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Microstructure and Microhardness Alterations of Inconel 718 under Cryogenic Cutting

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ABSTRACT

This paper presents the experimental investigations to identify the effect of different machining parameters on the microstructure and microhardness alterations beneath the machined surface of Inconel 718. The high-speed milling experiments were conducted using PVD multi-coated ball nose carbide inserts, under cryogenic CO_2 *condition at controlled cutting speed of 120-140 m/min, feed rate of 0.15-0.25 mm/tooth, depth of cut of 0.3–0.7 mm and a fixed width of cut at 0.4 mm. The experimental results discovered that the formation of plastic deformation could only be observed when cutting with the highest value of feed rate and depth of cut, deepened until 8.87 µm from the machined surface. At the same time, those factors also significantly increased machined surface hardness, made the workpiece harder than its bulk hardness. However, the hardness values were found reduced towards the sub-surface and back to its bulk hardness approximately 250 - 300 µm from the top surface. This study suggests that the finishing milling process of Inconel 718 under cryogenic* CO_2 *condition and at predetermined parameters can be performed at a depth of cut less than 0.3 mm as its machined sub-surface microhardness and microstructure alteration were observed to be inconsequential. Thus, a more economical machining process can be performed.*

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Introduction

Super alloy Inconel 718 is one of the Nickel-based super-alloys. It is widely applied in aerospace industries due to its high strength at elevated temperatures and high resistance to corrosion. However, when cutting this difficult-to-machine material at high-speed, its low thermal conductivity caused the heat that inherently generated accumulating in the cutting zone to extreme levels. Researchers such as Musfirah et al. [1], Kasim [2], and Sonawane and Joshi [3] reported there were microstructure and microhardness changes beneath the machined surface when high-speed milling Inconel 718 under cryogenic, minimum quantity lubrication (MQL) and dry conditions, respectively. As reported, the combination of elevated cutting temperatures and the mechanical shock from the intermittent cutting of milling process accelerates wear rate which then facilitates sub-surface defects like plastic deformation and the tendency of the machined surface to work-harden [4]. These undesirable changes reduce its surface integrity while increasing its difficulty to be machined.

The correlation between different machining conditions and the levels of microstructure and microhardness alteration at machined sub-surface have been numerously examined by previous studies. Cutting speed, feed rate, depth of cut, tool type, geometry, as well as lubrication or cooling conditions, are some of the common factors that have been investigated [5]. The finding is important as the alterations affect the fatigue life, functionality, and durability of the final products, mainly the one serviced in high temperatures or stress loads and aggressive environments [6]. Meanwhile, Grzesik et al. [7] used terms abusive, conventional, and gentle machining processes which related to the level of heat and strain rates generated during cutting to demonstrate their influence on machined surface integrity.

Generally, the depth of plastic deformation below the machined surface to which it extends significantly influenced by the tool geometry, depth of cut, machining conditions as well as the absence or presence of coolant or lubricant during cutting [7]. For instance, Sharman et al. [8] found that the worn tool produced greater degree of grain boundary microstructural plastic deformation than the new tool in turning of Inconel 718. Meanwhile, a study by Musfirah et al. [1] revealed obvious grain structure deformation near the machined surface in dry milling of Inconel 718 rather than in cryogenic condition using liquid nitrogen (LN_2). This is apparently related to the elevated temperature of dry milling due to the absence of any coolant or lubricants during cutting [9]. However, the extremely low temperature of cryogenic LN_2 at -196 ºC tends to work-harden Inconel 718, thus increase its microhardness. As also found by

Iturbe et al. [10], 160 – 200 µm below the machined surface of Inconel 718 were 50-130 HV harder than its base hardness after milled under cryogenic LN_2. This finding proved the significant influence of the coolant on the cold hardening of the material. A similar finding was observed by Shokrani et al. [4] when milling titanium alloys under dry, flood and LN_2 cryogenic, where subsurface microhardness was found highest under cryogenic cooling compared others.

Meanwhile, a study by Kasim relates the increase of surface microhardness with the increase of cutting speed in the milling of Inconel 718 under MQL condition [2]. As explained by Liao et al. [11] and Halim et al. [12], cutting temperature is significantly increased with cutting speed, while below 650 ºC, Inconel 718 tends to become harder and harder with the increase of cutting temperatures. However, in the case of titanium alloy, contradict finding reported by Ginting and Nouari [13] where the hardness of the machined surface was 8% less than the bulk hardness. They relate it with the thermal softening of the sub-surface region due to the ageing process during cutting.

Recently, the application of cryogenic carbon dioxide (CO_2) in metal cutting has been substantially increasing among researchers with the latest by Pereira et al. [14], Luka et al. [15] and Khanna et al. [16]. Promising results associated with cryogenic cutting of difficult-to-machine materials have been reported. Liquid CO_2 at -76 ˚C offered less cooling effect as compared to LN_2. Thus, lower work hardening effect on the machined surface with better surface integrity is one of the targeted advantages from this approach. However, information regarding the microstructure and microhardness alterations when milling Inconel 718 under cryogenic CO_2 is scarce particularly pertaining the influence of cutting parameters.

Thus, this paper study the microstructure and micro-hardness changes of the machined surface layer of Inconel 718 after high-speed milling under cryogenic CO_2 condition affected by the different machining parameters. The microstructure alteration focuses on the grain deformation beneath the machined surface, while the microhardness alterations cover the relationship between the change in sub-surface hardness with the deepening of measurement points or distances from the machined surface. For the cryogenic CO_2, it is also considered as a sustainable approach to substitute conventional cutting fluids, as it offers a clean and safe cutting environment. Once supplied to the cutting area; it automatically evaporates to the atmosphere without any residues [17].

Methodology

Experimental milling setup

The experimental high-speed milling processes were performed via a CNC milling machine. In total, five experiments were conducted according to the identified finishing process parameters as listed in Table 1. For the milling inserts, commercially available PVD carbide coated ball nose type from Sumitomo were applied. The diameter of the insert is 10 mm, and it is coated with the alternate layers of TiAlN and AlCrN at 3 µm thickness. Before cutting, the insert was attached to the 16 mm diameter of a BIG Hi-power milling cutter at radial rake angle of 0°, relief angle of 11°, approach angle of 90°, axial rake angle of -3°, and an overhang length of 30 mm. The workpiece for the experiments was an aged AMS5663 Inconel 718 in the form of a solid block, 170 mm in width, 100 mm in height and 50 mm in length. Its hardness is 42 ± 2 HRC with its chemical composition is as listed in Table 2. Before cutting, a thin layer of 0.3 mm was removed from its top surface prior to the experiments in order to get an even machined surface. The milling process was continued until the tool notch wear, *Vbmax* reaches 0.2 mm to avoid excessive temperatures, and severely worn tool that may affect the machined surface.

Table 1: Experimental milling parameters

Experiment	Milling parameters			
	Cutting speed, *Vc* (m/min)	Feed rate, *fz* (mm/tooth)	Depth of cut, *ap* (mm)	Width of cut, *ae* (mm)
1	120	0.2	0.3	0.4
2	130	0.2	0.3	
3	130	0.25	0.7	
4	140	0.15	0.5	
5	140	0.2	0.3	

Table 2: Composition of the workpiece

wt.%	Ni	Cr	Fe	Nb	Ti	Al	B
	53.0	18.30	18.7	5.0	1.05	0.49	0.004
	C	Cu	Mn	Mo	Si	P	S
	0.051	0.04	0.0.23	3.05	0.08	< 0.005	< 0.002

For the cryogenic CO_2 coolant, a mixture of gaseous CO_2, liquid CO_2 and compressed air was supplied directed into the cutting tip by using a nozzle as shown in Figure 1. The controlled minimum temperature of the cryogen was approximately -55 ± 5 °C, which was confirmed using a K-type thermometer.

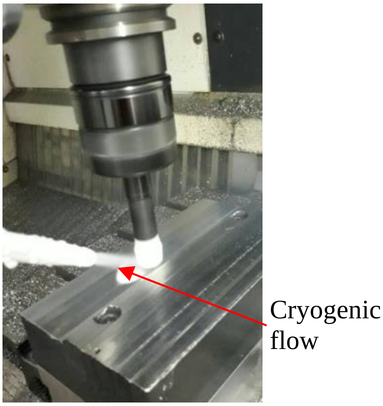


Figure 1: The milling process under cryogenic condition.

Samples preparation

The experimental samples over the cross-section of the workpiece were prepared according to the sequence shown in Figure 2. The workpiece was sectioned into pieces by using electrical discharge wire machining, before being hot mounted in Bakelite at 160 °C. The cross-section of the samples then underwent continuous grinding processes by using sandpapers and polishing processes to get a mirror-like finish, per ASTM E3-80/95. The process was followed by an etching process of 20 seconds using Kalling's reagent containing 100 ml hydrochloric acid (HCL), 100 cc ethyl alcohol and 5 g cupric chloride ($CuCl_2$) before being rinsed in water and dried by air [18].

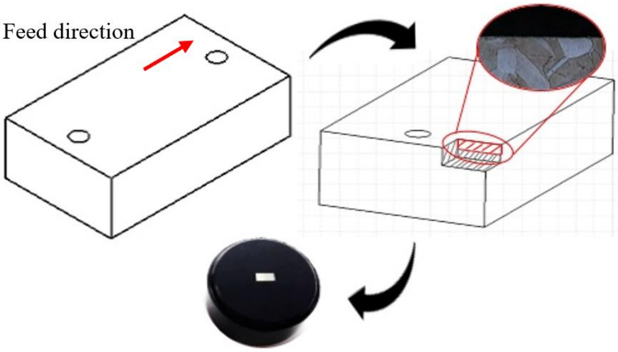


Figure 2: Experimental samples preparation.

Microstructure and microhardness observation

The changes in microhardness along the cross-section of the machined surfaces were measured using a Vickers microhardness tester. The measurements were conducted at depths of up to 600 µm with 100 µm intervals between successive readings from the edge of the sample. At each interval, three readings were taken from three different spots to get the average hardness for that particular depth. The indentation mark on the surface was generated by a diamond indenter in a pyramid form under a consistent load of 98.07 N (10 Kp) with 15 seconds dwell time. For the indentation mark, the angle between opposites was 136º. This approach was in parallel with that of researchers like Devillez et al. [19], Kenda et al. [5] and Kasim [2] which used 50-500 gf of indentation load and 10-15 seconds of holding time for Inconel 718. For microstructure observation, an Olympus optical microscope model BX51M at 10X magnification was used.

Results and Discussions

Figure 3 shows the microstructure of aged-hardened Inconel 718 before the machining process. As can be seen, the presences of micro-twinning structures known as annealing twins were found in the microstructure. These needle shapes were believed to have been created due to re-crystallization and growth of new grains during heat treatment process [20]. According to Ramirez [21], these structures made the material stronger in withstanding any plastic deformation due to the shearing force of the cutting process. Due that, the hardness of the aged-hardened Inconel 718 was found to be 65% higher as compared to its initial hardness before the heat treatment process. The heat-treated material is believed offer consistent thermal shock and creep properties at higher cutting temperatures as in high-speed machining.

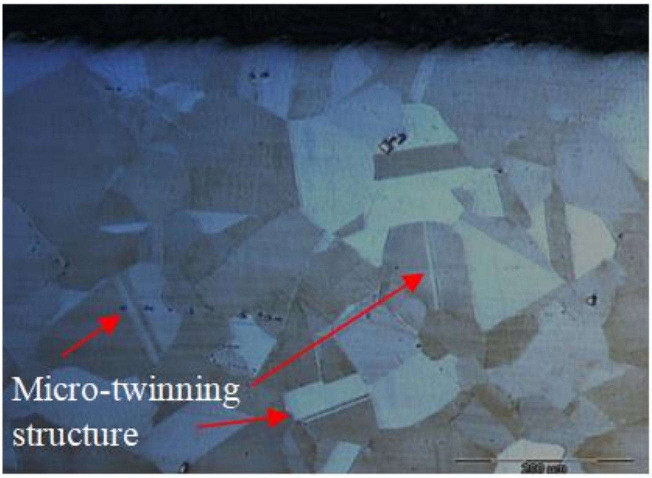
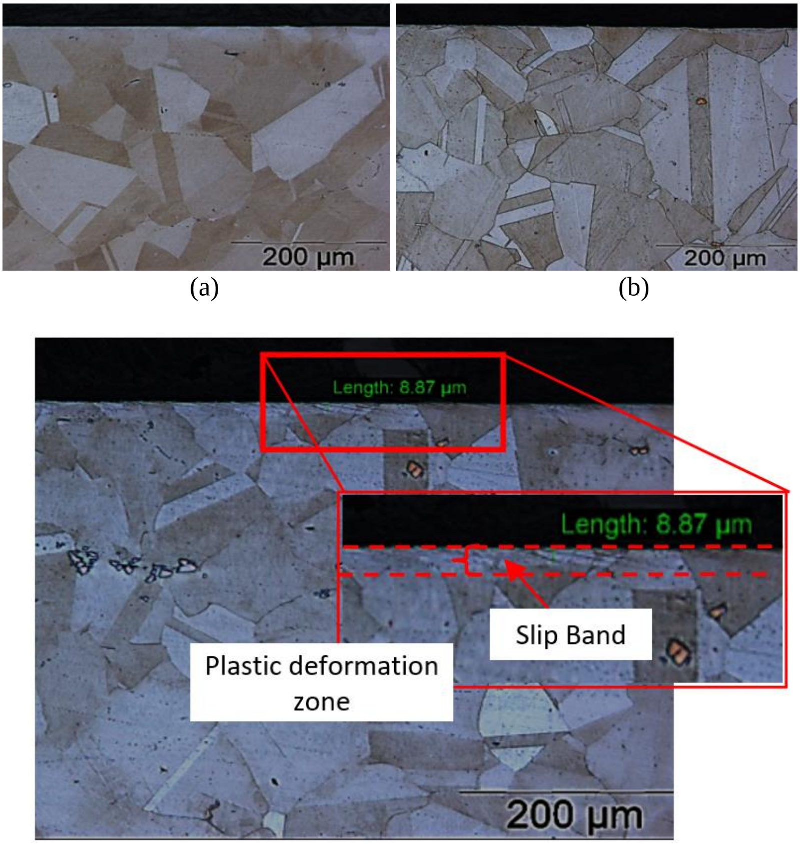


Figure 3: Microstructure of Inconel 718 (before being machined).

Figure 4 depicts the microstructure of Inconel 718 after high-speed milling at different cutting parameters. Neither of the samples from Experiment 1 (Figure 4a) or Experiment 4 (Figure 4b) showed any plastic deformation. However, plastic deformation with a slip band was observed on the sample from Experiment 3, as shown in Figure 4c. As found, the length of the grain structure deformation was 8.87 µm from the machined surface. Slip band is the dislocation microstructure formed during the cyclic deformation of the cutting process. According to Antolovich [22], slip band is one of surface damage modes which tends to cause cracking on the machined surface.

Generally, these findings showed that cutting Inconel 718 at the highest value of feed rate (*fz*) and depth of cut (*ap*) as applied in Experiment 3, altered its microstructure underneath the machined surface (as shown in Figure 4c). The findings are consistent with Griffiths [23], where it was found that factors related to the increase of cutting forces and temperatures increase the level of plastic deformation as well.



(a) (b)

(c)

Figure 4: Microstructure alteration from; (a) experiment 1, b) experiment 4, and c) experiment 3.

To see the degree of work hardening experienced by the machined surface, the value of microhardness of each sample was measured from a depth of 25 µm until 600 µm beneath the machined surface. Figure 5 clearly shows that aged-hardening occurred during machining as the average hardness value of each sample was higher than its bulk hardness (452.5 ± 2.5 $HV_{0.1}$). Every sample resulted in a different value of hardness, with the highest value of each were at the depth closest to the machined surface. The values then were reducing as the profile go down beneath the surface. Regarding the work of Sadat and Reddy [24], this occurred because a massive amount of strain hardening was concentrated at the area nearest to the machined sub-surface as a result of high temperature and shearing force. This notable finding was consistent with Hadi [25], Kasim [2] and Pusavec et al. [26], who were also concentrated on high-speed cutting of Inconel 718.

In this analysis, the highest value of hardness was obtained in Experiment 3 with an average value of 474 $HV_{0.1}$, 4.2% higher than its bulk hardness. In comparison, Hadi [25] and Kasim [2] recorded an increase in hardness of 8.9% and 8.8% in LN_2 cryogenic and MQL, respectively. Clearly, the effects of controlled cryogenic cooling and the use of a cutting tool with a maximum wear rate $Vbmax \geq 0.2$ mm helped to reduce the effects of heat and work hardening on the machined surface. The hardness values were found to decrease with the deepening of the measurement point from the sub-surface until it almost approached the bulk hardness approximately 0.3 mm from the machined surface. This was consistent with the findings of Devillez et al. [19], Hadi [25], Kasim [2], and Pusavec et al. [27]. The zone where age-hardening occurred is known as the machining affected zone, MAZ as proposed by Sonawane and Joshi [3]. MAZ results from work hardening during machining, which forms a plastic deformation layer at a certain distance from the machined surface. Ginting and Nouari [13] defined these two zones as the hard sub-surface region and the bulk material region as also adopted in Figure 5.

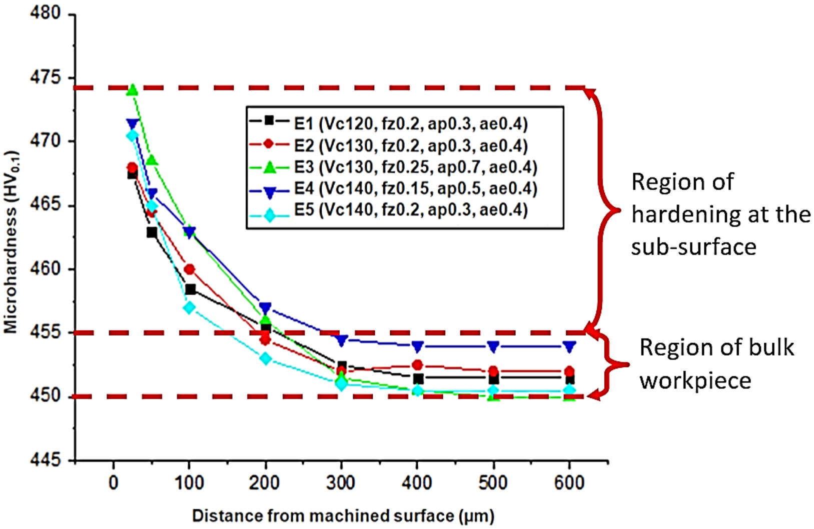
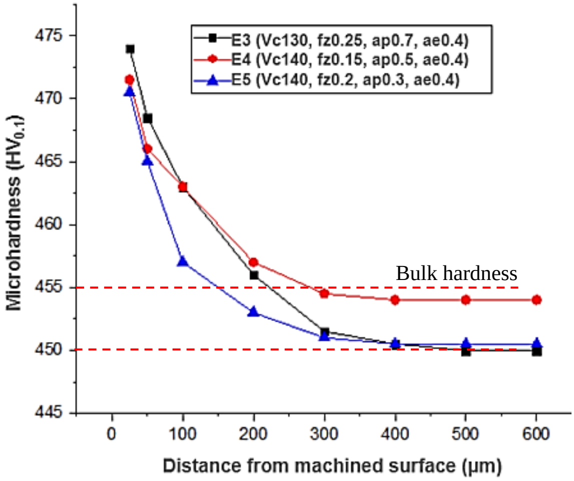


Figure 5: Micro-hardness at the sub-surface of the machined area.

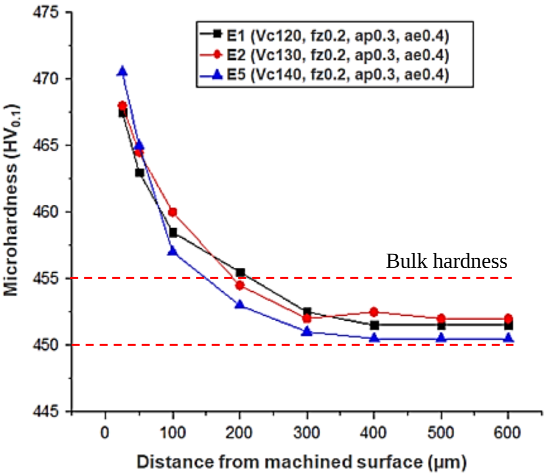
Figure 6a shows the effects of a feed rate (*fz*) and depth of cut (*ap*) on micro-hardness in Experiment 3, Experiment 4 and Experiment 5. It is shown that the microhardness (starting at 50 µm beneath the machined surface) increased with the depth of cut. The highest value of feed rate also resulted with the highest microhardness. This result is consistent with the findings of

Kasim [2] and Hayati et al. [28] where they mentioned that the increase of feed rate and depth of cut increase not only the size of cut but also the cutting force that needed to be borne by the cutting tool. This condition resulted in a higher strain rate on the machined surface. Meanwhile, Tsirbas et al. [29] connected the increase of depth of cut with the increase in machining temperature.

The increase of cutting speed (*Vc*) also significantly increases the microhardness, as shown in Figure 6b. At the highest cutting speed (140 m/min) as in Experiment 5, the microhardness increases until 3.6% as compared to its bulk value. While Experiment 2 at cutting speed 120 m/min resulted with the lowest. This finding was consistent with Sonawane and Joshi [3] who also milled Inconel 718 but under dry condition. According to Thakur and Gangopadhyay [30], the increase of cutting speed tends to change the residual stress from compressive to tensile, which was related to the increase in machining temperature. This caused the workpiece exposes to higher temperature and pressure during cutting. The attribute of Inconel 718, its low thermal conductivity property was also believed to contribute to the increased machining temperature as well as affect the machined surface integrity. At temperatures lower than 650 ºC, Inconel 718 tends to work harden along with the increase in machining temperature [11], [31].



(a)



(b)

Figure 6: Micro-hardness; (a) effects of feed rate (*fz*) and depth of cut (*ap*); and (b) effects of cutting speed (*Vc*).

Conclusion

Microstructure and microhardness alterations on the sub-surface of Inconel 718 after high-speed cutting Inconel 718 under cryogenic CO_2 condition using PVD carbide coated ball nose milling insert were analyzed. In was found that the depth of plastic deformation depends greatly on the machining parameters. The highest value of feed rate and depth of cut resulted with obvious grain structure deformation, deepening until 8.87 µm from the machined surface. At the same time, those factors also significantly increase the sub-surface microhardness, made the machined surface harder and more difficult to be machined. Cutting speed also plays an important role in increasing the subsurface microhardness. At the highest cutting speed, the machined sub-surface microhardness was 3.6% harder than bulk hardness. Also found that the depth of machined affected zone was reduced as the profile go down beneath the surface. The workpiece’s hardness was back to its bulk hardness approximately 300 µm from the top surface. Thus, it can be suggested that the finishing process of Inconel 718 under cryogenic condition can be performed at a depth of cut lower than 0.3 mm to remove any hardening effect on the machined surface.

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