Tool hang, mm	32 (constant)
Cutting inserts	Micro-grained carbide inserts
Workpiece alloy	IN718

Table 4 Experimental scheme employed for the additional machining runs

Test run	Input process variable	Cutting condition
10	ν_c 65 m/min, f_z 0.10 mm/flute, a_p 0.4 mm	A
10′	ν_c 65 m/min, f_z 0.10 mm/flute, a_p 0.4 mm	B
10″	ν_c 65 m/min, f_z 0.10 mm/flute, a_p 0.4 mm	C
11	ν_c 95 m/min, f_z 0.10 mm/flute, a_p 0.4 mm	A
11′	ν_c 95 m/min, f_z 0.10 mm/flute, a_p 0.4 mm	B
11″	ν_c 95 m/min, f_z 0.10 mm/flute, a_p 0.4 mm	C



(a)

(b)

(c)

Fig. 1 Experimental details for the milling of IN718; (**a**) schematic of flooded lubrication approach, (**b**) nozzles position at 120° angle, and (**c**) micro indents scheme for hardness analysis

cause acting adversely on the part's surface quality [31]. Moreover, high SR values are related to small cutting speeds and high feeds in the literature for the machining of IN718 [20, 26]. For the case of low cutting speed, poor surface quality is attributed to the high tensile stresses due to friction, while increased distance between two successive tool runs at high feed rate resulting into unmachined metal is the reported cause of high SR values [32].

Contrarily, an opposite trend can be observed during this work wherein smaller SR is assigned to the lower ν_c and high f_z. From Table 6 and Fig. 2, it can be noted that the minimum SR (0.45 μm) is reported for the vegetable ester-based

Table 5 List of variables used for flooded approach (B and C)

Mineral oil-based flooded strategy (B)		Synthetic vegetable ester biodegradable oil-based flooded strategy (C)	
Parameters	Specifications	Parameters	Specifications
Cutting fluid	Hocut WS8065	Cutting fluid	Mecagreen 450
Concentration ratio	6%	Concentration ratio	6%
Number of nozzles	2 each of 2-mm diameter	Number of nozzles	2 each of 2-mm diameter
Applied pressure	20 bars	Applied pressure	20 bars
Applied angle to target the machining zone	120°	Applied angle to target the machining zone	120°
Flow rate	0.05 l/s	Flow rate	0.05 l/s

Table 6 Average SR values obtained after the slot milling of IN718 as per L_9 Taguchi array

Test run	Cutting environment	Cutting speed v_c (m/min)	Feed/flute f_z (mm/flute)	Surface roughness SR (μm)
1	A	65	0.10	2.50
2	A	80	0.15	2.32
3	A	95	0.20	2.15
4	B	65	0.15	1.91
5	B	80	0.20	1.74
6	B	95	0.10	1.68
7	C	65	0.20	0.45
8	C	80	0.10	0.68
9	C	95	0.15	1.23

biodegradable oil-assisted cooling strategy. Vegetable ester-based biodegradable oil offers a sustainable alternative with respect to eco-friendly and machining advantages. If the eco-efficient aspects are considered, readily biodegradability and less environmental pollution with respect to their use and disposal are the main benefits. The carbon cycle of vegetable oil is a closed loop, i.e., amount of carbon dioxide released in the atmosphere during disintegration is equal to the amount absorbed by plants [25]. Moreover, vegetable based-synthetic ester (Mecagreen 450) are considered 100% biodegradable compared with other biodegradable fluids [29].

As far as the machining gains are concerned, the vegetable-based oils consist of fatty acids; the adhesive layer of these fatty acids provides a very strong lubrication film at the tool-chip interaction during the cutting operation. Moreover, it reduces the friction between two metallic surfaces (tool and workpiece) due to the polar nature of fatty acids. The polarity of oriented molecular layer produces oiliness and thus delivers anti-wear properties [10]. Consequently, better surface integrity of machined component is achieved. Additionally, vegetable-based cutting fluids possess higher flash point values than mineral oils [12]. The high flash point reduces the smoke formation and fire hazards during the machining of IN718 where high cutting temperature is expected.

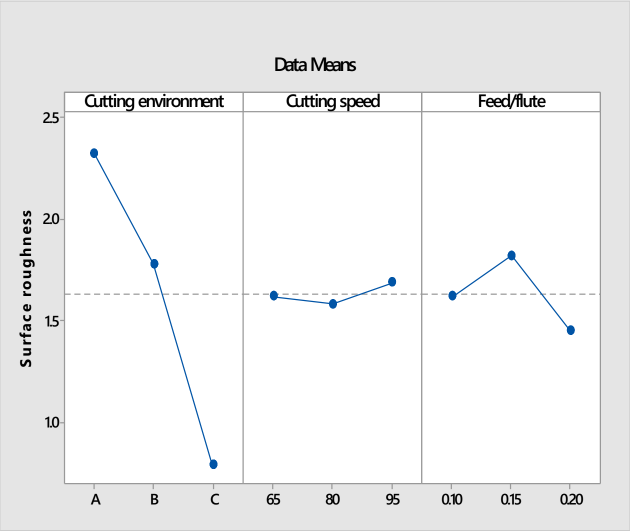


Fig. 2 Main effects plots for SR of IN718

After the parametric effect analysis for SR of IN718, the quantitative analysis of process parameters has been carried out using ANOVA at 95% confidence interval ($\alpha = 5\%$) and is presented in Table 7. It can be seen that the cutting environment proves significant with a "p value" less than 0.05 with 89.85% contribution.

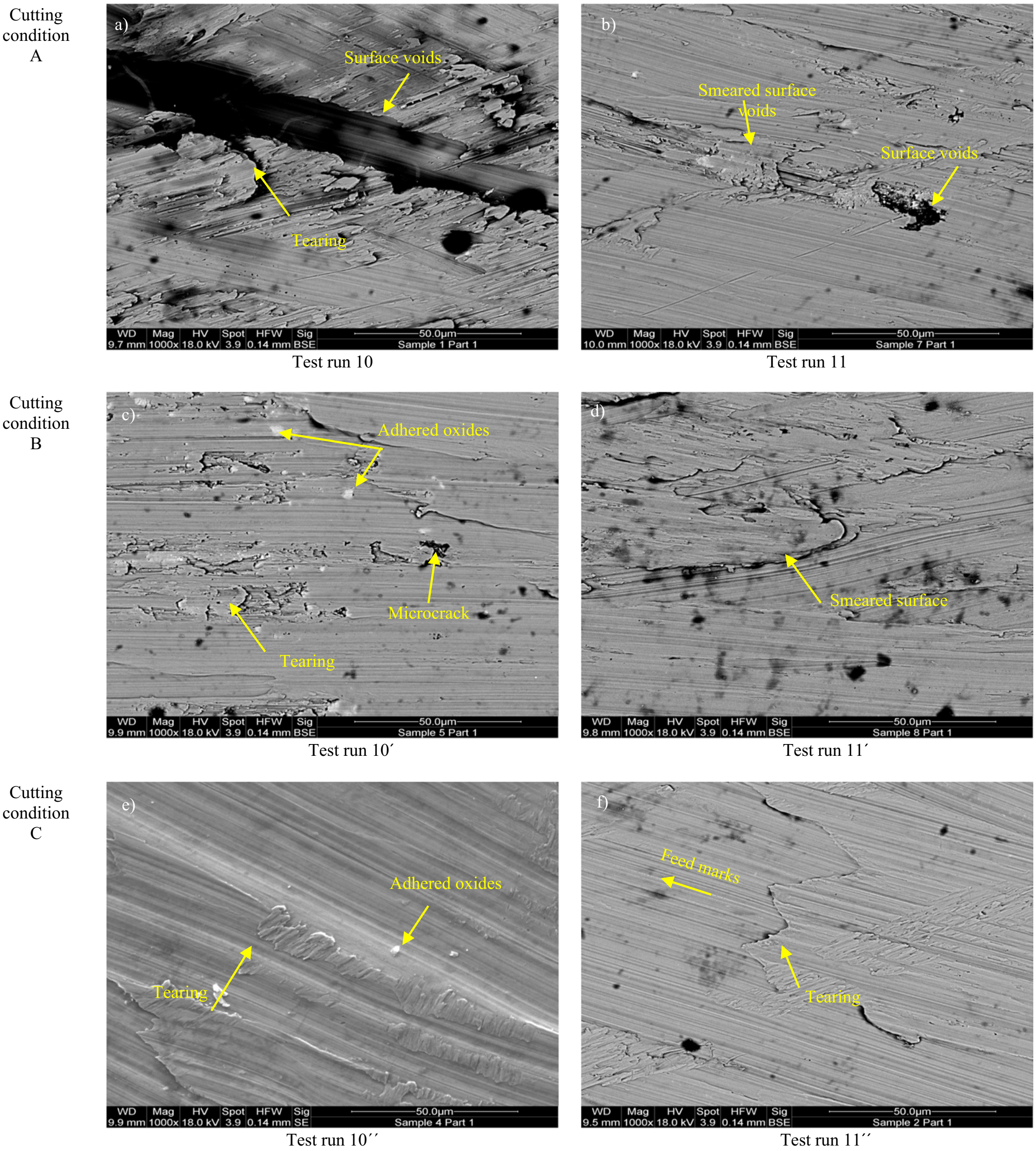
3.2 Surface topography

To perceive the effects of three different cutting environments, qualitative measurements of machined surface in terms of surface defects were recorded at the same reference point for the test trials listed in Table 4. Figure 3a–f show the SEM micrographs for all the three machining environments. The micrographs of test runs indicate the presence of smeared material in the form of BUL, adhered oxides, surface voids, microcrack, and tearing. Generation of high temperature and larger mechanical stresses during the cutting process are the possible causes of these surface defects. It can be validated from Fig. 3a–b where the irregularities on the machined surface are more intense in case of dry cutting condition.

Whereas a relatively smooth surface pattern is apparent in case of flooded approach integrated with the conventional mineral oil as shown in Fig. 3c–d, there are regular feed marks

Table 7 ANOVA results for the slot milling of IN718

Source	DF	Adj SS	Adj MS	F value	p value
Cutting environment	2	3.64029	1.82014	19.77	0.04
Cutting speed	2	0.01742	0.00871	0.09	0.914
Feed/flute	2	0.20942	0.10471	1.14	0.468
Error	2	0.18416	0.09208		
Total	8	4.05129			



Test run 10 Test run 11

Test run 10′ Test run 11′

Test run 10′′ Test run 11′′

Fig. 3 Surface topography of IN718 machined at ν_c 65, 95 m/min, f_z 0.10 mm/flute, a_p 0.4 mm under different cutting environments: (**a**–**b**) test run 10, 11; (**c**–**d**) test run 10′, 11′; (**e**–**f**) test run 10″, 11″

with less BUL formation. It is also visible that the surface defects are more at low cutting speed which is supported by previous research work [33]. Devillez et al. [33] conduct machining of the same superalloy under wet and dry environments. Three levels of cutting speeds 40 m/min, 60 m/min, and 80 m/min were used for cutting. The study reveals that the existence of surface irregularities and BUL reduces at high cutting speed under wet environment.

While the samples machined under the flooded approach integrated with Mecagreen 450 biodegradable oil exhibit a fine topography and is quite obvious in Fig. 3e–f, a homogenous texture consisting of very noticeable fine feed traces can be seen which demonstrates almost an adhesion-free machined surface. Fig. 3e–f also reveal that the linear surface texture pattern is more visible in test trial 10″ performed at low ν_c (65 m/min). These results are aligned with reported studies wherein authors conclude that the use of biodegradable oil in flooded condition and MQL enables the cutting operation to produce smaller SR [26, 27]. For instance, Fontanive et al. [26] compared the SI aspects of Inconel 718 milled under dry and MQL conditions. Four process parameters, 40 m/min cutting speed, 0.4-mm axial depth of cut, 0.009 mm/tooth feed, and edge preparation, were used. The work concludes that the vegetable oil-based MQL approach offers better machinability characteristics in terms of surface topography and surface quality.

Additionally, an EDS was performed to validate the adhesion of chip material on the machined surface (BUL) for all the test runs. For illustration purpose, EDS result of a selected test run 10 is presented in Fig. 4. The presence of main elements of the superalloy, Ni, Fe, C, Cr, Nb, and Ti, are confirmed through the spectroscopy results.

3.3 Microhardness

The microhardness measurements were taken perpendicular to the machining direction for all the machining test runs milled under three lubrication techniques as per L_9 array. Five points were recorded with 30-μm interval in between started from 20-μm depth beneath the machined surface and is presented in Fig. 5a–c. An increase in the microhardness values under the depth of 20 μm against the bulk hardness (342 HV) is observed in case of dry and traditional wet machining conditions (Fig. 5a–b). It is attributed to the rapid work-hardening characteristics of IN718 due to the formation of carbides [34], whereas Fig. 5c shows a slight increment in the microhardness to a depth of 130 μm where microhardness reached to the bulk value.

Figure 5a–c illustrates that the cutting conditions and the feed/flute are mainly responsible for the microhardness increment, i.e., high values of feed/flute produce larger increment in microhardness. This effect is more significant in case of dry condition where highest value of microhardness 367 HV (6.8% increment) can be observed at 0.20 mm/flute f_z. It is attributed to the increased plowing effect of tool on the machined surface at high feed/flute values which causes plastic deformation at the subsurface level. This result is in agreement with the literature [35]. Zahoor et al. [35] conclude that feed rate and spindle vibration amplitude have the major effects on microhardness during the milling of AISI P20 tool steel.

For the comparison view point, the results obtained at 65 m/min ν_c, 0.10 mm/tooth f_z, and 0.4 mm a_p under all the three cutting approaches are plotted against the base material as shown in Fig. 6. During this experimental investigation, it is revealed that the microhardness is greatly influenced by the cutting environment. From Fig. 6, it is obvious that high hardness values (360 HV) are assigned to the dry environment which is consistent with the reported work [13]. Umbrello et al. [13] evaluate the SI for the dry turning of Inconel 718. During research, largest hardness value (530 HV) was achieved at high value of feed rate (0.10 mm/rev) and cutting speed (70 m/min) under dry conditions. During this study, a 5.0% and 3.9% enlargement are achieved at 20-μm depth under the top surface compared with the parent metal for the dry and the conventional flooded approaches, respectively, whereas the cutting approach integrated with Mecagreen 450 biodegradable oil presents even smaller hardness value (340 HV) compared with the bulk hardness, i.e., 342 HV. It is worth noting that the average microhardness achieved with Mecagreen 450 is not only close to the parent metal even lesser at the subsurface layer adjacent to the machined surface.

Generally, the heat produced during the machining operation tends to increase the hardness of machined surface and subsurface [36, 37]. It can be corroborated on the basis that the workpiece materials having high thermal conductivity absorb the generated heat which leads to the plastic deformation and reorientation of grain boundaries. It is a machining phenomenon which can alter the mechanical properties of component and affects the machinability of alloys as well. Furthermore, the absence of coolant or ineffective cooling method cannot

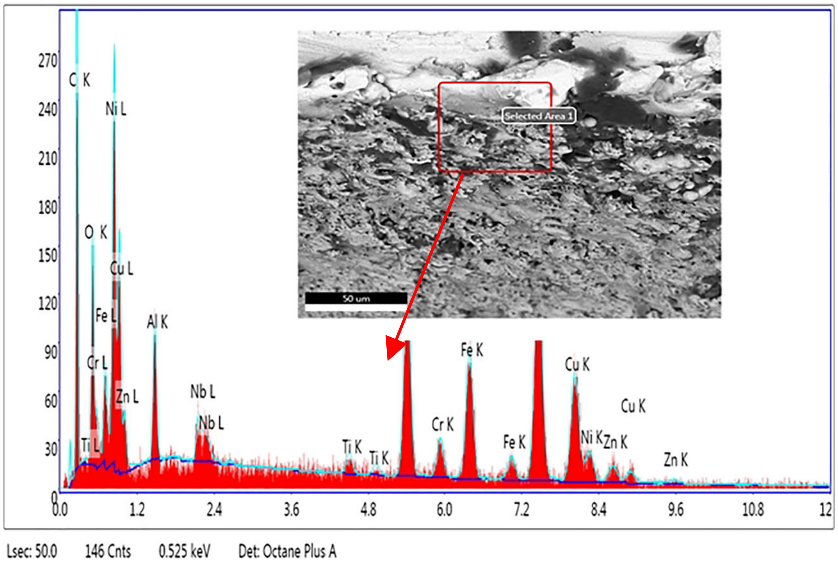
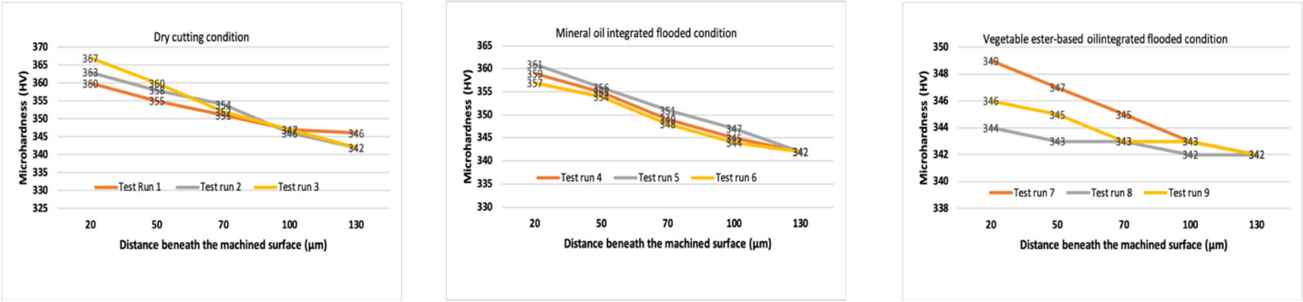


Fig. 4 EDS results for test run 10 at ν_c 65 m/min, f_z 0.10 mm/flute, and a_p 0.4 mm under dry cutting environment



a) Test run 1-3; ν_c 65, 80, 90 m/min
f_z 0.10, 0.15, 0.20 mm/flute
a_p 0.4 mm

b) Test run 4-6; ν_c 65, 80, 90 m/min
f_z 0.10, 0.15, 0.20 mm/flute
a_p 0.4 mm

c) Test run 7-9; ν_c 65, 80, 90 m/min
f_z 0.10, 0.15, 0.20 mm/flute
a_p 0.4 mm

Fig. 5 Microhardness values of IN718 for machining condition; (**a**) dry, (**b**) mineral oil integrated with flooded approach, and (**c**) vegetable ester-based oil integrated with flooded approach

dissipate the heat away from the cutting zone and, thus, causes the aggressive tool wear. This leads to the severe strain hardening and plastic deformation at the subsurface levels.

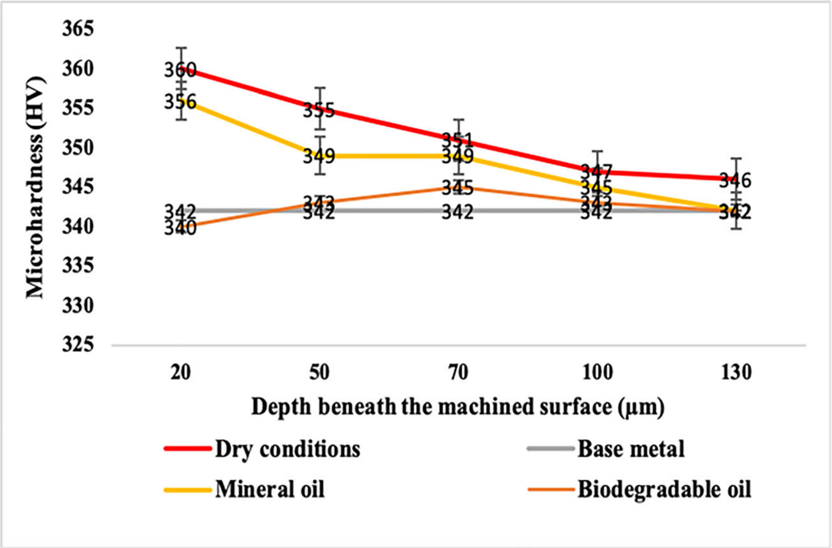
Contrarily, in case of IN718, the generated heat in the machining envelope cannot be absorbed due to its low thermal conductivity (11.2 $\mathrm{Wm}^{-1}\ \mathrm{K}^{-1}$). Additionally, excellent lubrication and cooling characteristics of vegetable ester-based biodegradable oil integrated flooded approach dissipate the heat from the shear zone effectively. The polarized fatty acid layer at tool-workpiece interaction reduces the tool wear and, consequently, leads to less work hardening of IN718.

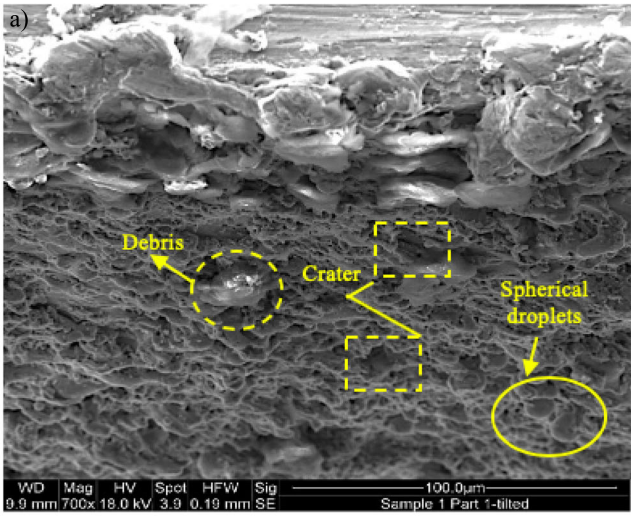
3.4 Microstructural alterations, grain refinement, and white layer formation

Machining of IN718 is characterized by high-temperature generation in the cutting zone. Therefore, surface and subsurface metallurgical alterations are inevitable [38]. To compare the effects of the employed three cutting approaches on the subsurface changes, the SEM micrograph display in Fig. 7a–c reveal the typical microstructure spotted below the machined layer parallel to the machining direction. Figure 7a shows that the subsurface layer corresponds to the test run 10 machined under dry condition at 65 m/min cutting speed, 0.10 mm/flute feed, and 0.4 mm axial depth of cut. The subsurface irregularities such as re-deposited material, debris, crater, and spherical drops can be visualized at the cross section. It can be due to the presence of excessive heat in the cutting zone which caused more deeper crater inside the subsurface.

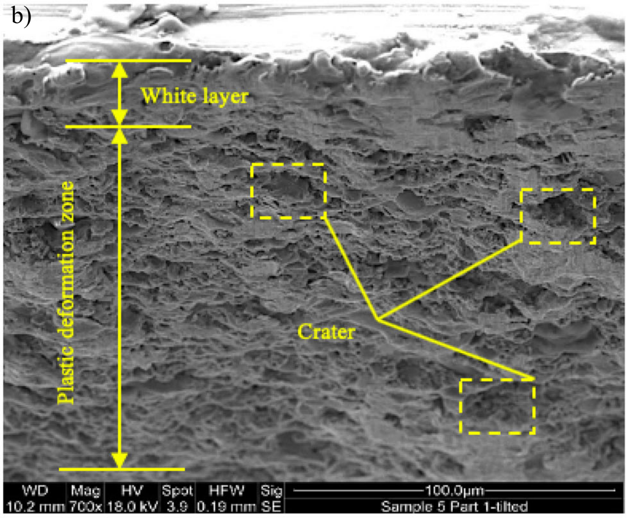
While the micrograph for the flooded condition with conventional cutting fluid depicts the shallow crater as illustrated in Fig. 7b, Fig. 7c demonstrates an almost a defect-free surface in case of biodegradable oil, thus validating the microhardness results presented in Section 3.3 above which are very close to the parent material. It is also observable from Fig. 7a–c that the surface degradation is severe in case of dry conditions. However, the phase alteration and grain size refinement are not found in any of the test sample. These results can be

Fig. 6 Microhardness comparison with base material for test runs 10, 10′, and 10″ at ν_c 65 m/min, f_z 0.10 mm/tooth, and a_p 0.4 mm

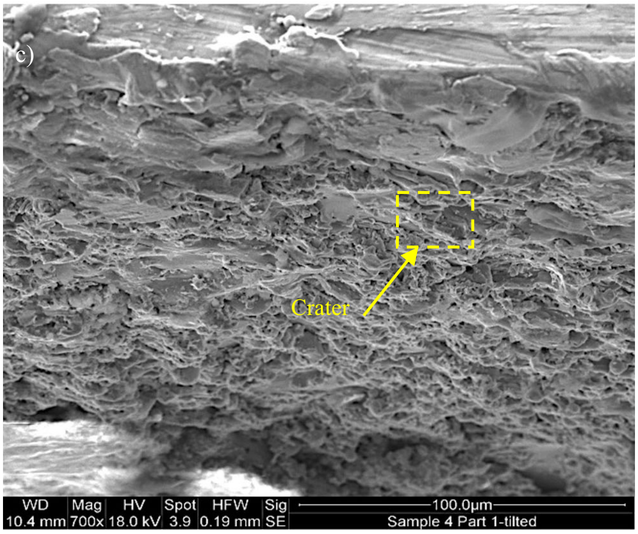




Test run 10



test run 10′



Test run 10′′

Fig. 7 SEM micrographs for samples at v_c 65 m/min, f_z 0.10 mm/tooth, and a_p 0.4 mm under (**a**) dry condition, (**b**) flooded condition with mineral oil, and (**c**) flooded condition with vegetable ester-based biodegradable oil

verified from published studies [26, 33]. Fontanive et al. [26] share the similar results in their experimental investigation related to SI of Inconel 718 under dry and MQL approaches.

As far as the white/featureless layer is concerned, a very thin layer of structure (1–3 μm) is observed in very close vicinity to the machined surface in case of conventional wet and dry environment, whereas no obvious feature is spotted for the test run machined under Mecagreen 450 integrated flooded strategy. The white layer phenomena are investigated in several studies [39, 40]. The literature suggests that the thermal influence plays a crucial role in the formation of white layer. It generally consists of refine grained, non-crystalline structure and harder than the bulk metal which is caused by high-temperature gradient, plastic deformation, phase transformation, etc. The research agrees that by reducing/eliminating the white layer formation improves the surface integrity of machined components.

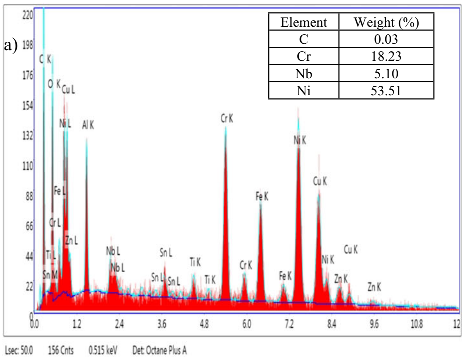
To strengthen these microscopic outcomes, EDS results of white layer are compared with bulk metal for test runs 10, 10′, and 10″ (see Fig. 8a–d). It is exposed from Fig. 8a–c that the elemental composition of white layer is different from the base alloy. The carbon content percentage has been increased from 0.03 to 31.45 (dry) and 25.17 (mineral oil + flooded condition), respectively, while from Fig. 8d, no significant increment in carbon contents is seen in case of flooded condition with vegetable ester-based biodegradable oil, thus validating SEM results regarding the presence of white layer.

Metallurgical decomposition of IN718 occurs after machining which caused the formation of carbon compounds. The increased carbon tends to form carbides with Nb and Ti which induce the pitting corrosion on IN718 surface. Additionally, the work-hardening properties of IN718 are enhanced due to the carbide formation as discussed earlier. The EDS results supplement the microhardness findings presented in Section 3.3. Moreover, Nb contents determine the strength of the nickel alloy which decreased after the formation of carbides [41].

3.5 Residual stresses

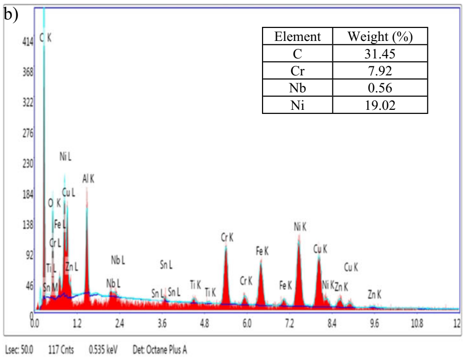
Residual stress analysis in terms of compressive and tensile stresses was performed through X-ray diffraction method. Figure 9 compares the residual stresses obtained from the test runs (10, 10′, 10″) conducted at the same parametric combination under three machining conditions.

From Fig. 9a–b, much larger tensile residual stresses can be observed in case of dry condition followed by the mineral oil-based wet condition. Larger tensile residual stresses are often attributed to the profound localized thermal effects in the cutting zone, which is primarily caused by the excessive heat formation during machining and ineffective dissipation of heat from the shear zone and, consequently, leads to the aggressive tool wear which results into high tensile stresses.



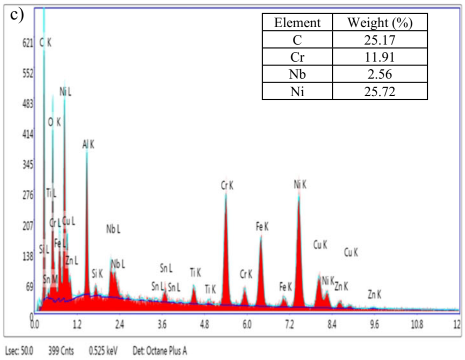
Element	Weight (%)
C	0.03
Cr	18.23
Nb	5.10
Ni	53.51

Bulk material



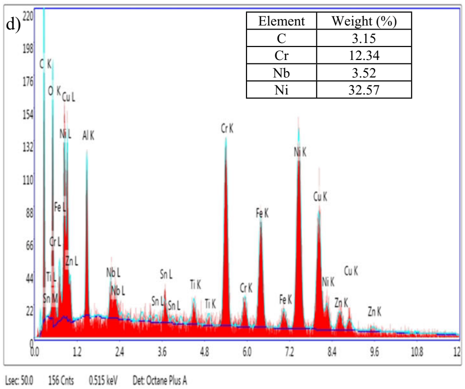
Element	Weight (%)
C	31.45
Cr	7.92
Nb	0.56
Ni	19.02

Test run 10



Element	Weight (%)
C	25.17
Cr	11.91
Nb	2.56
Ni	25.72

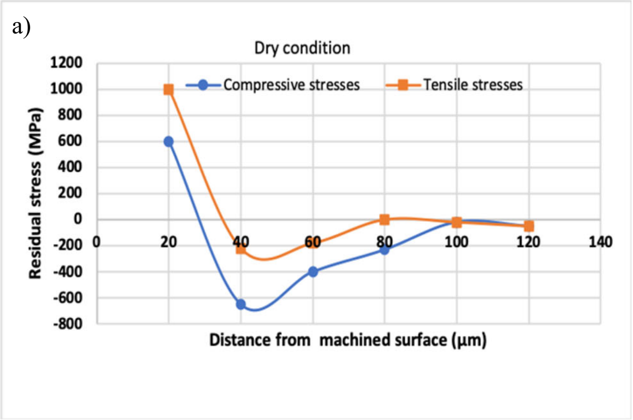
Test run 10´



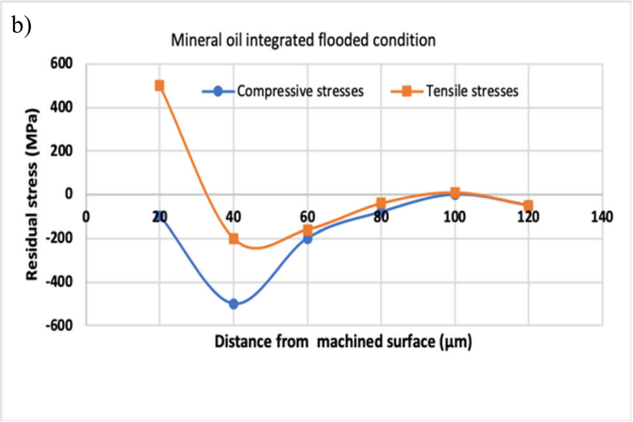
Element	Weight (%)
C	3.15
Cr	12.34
Nb	3.52
Ni	32.57

Test run 10´´

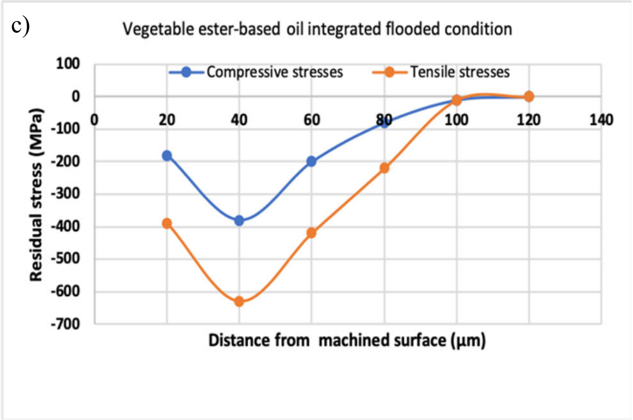
Fig. 8 EDS results for IN718 at ν_c 65 m/min, f_z 0.10 mm/tooth, and a_p 0.4 mm; (**a**) bulk material, (**b**) dry condition, (**c**) mineral oil integrated flooded condition, and (**d**) flooded condition with vegetable ester-based biodegradable oil



Test run 10



Test run 10´



Test run 10´´

Fig. 9 XRD results for residual stresses of IN718 at ν_c 65 m/min, f_z 0.10 mm/tooth, and a_p 0.4 mm; (**a**) dry condition, (**b**) mineral oil integrated flooded condition, and (**c**) vegetable ester-based oil integrated flooded condition

High values of tensile residual stresses are undesirable in metal cutting as they deteriorate the surface integrity of machined component.

Contrarily, a shift in subsurface residual stresses for vegetable ester-based oil integrated flooded condition can be seen from Fig. 9c. They were found to be compressive instead of tensile. Efficient thermal dissipation from the machining envelope is associated with the compressive stresses. In case of vegetable oil-based wet approach, fast removal of heat resulted into lower values of tensile stresses.

4 Conclusions and suggested future research

This research work compares the machining results in terms of surface integrity (surface roughness, surface topography, microhardness, microstructural alterations, grain refinement, white layer formation, and residual stresses) to comprehend the impact of different cutting strategies in the milling of IN718 superalloy. The following points are the main conclusion deduced from the results and discussion:

1. For the surface roughness, machining environment demonstrates a profound impact. Parametric effect analysis reveals that the wet condition integrated with Mecagreen 450 biodegradable oil shows an obvious improvement in the surface roughness values (smaller SR value 0.45 μm) when small cutting speed 65 m/min and high feed 0.20 mm/flute are selected. Additionally, ANOVA also confirms the parametric analysis results as the cutting environment turns out to be the most influential process parameter statistically with 89.85% contribution.
2. For all the investigated test runs under the three machining conditions, surface topography is mainly affected by the smeared material as a form of BUL, adhered oxides, surface voids, microcrack, and tearing. The surface defects are more visible on the samples machined under the wet (Hocut WS8065 + flooded) and the dry conditions, whereas relatively a defect-free surface is observed in case of Mecagreen 450 integrated flooded approach.
3. The conventional wet and the dry environment and high feed/flute cause larger microhardness values as well as more deeper alterations at a depth of 130 μm, while the vegetable ester-based biodegradable oil integrated wet strategy exhibits the comparable hardness values, even lower value of microhardness (340 HV) than the parent material (342 HV) on the subsurface layer at a depth of 20 μm in test run 10″.
4. The examined surfaces machined under the traditional wet and the dry conditions display microstructural changes and featureless layer formation at a very small depth of 1–3 μm attributed to the high thermal effects. The grain size refinement is not revealed though, whereas no obvious changes are witnessed on the machined samples for the biodegradable oil integrated wet approach. Additionally, the energy-dispersive spectroscopy results indicate the metallurgical decomposition with more carbon contents at the featureless layer for test run 10 and 10′.
5. The investigated surface of machined samples demonstrates a depth profile of the subsurface residual stresses. The compressive and tensile residual stresses are produced due to the localized thermal effects and microstructural changes. The cutting strategies noticeably influence the magnitude of stresses. The compressive stresses are produced only in case of Mecagreen 450 enriched flooded approach, while fairly high tensile stresses are observed for the Hocut WS8065 enriched flooded and the dry conditions. Thus, biodegradable oil enriched flooded approach displays a huge possibility to improve the surface integrity of nickel-based alloys.
6. To summarize these results, it may be concluded that the surface integrity of IN718 can be enhanced promisingly with the application of biodegradable cutting fluid-based flooded cooling method. It can mitigate well the thermal and the frictional effects during the cutting of heat-resistant superalloys. Moreover, it presents itself as an environmentally conscious approach compared with the mineral oil-based-assisted wet method.

For the future discussion, it is suggested that the effects of various vegetable-based biodegradable oils mixed with eco-efficient nano-particles such as halloysite clay nano-tubes (HNTs) in flooded condition should be evaluated along with other machining parameters, i.e., tool-edge preparation and tool coating materials.

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