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RESEARCH ARTICLE

The correlation of surface roughness and tool edge condition under sustainable cryogenic machining

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ABSTRACT - This paper investigates the correlation between surface roughness of Inconel 718 and tool edge condition of ball nose inserts when milled at high speed. The cutting parameters were varied as follows; cutting speed: 120–140 m/min, feed rate: 0.15–0.25 mm/tooth, and axial depth of cut: 0.3–0.7 mm. For a sustainable machining approach, the experimental works were carried out under a smooth supply of cryogenic coolant which is a mix of liquid CO_2, gas CO_2, and compressed air. The experimental results revealed that the range of surface roughness obtained is from 0.114 to 0.197 µm. Along the cutting process, the tool wear patterns such as the abrasion, chipping, and the intermittent build-up-edge near the depth of cut cause the rapid increase of tool wear as well as the roughness of the machined surface with a significant correlation between them. However, the roughness was slowly reduced and became stable with the increase of notch wear. The finding could be used as a prediction reference for monitoring surface roughness and tool wear progress under cryogenic conditions. It also provides foundations for further research on machinability under this sustainable approach.

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1.0 INTRODUCTION

One of the best superalloys to employ nowadays for the fabrication of aircraft engine components is nickel-based alloys like Inconel 718 [1]. Its main characters that are the combination of high strength at high pressures and temperatures, excellent resistance to oxidation and corrosion, poor heat conductivity, and strong work-hardening have made Inconel 718 well known as a super alloy that is difficult-to-cut especially under challenging dry cutting conditions [2]. Extensive studies have been conducted for evaluating and improving its machinability as high-speed cutting of Inconel 718 commonly resulted in severe tool wear, shorter tool life, and poor surface quality [3, 4]. Researchers previously were focused more on varying the machining parameters and analyzing their influence, particularly on the tool life and machined surface integrity. Varying the machining conditions was also found very significant with the recent attention on the sustainability approaches such as under cryogenic conditions which reported positive implications [5, 6]. This effort is very important for productive and successive machining without compromising the environmental aspect.

Surface roughness and tool wear rate are among the main criteria used for evaluating the machinability and quality of the machined surface. Many in-depth studies particularly on the influence of cutting parameters such as feed rate, cutting speed, and depth of cut have been reported [7, 8]. However, it is still in effort to identify the optimum machining process with the combination of appropriate cutting parameters, workpiece and cutting tool materials, and cutting conditions (with or without coolant or lubricant). Thakur and Gangopadhyay [9] summarized that apart from cutting parameters, the formation of built-up edge and tool wear that generate heat and friction at chip-tool and workpiece-tool interfaces provide a major influence in altering surface roughness. This is in line with Elbestawi [10], who found that surface roughness tends to increase considerably when the tool wear rate exceeds a certain value. This is because a worn tool edge generates more friction and heat that induce high temperature which leads to shorter tool life and poor surface quality. However, it is a fact that a detailed analysis of the correlation between tool edge condition and surface roughness progress along a cutting process under cryogenic conditions using CO_2 could hardly be found. It is because the analysis requires intensive data collection and analysis along the cutting process that consumes time and cost. Yet, the use of CO_2 as a cryogen in the milling process of Inconel 718 can be considered new with huge areas that need to be explored.

Even though CO_2 is known to be one of the main reasons for the global warming effect [11], its application in metal cutting is considered a good alternative to reusing it instead of being vented directly to the environment as wastes of primary processes. In metal cutting, its application offers an environmentally benign approach that is safe to machine operators and also leaves a dry and clean machined surface. Once used, the coolant automatically dissipates into the atmosphere, necessitating no additional cost for treatment or cleaning. This is contradicted by traditional flood cutting that leaves a residue to be recycled or disposed of, or under the Minimum Quantity Lubricant (MQL) approach that leaves oily machined surface and environment.

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Cryogenic cutting also reported encouraging improvement in high-speed cutting performance, particularly when compared with dry or flood cutting approaches [12]. During machining, CO_2 is supplied at high velocity through a nozzle directly to the tool-workpiece interface. According to Aiman et al. [13], this approach is a convection-based heat transfer method and is very effective to improve the efficiency of local heat transfer and reduce cutting temperature. Significantly, temperature-dependent output such as tool wear rate and surface finish improved as well.

Thus, in this study, the correlation between surface roughness and tool edge condition of ball nose milling inserts when high-speed milling Inconel 718 using a novel cryogenic CO_2 cooling system was thoroughly investigated. The main focus is on the progress of surface roughness and how it was influenced by the tool wear rate and the changes in tool edge condition. The milling process is one important process, particularly when to achieve a specific machined surface quality or dimensional accuracy of the finished product.

2.0 METHODS AND MATERIALS

Under cryogenic cooling supply, a block of Inconel 718 AMS 5663 at a size of 170x100x50 mm (WxHxL) was high-speed milled using PVD multi-coated carbide ball nose milling inserts. The grade of inserts was ACK300 from Sumitomo with the alternate coating materials of TiAlN and AlCrN at a total thickness of 3 µm. The details and geometries of the insert should be referred to in the Sumitomo catalog [14]. A three-axis vertical CNC milling machine, model DMG 635 with a maximum spindle speed of 8000 rpm was applied. As shown in Table 1, three experiments were carried out using the variables of regulated cutting speed (*Vc*), feed rate (*fz*), axial depth of cut (*ap*), and radial depth of cut (*ae*).

A coolant containing a mixture of gaseous and liquid CO_2 and compressed air was utilized to create a cryogenic environment for the high-speed milling operation. They were mixed in a chamber before being dispensed through a nozzle at -65±5 ˚C. This cryogenic temperature results from the Joule-Thomson phenomenon, and a type-K contact rod thermometer verified the data. [15]. Theoretically, when CO_2 enters the ambient environment and expands at room temperature and air pressure, CO_2-snow is inherently created from the Joule-Thomson effect of phase transformation [16]. Thus, this new cryogenic approach was introduced to develop a smooth flow of coolant without the formation of CO_2 snow which might block the flow mainly around the nozzle outlet and reduce the efficiency of the cooling effect to penetrate deep into the cutting point. Figure 1 shows the experimental work conducted under cryogenic CO_2 condition.

Table 1. High-speed milling parameters

No. of	*Vc* (m/min)	*fz*	*ap* (mm)	*ae* (mm)
1	120	0.15	0.5	
2	130	0.25	0.7	0.4
3	140	0.20	0.3	

Figure 1. High-speed milling process under cryogenic CO_2 condition

Using a Mitutoyo toolmaker's microscope, the flank wear rate was recorded during the cutting operation at predetermined intervals. At the same time, a portable surface roughness tester, the Mitutoyo SJ-310, was used to measure the roughness in the arithmetic average (*Ra*). According to ISO 4288 1996, the direction of the stylus feed with the stylus traversal length was fixed at the cut-off length of 0.8 mm. To characterize the *Ra*, the measurement was repeated five times to obtain values at arbitrary positions along the cutting pass. By referring to Eq. (1) [17], the radius of the insert (r) and the feed rate (*fz*) have a theoretically significant impact on the surface roughness of a milling operation utilising a ball nose milling insert.

$$Ra = \frac{r - \sqrt{r^2 - \left(\frac{f_z}{2}\right)^2}}{2} \quad (1)$$

To identify tool life, tool wear rate, and their significant influences on surface roughness, the cutting and measuring processes were continued until the localized flank wear (*VBmax*) reached the limit of 0.2 mm. This limit was set to avoid severe machined surfaces induced by severe tool wear conditions as suggested by researchers such as Pereira et al. [18], Tapoglou et al. [6], and Grzesik et al. [19], in metal cutting studies. The worn inserts were characterized using a Scanning Electron Microscope (SEM) (model SUPRA 55VP) which is equipped with an EDAX element mapping instrument.

3.0 RESULTS AND DISCUSSION

From the first path of cutting, the experimental results as shown in Figure 2 revealed that the high-speed milling using the ball nose insert under cryogenic CO_2 capable to produce a superior machined surface at the predetermined parameters. The range of surface roughness (*Ra*) was 0.123 – 0.195 µm which is near to the super finishing condition (<0.1 µm). This is believed to happen due to the geometries of the ball nose insert that provides a larger contact area with the workpiece during cutting which in turn increases frictional heat. According to Arunachalam et al. [20], this thermal effect increased the cutting temperature which then softened the material and resulted in a smoother surface finish. At the same time, the wider peak-to-peak distance of the feed mark on the machined surface formed by the rounded edge also helped to produce a better surface finish as found by Ulutan and Ozel [21]. This result fulfils the requirement for some airplane components such as turbine blades where the *Ra* has to be in the range of ≤ 0.2 µm [22].

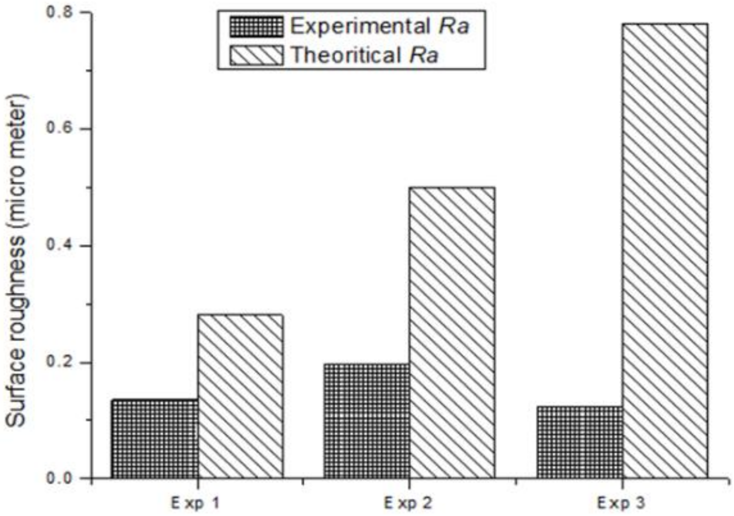


Figure 2. The comparison between experimental results and the theoretical value of surface roughness (*Ra*)

Generally, this study shows that the highest *Ra* produced at maximum ffed rate and axial depth of cut. This is compatible with Kasim [23], who stated that the *Ra* depends on the kinematic effect of the insert which is influenced by the shape of the ball nose and the feed rate, and the depth of cut values. The rounded edge of the ball nose insert generates an unmachined area on the machined surface which then creates feed marks by the next insert rotation, as shown in Figure 3. The increase in feed rate and depth of cut increases the size of feed marks as well as the *Ra* value. Meanwhile, the cutting speed showed an insignificant effect on *Ra* as also reported by Mia et al. [24].

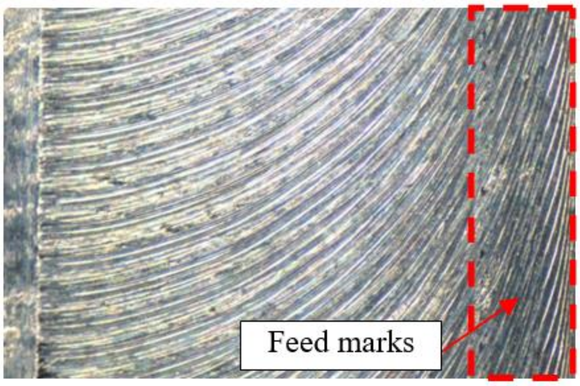
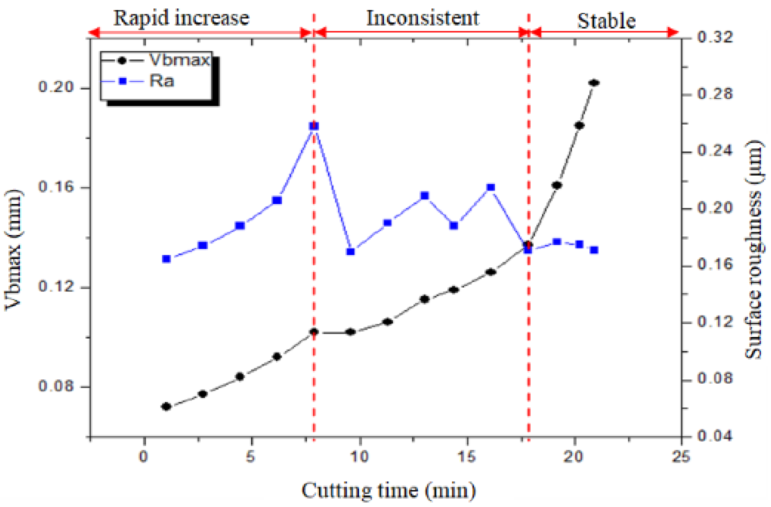


Figure 3. Feed marks on the machined surface under experiment 1, machining time: 1.4 minutes, 20X magnifications

When compared with the theoretical surface roughness calculated using Eq. (1) as in Figure 2, the values were found higher than the experimental results. The percentages of difference ranged from 108.1% to 306.5%, with an average of 237%. The cooling action of the cryogenic coolant, as also described by Halim et al. [3] and Bakar et al. [25], was thought to be the cause of the efficient temperature reduction and thermal distortion on the machined surface within a stable cutting condition.

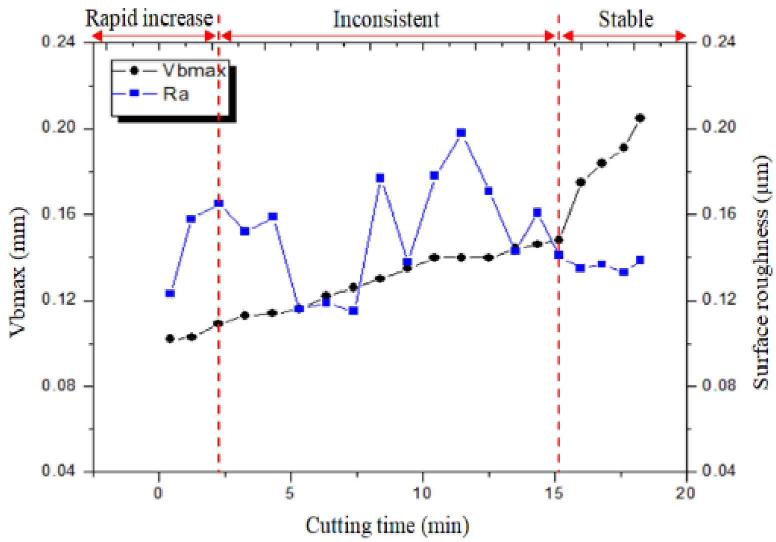
Figure 4(a) and 4(b) show the progression of surface roughness *(Ra)* with respect to cutting time and notch wear rate (*Vbmax*) under experiment 1 and experiment 3, respectively. As can be seen, the highest *Ra* of 0.258 µm was recorded in experiment 1 at 7.8 minutes, while the lowest *Ra* of 0.115 µm was recorded in experiment 3 at 7.3 minutes. Both experiments showed approximately similar *Ra* progress which could be classified into 3 main stages: rapid increase, inconsistent and stable conditions. A detailed analysis on the *Ra* progress revealed a significant correlation between it and the condition of the cutting tool edge.

Also, from Figure 4, it was found that the *Ra* rose sharply with respect to the steady increase of the tool wear rate after the first cutting interval. Figures 5 shows the cutting-edge conditions before and after the first cutting interval with abrasive wear was found generated on both flank and face faces. Thorough observation by SEM showed the formation of abrasive wear along the cutting edge and chipping near the depth of cut line as in Figure 6. It caused the rapid increase of tool wear as well as surface roughness at the beginning of cutting. This condition generally occurs due to continuous rubbing and sliding friction between the tool and the abrasive carbide particles in the alloys of Inconel 718. The analysis of the EDAX element mapping images of the workpiece as shown in Figure 7 shows the presence of NbC and TiC particles in Inconel 718. The precipitation of these particles in the grains of Inconel 718 was to enhance the creep resistance due to their high melting temperature (3600 °C) and strength (around 19.6 GPa) [26]. However, the particles encouraged abrasion which rapidly deepened chipping on the tool surface and increased wear rate. As stated by Musfirah et al. [22], the presence of NbC particles in Inconel 718 exacerbates the scratching and abrasive marks on the tool surface. Surface roughness which is known sensitive to any changes on the tool edge was increased as well.



(a)

Figure 4. Progression of *Ra* with respect to tool life and notch wear rate (*Vbmax*) under; (a) experiment 1



(b)

Figure 4. Progression of *Ra* with respect to tool life and notch wear rate (*Vbmax*) under; (b) experiment 3 (cont.)

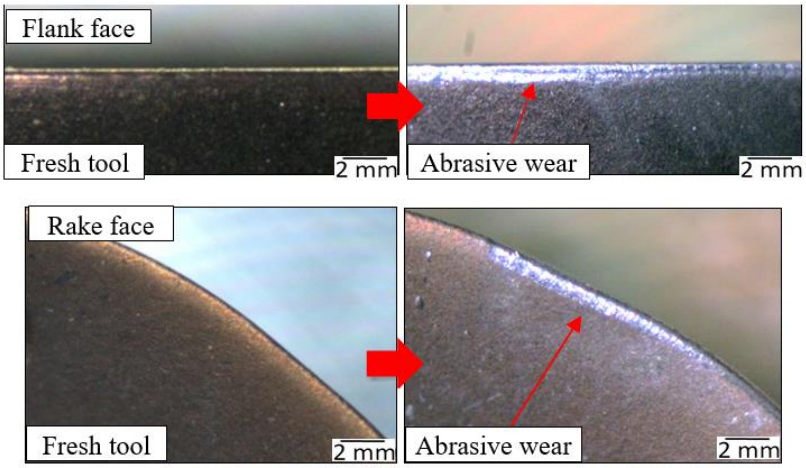


Figure 5. Cutting edge conditions before and after the first cutting interval (experiment 1: machining time 0.3 minutes)

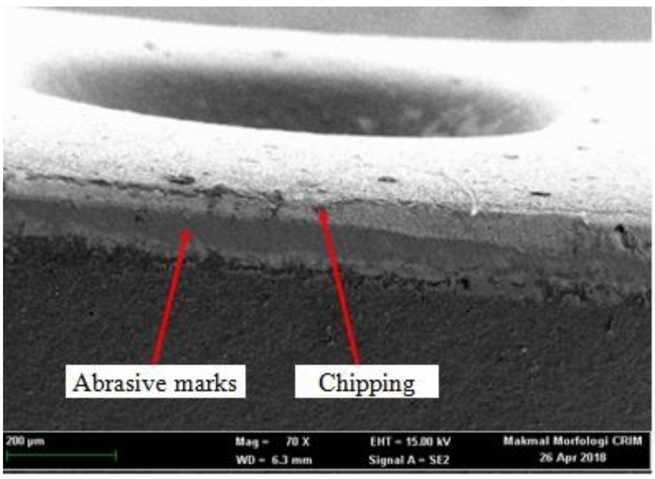


Figure 6. SEM image of the tool edge after the first cutting interval (experiment 1: machining time 0.3 minutes)

Once the *Ra* reached its peak point (as shown in Figure 4), it then continued with inconsistent readings. The resumption of cutting caused the chipping (as shown in Figure 6) to get bigger and deeper at the tool flank face due to continuous friction during sliding contact. At the same time, the dynamic cutting forces due to the intermittent milling process led to the growth of chipping. The build-up edge (BUE) was also observed adhering near the depth of cut line as shown in Figure 8(a). This condition was attributed to the adhesive wear mechanism where chips tend to weld at the cutting edge, thereby forming BUE. This is because Inconel 718 has strong adhesive properties at high temperatures which cause the chips to easily adhere to the hottest area of the cutting edge [27]. According to Kasim et al. [28], the area close to the depth of cut line is where the maximum force is exerted during the tool engagement with the workpiece. Thus, the cutting edge experiences the highest friction and temperature which are generated during cutting, which then results in rapid tool wear. This phenomenon causes the drastic increase of *Ra* as it is considered sensitive with the progress of the tool wear.

Observation of the wear pattern along the cutting process revealed that the BUE appeared at irregular intervals and caused inconsistent readings of *Ra*. The BUE was removed either by the repetitive cyclic load of the milling process or by the high-pressure flow of cryogenic CO_2. When detached, the BUE dragged along the coating material resulting in the delamination of the coating materials which exposed the base material of the tools. Sliding of the uncoated tool over the workpiece increased tool wear and resulted in notching at the flank face as shown in Figure 8(b). By referring to Figure 4, as the *Vbmax* exceeded 0.14 mm, the *Ra* slowly reduced and stabilized. The same phenomenon was reported by Li et al. [29] when cutting Inconel 718. The notching on the flank face caused the position of the tool's trailing edge has further gone down close to the machined surface. During cutting, it acted as a wiper where its polishing action removed the peaks of the feed marks (as shown in Figure 3) due to the kinematic effect of the ball nose-shaped insert. This situation continued with the better and stable values of *Ra* as well as the increase of notch wear.

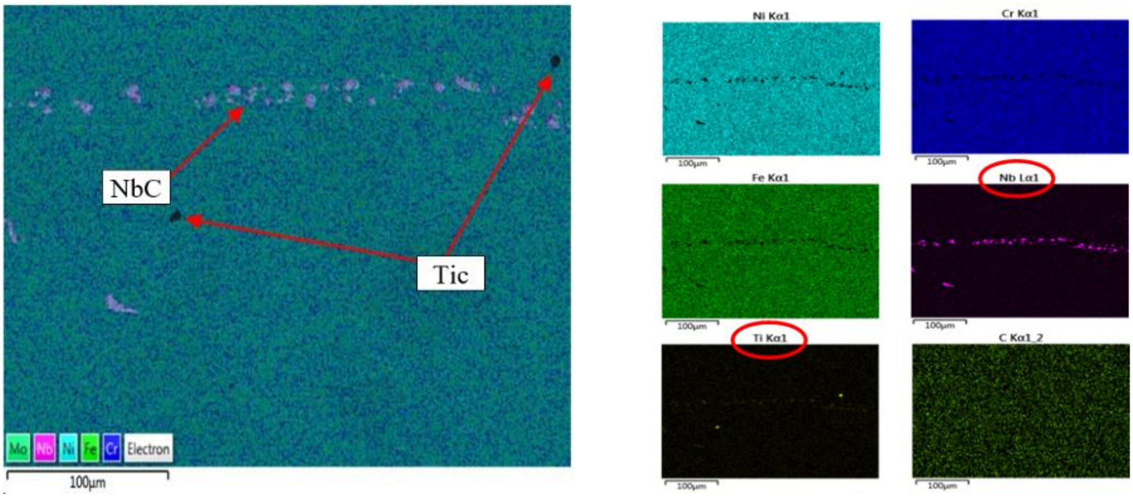
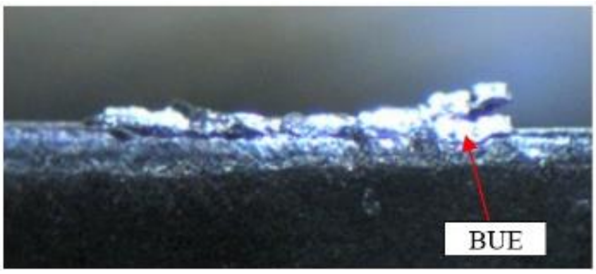
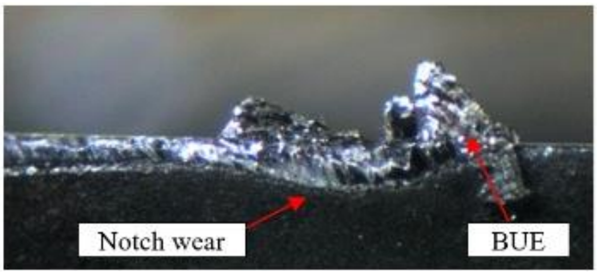


Figure 7. EDAX element mapping images of the workpiece to identify the NbC and TiC particles in Inconel 718



(a)



(b)

Figure 8. BUE adhering near to the depth of cut line of insert (experiment 1); (a) machining time 6 minutes, and (b) machining time 12 minutes

Nevertheless, the three stages of *Ra* progress cannot be matched with the finding in experiment 2 due to the rapid tool wear rate. Thus, the *Ra* progress was directly correlated with the tool wear patterns as in Figure 9. As shown, the first cutting interval produced the highest *Ra* at 0.195 µm due to severe chipping and pitting along the tool edge, while the increase in wear rate and formation of BUE caused the *Ra* to increase drastically and reach its peak point at 0.333 µm at *Vbmax* approximately 0.1 mm. The formation of notching also helped to reduce the *Ra* as in experiments 1 and 3. This finding indicates that the increase in feed rate and axial depth of cut increases the *Ra* and tool wear rate significantly. It may be attributed to the increase in the size of cut and the cutting load per tooth [3] which directly increase the generation of heat and friction force during cutting.

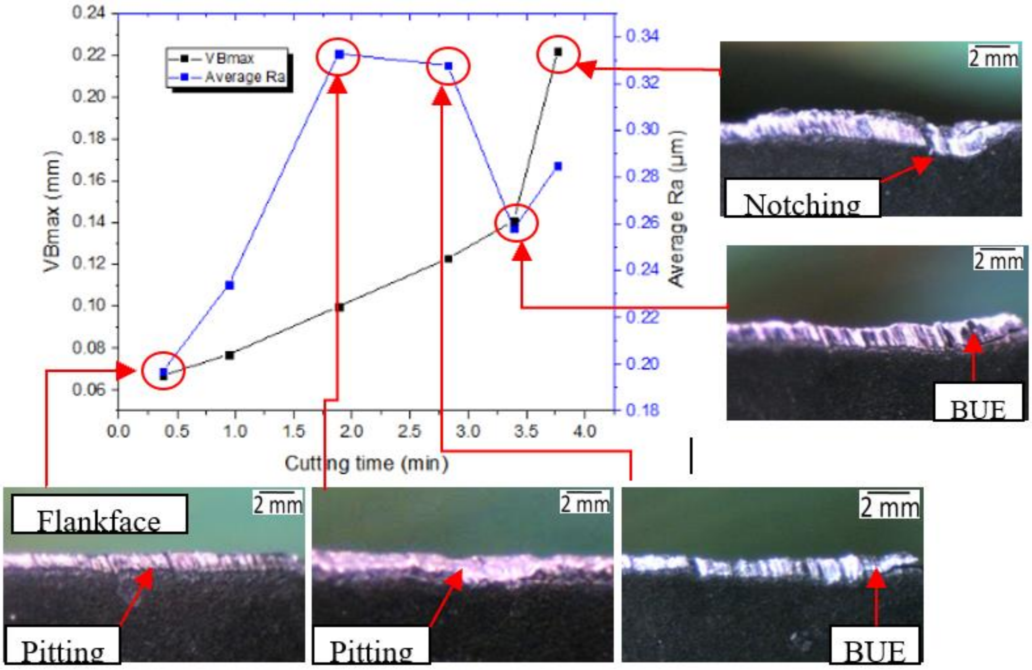


Figure 9. Progression of *Ra* with respect to tool life and notch wear rate (*Vbmax*) at experiment 2

4.0 CONCLUSIONS

This paper examines the correlation between surface roughness (*Ra*) and tool wear pattern when conducting high-speed milling Inconel 718 using a new cryogenic CO_2 cooling system. Through the experimental works, it was found that:

1) The range of *Ra* obtained was from 0.123 – 0.195 µm which is near the superfinishing condition (<0.1 µm). The efficient cooling effect from the cryogenic flow of CO_2 and the use of ball nose milling inserts produced significantly better *Ra*.
2) Experiments 1 and 3 showed approximately similar *Ra* progress which can be identified into 3 main stages: rapid increase, inconsistent and stable conditions.
3) There was a significant correlation between the tool wear rates and patterns with the *Ra* as its progression showed it was highly influenced by cutting tool edge condition which generates friction and heat at chip-tool and workpiece-tool interfaces.
4) Experiment 2 indicates that the increase in feed rate and axial depth of cut significantly increased the *Ra* and the tool wear rate as it also increased the generation of heat and friction force during cutting.

Future study endeavours might focus on the different techniques of supplying the cryogenic CO_2 coolant such as the location, distance, and size of the nozzle, as well as the flow rate of the coolant. The main aim will be to improve the effectiveness of the cryogenic CO_2 cooling system so that it can be used in a more effective, consistent, economic, and sustainable way.

5.0 ACKNOWLEDGEMENTS

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