Chip Morphology of Inconel 718 in High-Speed Milling under Cryogenic CO_2 and Dry-Cutting Conditions

Nur Fatini Mohamad Fauzee, Nurul Hayati Abdul Halim[*]*, Zulaika Zulkifli, Zainoor Hailmee Solihin*
Faculty of Mechanical Engineering,
Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia
[*]*hayatihalim@uitm.edu.my*

ABSTRACT

This paper studies chip morphologies after high-speed milled Inconel 718 using PVD tungsten carbide-coated ball nose milling inserts collected over cryogenic and dry cutting conditions. Chip morphology results from specific chip formation mechanisms occurring during cutting. Characterisation of the chip properties in micro-hardness and the correlation between chip morphology and tool wear rate and patterns were analysed. The chip formation under cryogenic CO_2 and dry cutting were observed at constant cutting speed (Vc=130 m/min), feed rate (fz=0.25 mm/tooth), radial depth of cut (ae=0.4 mm), but varied in axial depth of cut (ap) at 0.3 mm and 0.7 mm. An optical microscope was used to measure the size and shape alterations of the chip. The observation results revealed that chip formation under dry cutting conditions was severe, distorted, and darker as it was thermally affected. Cryogenic machining generated bright, shiny, and smooth chip surfaces due to efficient heat dissipation at the tool-chip contact. In addition, dry cutting generated severe and common build-up-edges (BUE) in connection with the tool wear rate and patterns compared to cryogenic cutting. The morphologies of the chip under cryogenic conditions showed a significant correlation toward tool wear development. The microhardness analysis showed that alterations happened at the sub-surface due to cryogenic cooling effects and machining parameters. Moreover, both cutting conditions are recommended for sustainable manufacturing practice that positively impacts ecological and employee well-being and satisfy safety concerns.

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Introduction

Inconel 718 is classified into nickel-based superalloys that are in high demand, especially in the manufacturing of aerospace and aeronautic components, particularly for fabricating hot parts such as turbine discs, compressor blades, and other parts regarding their high-temperature strength and corrosion resistance [1]-[2]. In addition, this nickel-based superalloy was the most prominent alloy. Despite that, their poor thermal characteristics, low heat resistance, and significant work hardening propensity. These materials, particularly in abrasive dry cutting conditions, come under the category of very "hard to machine" materials [3].

Chips are produced during the material removal procedures in metal cutting. Without a doubt, these cutting chips are processed waste. The superalloy-produced serrated chips' chip formation during high-speed milling has been related to the shear localisation [4]-[5]. Other research from Aramcharoen and Chuan [6] and Yazid et al. [7] indicated that a chip is created when the material is sheared along with a shear plan due to the heat produced by the theoretical energy. This required to process the material is dissipated through the cutting tool, chip formation, and Inconel 718's workpiece; thus, Figure 1 shows the schematic of chip formation in metal cutting.

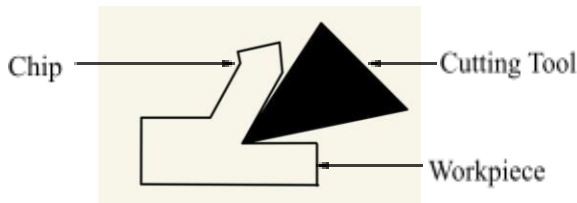


Figure 1: The schematic of chip formation during metal cutting.

The chip shape alterations were often affected by the cutting conditions and the characteristics of Inconel 718 [8]. According to Halim et al. [2], a strong contact within the tool and chip, and high-speed milling resulted from the cryogenic cutting process, which produced a lighter-coloured chip. When the chip was exposed to high temperatures in dry cutting, the chip colour turned darker and faded. In a previous study, Aramcharoen [6] noticed that dry-cutting chips were golden brown, implying a high cutting temperature during machining and that heat and oxidation are retained on the chip. However, shiner chips were produced during cryogenic cutting. Notice that dry-cutting chips were golden brown since this implies a

high cutting temperature during machining and that heat and oxidation are retained on the chip. However, shiner chips were produced during cryogenic cutting. This colour agreed with Dhar et al. [9], who investigated cryogenic cooling but used AISI 1040 and AISI 4320 steels in the turning method.

In the case of dry cutting, Rakesh and Datta [10] mentioned that the teeth of Inconel 718 became serrated due to the workpiece's thermo-mechanical instability during the process, creating a particular serrated form of the chip. Further study by Halim et al. [2] and Aramcharoen and Chuan [6] observed that under dry cutting, severe, longer, distorted, and deformed chips were formed due to the substantial heat build-up inside them, which stresses them thermally. In contrast, chip breakability was improved in cryogenic as shorter chips were produced. This is because the benefits of the cooling agent thus lower the cutting temperature and reduce the alteration in the workpiece and friction. Therefore, research on chip characterisation under both cutting conditions (cryogenic and dry) is essential to maximise the effectiveness and design sustainable high-speed machining [11].

According to published research, the machining of Inconel 718 at high speed produced rapid tool wear. Regarding this, the high cutting temperature also impacts the chip formation [12]. A study by Halim et al. [2] found that high-pressure coolant flow assisted in flushing, and the cryogenic CO_2 resulting from heat dissipation helped to flush out the chip morphology of the welded zone. This also decreased the build-up edge (BUE) of the tool wear. However, the severe BUE welding on the notch wear emerged early under dry conditions. Further study by Ayed et al. [13] and Chaabani et al. [14] found that cryogenic has been identified as a potential substitute for dry cutting to enhance the surface of Inconel 718 and reduce tool wear. This is due to poor lowering temperature and the CO_2 inadequate cooling penetration into the tool-chip contact as it was present as 60% of gas and 40% of snow [2].

To better understand chip formation, this study examined the Inconel 718 chip morphology following high-speed milling under cryogenic CO_2, compared it to dry-cutting settings, and identified a correlation between the chip formation and tool wear rate and patterns. The examination considers the change in microhardness and how it relates to the shape of the chips.

Methodology

Inconel 718 was the material chosen for the chip in this study. Chip samples were obtained after high-speed milling of Inconel 718 using multi-coated PVD tungsten carbide ball nose milling inserts under cryogenic and dry cutting conditions to evaluate the morphology and microhardness changes. Experiments were carried out at constant cutting speed (*Vc*), feed rate (*fz*), and radial depth of cut (*ae*), but varied in axial depth of cut (*ap*) at 0.3 mm

and 0.7 mm. Detailed machining parameters and the resulting tool life under both cutting conditions are summarized in Table 1.

Table 1: Machining parameters

Samples	Cutting parameters				Tool life (min)	
	Vc (m/min)	*fz* (mm/tooth)	*ap* (mm)	*ae* (mm)	Cryogenic	Dry
1	130	0.25	0.3	0.4	9.96	7.24
2			0.7		3.33	1.1

To analyse tool wear patterns and their correlation with chip formation, observation and measurement of chip shape alterations were realised using an *Olympus* BX51M system metallurgical microscope as in Figure 2. This microscope has a magnification of 5x and repeatability of ±0.003 mm to determine the shape alterations, tool wear rate, and patterns by measuring the dimensions of 2-D chip formation.

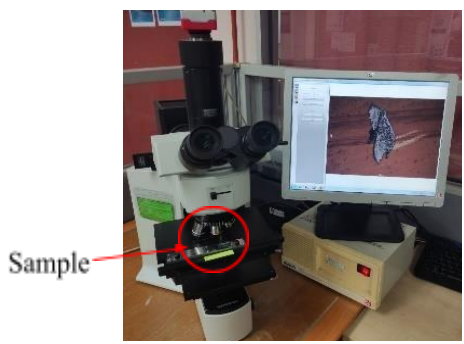


Figure 2: System metallurgical microscope *Olympus* series BX51M

For microhardness and microstructure observations, chip samples from the last cutting interval under both cutting conditions were embedded with a hot mounting press in resin mount. The chip samples were mounted with the shining part exposed for observation. The mounted chip samples were then ground manually using waterproof SiC with a sandpaper grit size of 400 to 1200. Later, the samples were polished manually using polishing powder at 1µm to obtain a scratch-free surface.

Microhardness measurement on the mounted chip samples was performed using a Vickers hardness tester (Mitutoyo MVK-H1). Additionally, the two diagonal distances of the pyramid's curve were measured to get the microhardness value, namely *d1* and *d2*, as shown in Figure 3. Later, the value of hardness was obtained automatically. For chip

samples of Inconel 718, the value of the indentation load was set to 100 gf for 15 seconds. This approach was in parallel with that of researchers like Haron et al. [15] used an indentation load of 50 gf – 500 gf and a holding time of 10 seconds – 15 seconds for Inconel 718. This is to ensure that the diamond-shaped indentation that followed was smooth.

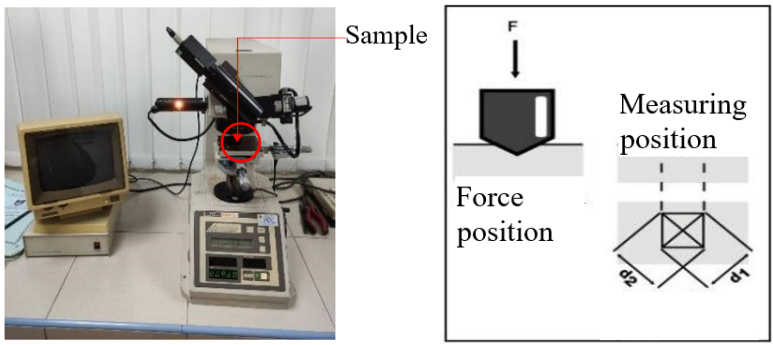


Figure 3: Vickers hardness tester and the measuring position

Results and Discussion

Chip morphology

The chip normally forms as the cutting edge rotates and one complete circle of the cutting tool during the milling process will produce one complete chip segment [2]. Figure 4 shows a chip with a concave form and a trailing effect, which is typically produced during milling using a ball-nose insert. Figures 4(a) and 4(b) compare the chip's free and back surfaces, respectively. The movement of the chip over the tool rake face during machining generates a smooth and shining appearance on the rear surface. Furthermore, it also creates frictional forces and contact temperature. The rough appearance and free surface resulting from the shearing procedures caused plastic deformation on the Inconel 718 surface. A structure may also be affected by heating and rubbing impacts at the interface resulting from the chip's tip that comes into contact with the uncut Inconel 718's surface.

Table 2 demonstrates the influence of axial depth of cut (*ap*) and radial cut (*ae*) on chip dimensions. It was observed that under both cutting conditions, the chip length increases as the value of *ap* increases. This is because the value of *ap* determines the depth of tool contact with the machined surface during cutting. It was also discovered that chip thickness increased in response to increasing *fz* values. However, Wagner et al. [16]

found that decreasing the value of *fz* will shorten the chip. Furthermore, the chip shape is unaffected significantly by the change in the value of *Vc*.

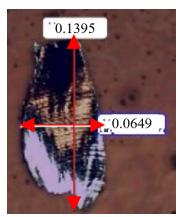
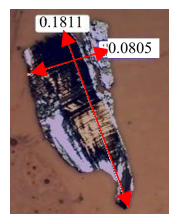
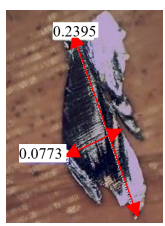
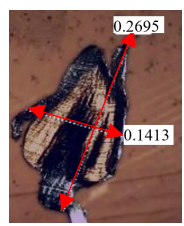
It was observed that the use of cryogenic coolant produced shorter chips than the dry-cutting method. This might be a result of the cooling advantage and decreased cutting temperature. In contrast, chips were longer and wider under dry cutting due to the high temperature during cutting. Similar findings were reported by Jebaraj and Kumar [17], [24].



(a) (b)

Figure 4: Chip characteristics; (a) back surface; (b) free surface, under cryogenic condition, sample 2

Table 2: Effect of axial depth of cut (*ap*) and radial of cut (*ae*) on chip's length and width (mm)

ap (mm)	*ae* = 0.4 mm	
	Cryogenic	Dry
0.3		
0.7		

The correlation between chip morphology and tool wear

Figures 5 and 6 show the tool wear patterns and chip morphology concerning the progression of maximum notch wear, $VB_{max,}$ and cutting time observed in cryogenic and dry cutting conditions. In general, there are three main stages in the development of tool wear: an early stage in which notch wear increases quickly; a stable stage in which notch wear increases steadily, causing the flank face to develop a notch and flake near the depth of cut (DOC) line.; and a final stage in which notch wear increased sharply until it reached the cutting limit. Kasim et al. [18] used the same approach when cutting Inconel 718 in dry and MQL conditions, respectively. Figures 5 and 6 also demonstrate the early wear stage's rapid and uniform development of abrasive wear on the tool flanks at the DOC line. The depth of notch wear was found to be increasing gradually with regard to cutting time. Additionally, the built-up edge (BUE) was seen to follow the DOC line. The adherence of chips that flow on the cutting tool's rake face is known as the BUE.

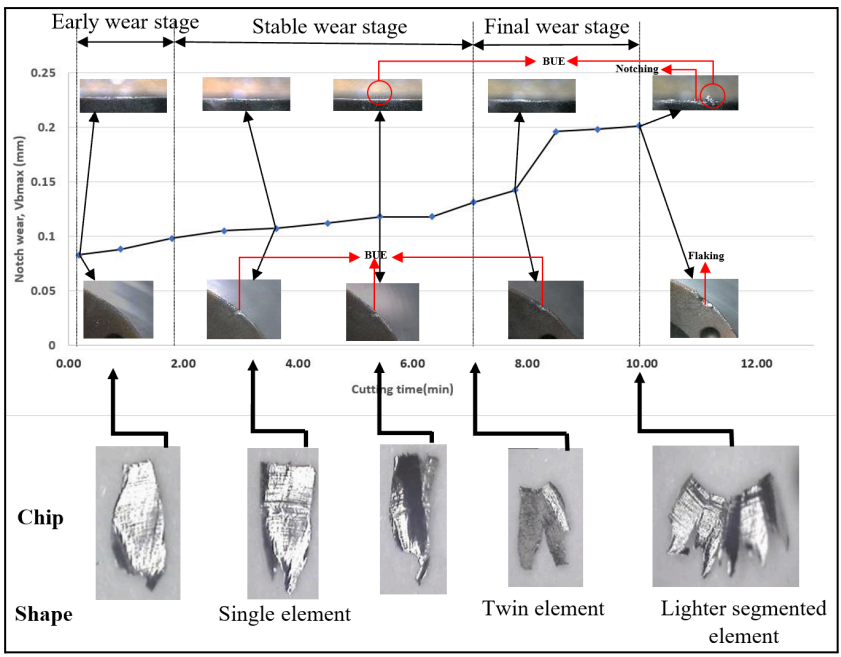


Figure 5: Tool wear progress and chip morphology under cryogenic cutting at tool flank and rake faces from sample 1

In Figure 6, under dry cutting, the adhering BUE was constantly present in almost all cutting intervals and worsened as the flank wear quickly increased. Under the cryogenic condition, the stable wear stage showed a longer cutting time and a smaller curve slope as the wear rate gradually increased. The BUE was less pronounced because cryogenic CO_2 effectively dissipated heat. According to Halim et al. [2], low temperatures decrease Inconel 718's susceptibility to attach to surfaces and generate BUE. The high-pressure coolant flow also helped wash chips away from the welded area, thus reducing BUE.

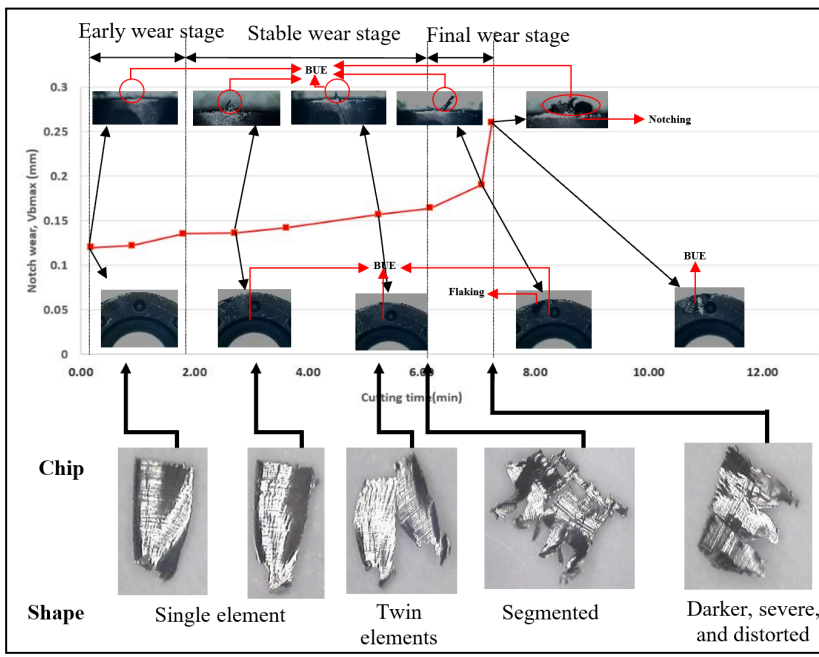
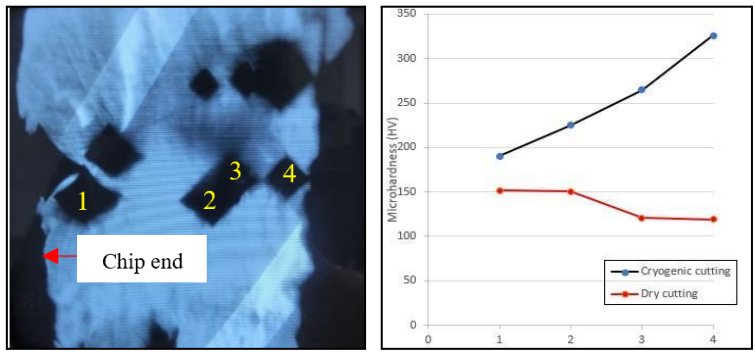


Figure 6: Tool wear progress and chip morphology under dry cutting at tool flank and rake faces from sample 1

Microhardness alteration

Figure 7a shows a sample of microhardness measurement locations on the chip from sample 2 under dry cutting. Referring to Figure 7b, the microhardness of sample 2 was compared between dry and cryogenic conditions. The results show that the chip under cryogenic cutting was work hardened as influenced by the cooling effect of the cryogen CO2 during cutting. Thus, its hardness is higher than the one under dry-cutting conditions. Pereira and Delijaicov [19] reported that the heat effect causes

plastic deformation, which impacts how the microhardness fluctuates. Kenda et al. [20] described how precooling by cryogenic conditions lowers the workpiece's (and the cutting tool's) temperature, increases compressive residual stresses, and increases hardness in the completed product. This study showed that cryogenic conditions caused the highest hardness on the machined surface.



(a) (b)

Figure 7: (a) measurement location of the chip under dry cutting and (b) microhardness on-chips surface for sample 2

Conclusion

This paper analyzed chip morphology on two sustainable machining approaches: cryogenic CO_2 and dry condition experimentally after high-speed milling of Inconel 718 using PVD tungsten carbide coated ball nose milling inserts. The following conclusions were drawn:

- The dry cutting was found to yield segmented chips earlier. As a result of the elevated cutting temperature compared to cryogenic cutting, the cutting process produced severe, deformed, and darker chips. When milling Inconel 718 at high cutting speeds, a good link between the cutting conditions and tool wear patterns with chip morphology can be observed to predict the tools' wear rate and patterns.
- Similar tool wear patterns were seen both during cryogenic and dry cutting. Around the cutting edge, they first developed a smooth abrasion and chipping, then flank wear, flaking, and notching at the rake and flank faces. On the other hand, dry cutting produced severe and frequent BUEs that accelerated the notching and increased flaking.

- It is recommended to employ cryogenic and dry cutting conditions because these methods positively affect the environment, the welfare of the workforce, and safety concerns.

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