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The effects of dry and chilled air on tool wear behavior during face milling of Inconel 718

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KEYWORDS

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Dry cutting condition
Flank wear
Optimization

ABSTRACT

Tool wear is one of the important criteria during the cutting process. It is mostly caused by the machining parameters, namely; cutting speed, feed rate, depth of cut, cooling condition, etc. This paper presents the behaviour of cutting tool during dry and chilled air condition of face mill with the cutting speed of 20 to 40 m/min, the feed rate of 0.1 to 0.2 mm/tooth and axial depth of 0.1 mm. The analysis of variance (ANOVA) is applied to identify the significance of these factors effect on tool performance, later the mathematical model for the tool life prediction was developed. The investigation revealed that the cutting speed, feed rate dominating wear rate whilst the chilled air found to be marginally significant. Finally, the optimum condition for machining parameter for greater tool life can be obtained by the combination cutting speed of 20 m/min, the feed rate of 0.1 mm/tooth under chilled air condition. Implementation of chilled air contributed 7% improvement with 45 min compared to a dry condition. The study exhibited the round type insert of dry face milling is more prone to rapid flank wear than chilled air with no BUE appearance on the tool cutting edge.

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1.0 INTRODUCTION

Inconel 718 is prominently known as a special material that has a certain characteristic which is highly in demand in a critical application. This nickel-based alloy has been widely used in aerospace component especially in turbine blade component due to the ability of the material to withstand at wear, corrosion environment and elevated temperature, thus 50% of engine component was made of this material (Krain et al., 2007). The drawback is poor machinability which is a major challenge during the cutting process. Inconel 718 material has generally known as a hard material to be machined, where it is 16, 6 and 4 times more difficult than aluminium, mild steel and stainless steel respectively (Ezugwu *et al.*, 2005; Li, Zeng and Chen, 2006). The presence of carbide particles (CrC, TiC, WC) as an alloying element to serve creep resistance tendency of abrading on the rake and flank face of the cutting tool which results in high tool wear (Krain et al., 2007; Sharman et al., 2015). Most of the common problems arise during machining Inconel was a flank wear, notch wear, crater wear (Jawaid et al., 2001). Because of having some criteria as the hardest material, all these wear frequently noticed during the machining process and will cause a deterioration of the cutting tool geometry. According (Liao and Shiue, 1996), the formation of build-up edge will make the cutting performance becomes worse by increasing the flaking formation and also notch wear. All these formations were unpredictable problems that will occur during machining process and obviously can lead to the premature tool failure (Kasim *et al.*, 2013). Some complex part structure requires milling operation. Most of the literature reported that the cutting speed, feed rate and depth of cut majoring in cutting tool life (Astakhov, 2006; Rao et al., 2013; Saleh and Ranjbar, 2018). However, less literature reported on face mill. The appropriate combination parameter is crucial so that the machining of Inconel can be done economically and effectively (Janos and Mrkvica, 2012). It is important to have a sharp cutting tool in order to obtain good accuracy and surface finish that directly effect on the quality of machined parts (Othman et al., 2018).

For milling process, the temperature generated generally lower than turning process due to friction between tool-chip and tool-workpiece that occurs intermittently. Since this material is high-temperature hardness, the material hardness increases as the temperature increase at the specific point of 650^{0}C (Chen et al., 2014). Since the material possesses low thermal conductivity, it was desired to put the cutting temperature at a minimum. Research done by (Kasim et al., 2014) indicated the temperature under minimum quantity lubrication (MQL) ranging from 68 to 359^{0}C while a study done by Ueda et al. shows that the temperature during dry milling can reach 660^{0}C. The other machining strategy by the application of cutting fluids that promisingly improve productivity and quality of parts. The cutting fluids cool down the cutting zone, reduce friction, and wear, enhancing tool life and remove chips from the workpiece (El Baradie, 1996; Ahmad-Yazid et al., 2010; Shankar et al., 2017). However, the negative effects of cutting fluids are disposal management and setup cost, human health and the environmental issue that creates another serious problem (El Baradie, 1996; Kalpakjian and Schmid, 2009). Thus there is a strong demand to minimize the use of coolants. The application of chilled air via vortex tubes is an alternative solution which is more economical and green.

There is numerous research has been done associate to vortex tubes application. Vortex tubes have been used as cooling and heating tool in many operations, thermal tests (Balmer, 1988; Markal et al., 2010; Xue et al., 2010), dehumidification, gas liquefaction, ice production and mixture or energy separation (Aydin and Baki, 2006; Xue et al., 2011) in chemical, gas and oil and gas research (Khodorkov et al., 2003) and in advanced space transportation systems (Crocker *et al.*, 2003). Besides that, (Yalçın et al., 2009) applied in milling machining. (Gao *et al.*, 2005) used it in the cryogenics area while, and (Eiamsa-ard and Promvonge, 2008) applied in the renewable energy area.

The application of chilled air system in the cutting process reduces the temperature in the vicinity of the cutting zone. Hence, it increases tool life, improves the surface finish and reduces the cutting forces (Rubio et al., 2015).

2.0 EXPERIMENTAL DETAILS

2.1 Machine and Workpiece Material

The tests were run on HAAS CNC Milling three-axis machine. The Inconel 718 AMS 5663 grade was used in this experiment conducted. The workpiece block has dimensions of 154 mm x 52 mm x 105 mm (*l x w x h*). The chemical composition and mechanical properties of the workpiece material are listed in Tables 1 and 2, respectively. The cutting processes were done in the straight line of 154 mm as shown in Figure 1. The vortex tube was mounted close to the cutting tool and the output temperature was set to 15^{0}C. The value was selected due to the condition considered below than the standard room temperature for scientific experiments (Helmenstine, 2018).

Table 1: The chemical composition of the Inconel 718 (Hynes, 2018).

Chemical composition (%)											
Ni	**Co**	**Fe**	**Cr**	**Nb.Ta**	**Mo**	**Mn**	**Si**	**Ti**	**Al**	**C**	**B**
52.0	1.0	19.0	18.0	5.0	3.0	0.35	0.35	0.9	0.5	0.05	0.004

Table 2: Mechanical properties of Inconel 718 (Metals, 2018).

Test Temperature (°C)	**0.2% Yield Strength (MPa)**	**Tensile Strength (MPa)**	**% Elongation in 50mm**
93	1172	1407	21.0
204	1124	1365	20.0
316	1096	1344	20.0
427	1076	1317	19.0
538	1069	1276	18.0
649	1027	1158	19.0
760	758	758	27.0

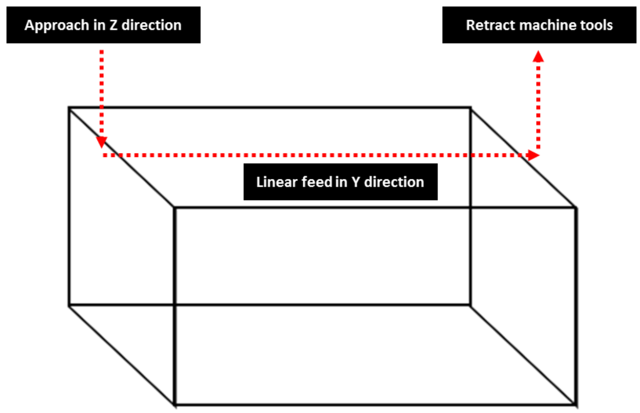

Figure 1: Schematic diagram of a machining process.

2.2 Cutting Tool and Measurement Instrument

Face milling operations was performed with a 50 mm diameter face mill cutter (Sumitomo, RSX 10050RS). The cutter can be fixed with five 10 mm dia. inserts. The inserts were TiAlN PVD coated carbide (ACM 300 grade – Roughing purpose) as shown in Figure 1. The tool having a hardness of 89.8 HRA and toughness of 3.4 GPa (SUMITOMO General Cataloque, 2018).

Figure 2: RDET 10T3 M0EN-G tool insert with 10 mm diameter.

These experiments were with two cutting conditions; dry and chilled air. The parameters range study based on the suggestion from tool manufacture (SUMITOMO General Cataloque, 2018) as shown in Table 3. The axial depth cut was set at 0.1 mm for the finishing process. It was similarly done by (Kurt, 2009) who investigated the cutting tool which recommends that value as to obtain minimum residual stresses on the workpiece. Based on full factorial approach as the design of the experiment, a total of 8 runs were performed throughout the experiment. For each runs, the fresh TiAlN PVD coated carbide cutting tool were used. The insert wears measured every subsequent cutting path by using toolmaker microscope. Experiment stops when the flank wear, VB_1 reaches defined tool life end (0.3 mm) as stated in the ISO 8688-2 (1989). The machining time to reach tool failure for the whole runs then is analyzed by the Design expert software.

Table 3: Factor and level used in the experiment.

Factors/Level	Minimum	Maximum
Cutting speed, Vc (m/min)	20	40
Feed rate, fz (mm/tooth)	0.1	0.2
Cutting condition	Dry	Chilled air
Axial depth of cut, ap (mm)	0.1	

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Variance

Table 4 shows the overall result where the maximum tool life of 46 min can be obtained by the combination of the lower side of parameter range. Chilled air, lower cutting speed and feed rate generally overperformed dry cutting condition, high cutting speed and feed rate respectively on tool life.

Table 4: Machining tool life obtained from the experiment.

Experiment No.	Cutting speed, Vc (m/min)	Feed rate, fz (mm/tooth)	Cutting conditions	Tool life (min)
1	20	0.10	Dry	44
2	20	0.20	Dry	20
3	40	0.10	Dry	27
4	40	0.20	Dry	16
5	20	0.10	Chilled air	46
6	20	0.20	Chilled air	24
7	40	0.10	Chilled air	34
8	40	0.20	Chilled air	18

Based on the ANOVA result in Table 5, the model is linear regression in which the model depicts significance with 95% of confidence level and F-value of 82.65. In this case, the feed rate is dominating on tool life followed by cutting speed and interaction cutting speed and feed rate. However, the cutting condition (chilled air and dry) found to be marginally significant.

Table 5: ANOVA for response surface 2FI model.

Source	Sum of squares	DF	Mean Square	F Value	p-value (Prob > F)
Model	9.36.38	4	234.10	82.65	0.0021
A-Cutting Speed	187.45	1	187.45	66.18	0.0039
B-Feed rate	675.67	1	675.67	238.54	0.0006
C-Cutting condition	27.80	1	27.80	9.81	0.0520
AB-Cutting speed and Feed rate	45.46	1	45.46	16.05	0.0279
Residual	8.50	3	2.83		
Cor Total	944.88	7			

By employing ANOVA, the relationship of the developed model has derived from a reduced 2FI model of tool life performance as summarized in Table 6.

Table 6: R^2 analysis for response surface 2FI model of tool life performance.

Response	**Index value**
Std. Dev.	1.68
Mean	28.88
C.V. %	5.83
R-Squared	0.9910
Adj. R-Squared	0.9790
Pred. R-Squared	0.9360

According to the statistical analysis, the developed model accords with the experimental data, model adequate, and has a satisfactory coefficient of determination (R^2) values of insert tool life. Likewise, some of the terms were set aside in the model despite it is insignificant since to preserve model hierarchy, for ensuring the reasonable agreement between the "Pred. R^2" and "Adj. R^2" also attain insignificant lack of fit. The results of R^2 were obtained 0.9910 and Adeq. Precision (AP)=23.893. AP greater than 4 is desirable, as it measures the signal to noise ratio. Hence, the linear regression models for tool life at two different cutting conditions are developed as:

$$\text{Dry condition} = 90.56 - 1.2\ Vc - 326.84\ fz + 4.77\ Vc.fz \quad (1)$$

$$\text{Chilled air condition} = 94.29 - 1.12\ Vc - 326.84\ fz + 4.77\ Vc.fz \quad (2)$$

The mathematical models that were given in Eq. 1 and Eq. 2 can be used to predict the life of the cutting tool by substituting the actual values of the respective process parameters. The developed response surface model for cutting tool life has also been investigated by the examination of using residual analysis. It is quite necessary to demonstrate that experimental data are found to be in agreement with the predicted results of the constructed model by Zhang et al. which by implementing coolant condition in dry milling, the tool wear of the cutting insert can be reduced. The normal probability plots of the residuals for the tool wear are shown in Figure 3. From the results, it indicates that displaced approximately in straight line, showing the error distribution is normal and observed results are consistent with those of predicted results. It confirms that the model proposed is adequate due to the residuals lie reasonably close to a straight line, giving support that terms mentioned in the model are the only significant.

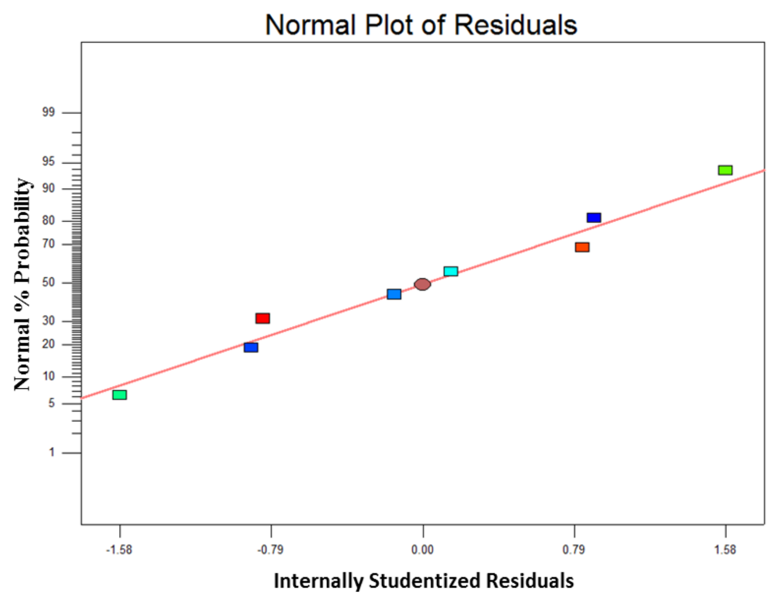

Figure 3: Normal plot of the residuals for insert tool life.

3.2 Effect of Parametric Study

Perturbation plots represent the influence of face milling factors on the cutting tool performance as dependent factors for two different type of cutting conditions. Figure 4 is related to the effect of independent factors on machining tool life. A steep slope for factor B (fz) is highly sensitive followed by factor A (Vc). In addition, the trends for factor A and B have a similar configuration. By increasing the respective parameter value, the tool life performance in minutes is reduced. Based on both results shown, Vc and fz has directly proportional on insert tool life, thus, it can be concluded that tool life has statistically significant effects and increases with the decreases of Vc and fz from 40 to 20 m/min and 0.2 to 0.1 mm/tooth respectively whilst in term of machining condition, the chilled air condition has better tool life rather than dry cutting condition in milling process (Figure 4).

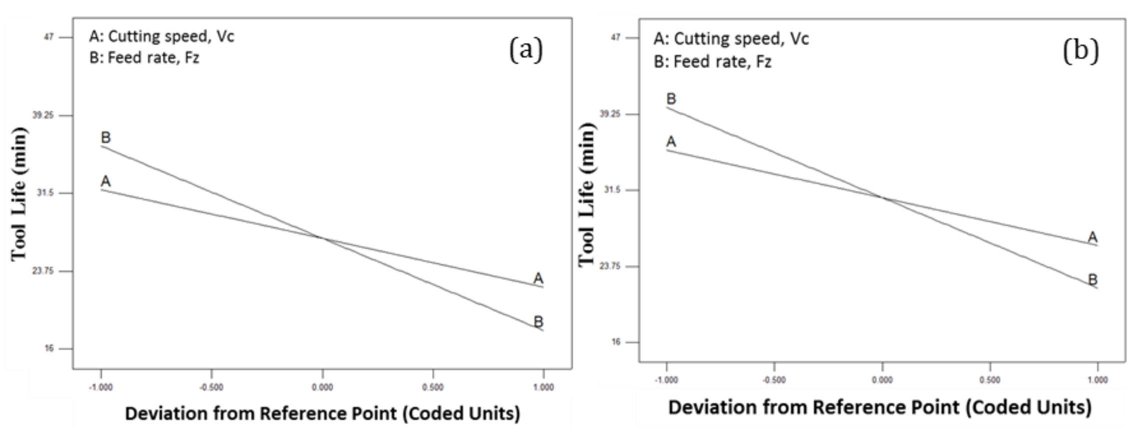

Figure 4: Perturbation plot for machining tool life (a) Dry condition (b) Chilled air condition.

Based on ANOVA results in Table 5, the percentage contribution evaluation of most of the factors was found to be a significant effect on the tool life. The feed rate seems to be highly significant with the highest percentage contribution ratio (PCR) of 72.20% (Figure 5). It was followed by cutting speed of 20.0%, while the interaction of cutting speed and feed rate of 4.8%. Finally, the effect of chilled air and dry (factor C) only contributes 3.00% to the response.

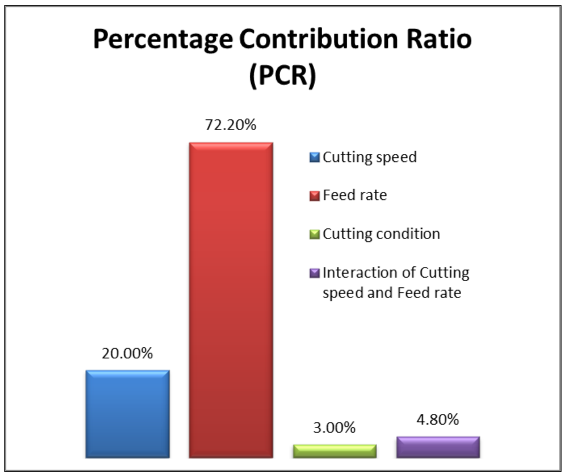

Figure 5: The PCR for each factor.

From the observation revealed that feed rate is the most contribution factor in determining cutting tool life. During machining, the temperature generates significantly low even during dry condition. As a result, low cutting feed leads to the corresponding decrease in the normal contact stress at the tool-chip interface and in the tool-chip contact area thus drops in temperature. It was in line with the research done by other researchers eg. Khan *et al.* (2012) and Kuram *et al.* (2013).

It was also notified that cutting speed less effect on tool life. The tool wear increases with the increasing cutting speed which reflects the chip flow on rake face. The temperature generated by the friction on the chip-tool interface softening cutting tool. Since the lower thermal conductivity characteristics of Inconel 718, the temperature localized in the vicinity cutting area, resulting in thermal softening which reduces the material strain hardening capacity. The shear instability takes place to cause plastic deformation of tool tip and wear on flank face. However, crater wear has not been observed when cutting with both chilled and dry conditions. This is because the temperature occurred does not reach diffusion temperature stage.

By means, Taha *et al.* (2013) justified which the application of cutting fluids significantly extend the life of the cutting tool rather than in dry states. E Kuram *et al.* (2010) agreed that the application of coolant capable to improve the tool life and surface finish by reducing thermal distortion and flushing away of machined chips. The primary deformation zone is significantly heated and bears high cutting force at dry state. By the implementation of cutting fluid, the friction between the tool-workpiece engagements is greatly reduced. Hence, minimizing the cutting force. Moreover, the cutting fluid allows to reach the processing area and carry away more cutting heat, which favours chip flowing and can effectively prevent the accumulation of cutting heat.

3.3 Response Surface Model of the Interactive Effect

Besides the individual terms that have been found significant, ANOVA results also initiate the significant among the factors as illustrated in Figure 6 with the confidence level is less than 0.05. According to ANOVA, the feed rate is dominating factor compared than cutting speed. Cutting speed and feed rate decrease trend line at low to the high value of interacted conditions. However, the maximum tool life can be achieved at high feed rate (0.1 mm/tooth) with less slope of cutting speed (20 m/min). For the dry condition in Figure 6(a), maximum tool life can be achieved is 44 min whilst chilled air condition as shown in Figure 6(b) indicated the greater tool life possibly achievable than dry cutting with 46 min.

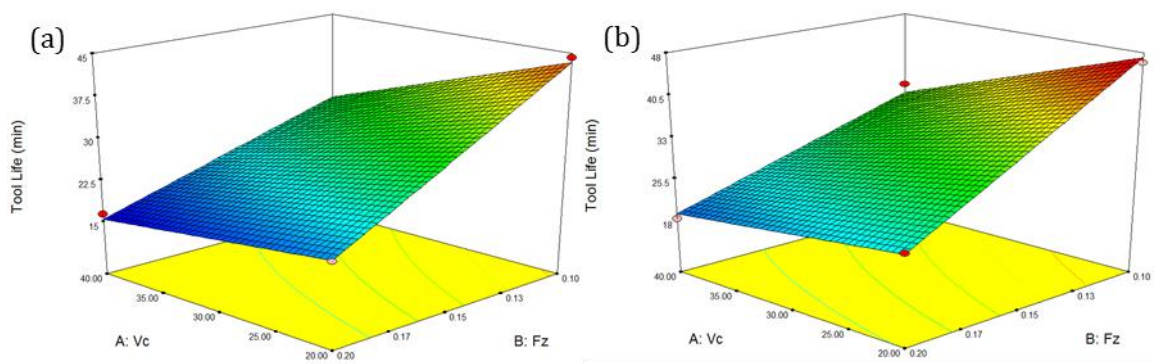

Figure 6: Response surface plots (3D) showing the effects of Vc and fz on machining tool life performance (a) dry condition (b) chilled air condition.

The results show supported by (Aspinwall *et al.*, 2007) which the high cutting speed will generate high cutting force and adversely affect the tool life. Due to poor conductivity of Inconel characteristics, the heat generated cannot be dissipated easily. Thus, the workpiece maintains high strength at high temperature especially on cutting tool-chip-workpiece interface. This phenomenon typically happens during high cutting speed and feed rate which are leads to high cutting forces and produce high temperatures due to material volume to be removed in the shear zone which cause plastic deformation of the cutting tool edge (Krain et al., 2007) and hence, will cause rapid tool wear during machining process (Li, Zeng and Chen, 2006).

3.4 Optimization of Tool Life

In this research work, the desirability function approach has been selected for optimization technique, which allows the multi-objective optimization. The desirability provides the estimation according to the responses calculated by the statistical model. Higher desirability value represents the better optimization of the response.

The goal of the optimization in this study is to maximize the machining tool life. The objective optimizes of tool life was offered by Factor A (20 m/min), Factor B (0.1 mm/tooth) and Factor C (Chilled air condition) that resulted in the highest desirability as much 1.000 for 47.16 min. Table 7 presents the optimal solutions and its confirmation experiment for achieving the maximum tool life.

Table 7: Optimal solutions generated for tool life response.

Optimum parameter			**Predicted response (min)**	**Experiment response (min)**	**% of error**	**Desirabili ty**
Factor A (m/min)	Factor B (mm/tooth)	Factor C				
20.00	0.10	Chilled air	47.16	45.01	4.56	1.000
20.00	0.10	Dry	43.43	42.07	3.13	0.904

Table 5 also showed the result validation of the experiment executed to confirm the actual tool life performance. According to (Cetin *et al.*, 2011), the predicted values and the experimental values are very close to each other. The reliable statistical analyses, error value must be less than 20%. (Hills and Trucano, 1999) supported in which acceptable percentage of error for any engineering experiments is should be less than 10%. Therefore, in these confirmatory trials, the error between the results of prediction and actual experiments for chilled air condition is 4.56% whilst dry condition is 3.13%.

3.5 Tool Wears Progression During Face Milling

The growth of flank wear over the cutting time was recorded and is shown in Figure 7. The wear trend was consistent with the pattern reported by others. A uniform (VB) for comparison of tool wear under dry and air-cut was recorded. From the observation, the growth of flank wear trend increased steadily with increases of cutting length. It is seen, when chilled air was jetted to the cutting zone at 15ºC, dry-cut exhibited a good tool life in 42 min and 16 min in cutting time at cutting condition; Vc, 20-40 m/min and fz, 0.1-0.2 mm/tooth respectively, only 3 min shorter than air-cut. Both conditions show the higher flank wear was observed during dry-cut condition. The differences in performance between the cutting conditions at minimum cutting speed and feed rate, the air-cut improved up to 7% of the machining tool life. However, a different trend was observed at maximum cutting speed and feed rate. Under chilled air cutting conditions, the tool wear was low, thus improved the TiAlN PVD tool life up to 18%.

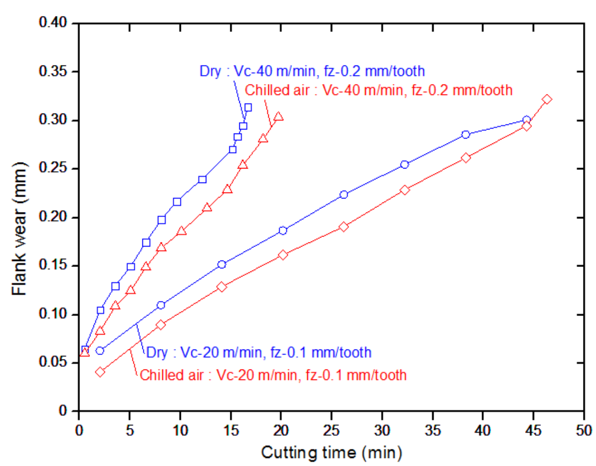

Figure 7: Measured flank wear progression during the face milling of Inconel 718. Vc=20-40 m/min, fz=0.1-0.2 mm/tooth, ap=0.1 mm.

Welding and adhesion of the worked material onto the cutting tool, which frequently occur during machining, are the predominant factors affecting the tool tip performance from the consequent pull-out of coating and tool substrate. The life span of the cutting tool was determined from the tool wear, as a worn cutting tool may affect the surface quality. In milling, the cutting tool is subjected to a rubbing process, and the friction between the cutting tool and the workpiece generates heat. Abrasion and adhesion were the main tool wear mechanisms, and a BUE is formed by high pressure on the tool tip.

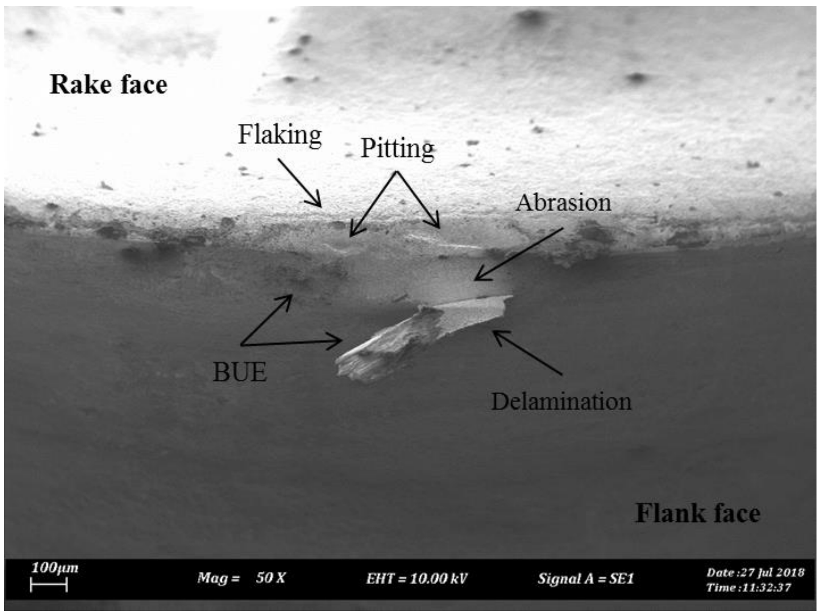

Figure 8: Flank wear at cutting condition, Vc, 20 m/min; 0.1 mm/tooth; dry-cut. Flaking, pitting, delamination and BUE form on the flank face near the DOC line.

Figure 8 shows a very smooth wear was observed near the tool tip region. The observed wear mechanisms were abrasion, BUE, pitting, and delamination. The abrasive wear was caused by the rubbing action between the cutting tool and the workpiece. During dry-cut, excessive BUE intermittently occurred on the flank face near the DOC line. The BUE often leads to chipping of the tool cutting edges (Xavior *et al.*, 2017).

Besides, pitting problem is observed on the tool tip region at cutting speed (40 m/min) and feed rate (0.2 mm/tooth), which occurs during interrupted machine operation and is typically found; a similar situation was reported by (Kramer and von Turkovich, 1986; Sharman et al., 2001). The pitting problem will enlarges to form chipping (Figure 9). Increases of Chipping and abrasive wear will form notch wear a groove that occurs at both the flank and rake faces of the cutting tool near the DOC line (Kasim *et al.*, 2013).

Figure 8 also shows the detail of the tool damage on the DOC line, which consists of abrasive wear on the flank and rake face, cavities that expose the base material and delamination of the TiAlN PVD coating that ruins the original shape on the tool tip region. The base material was covered with some adhering residual chips of the Inconel 718 material during chip flow.

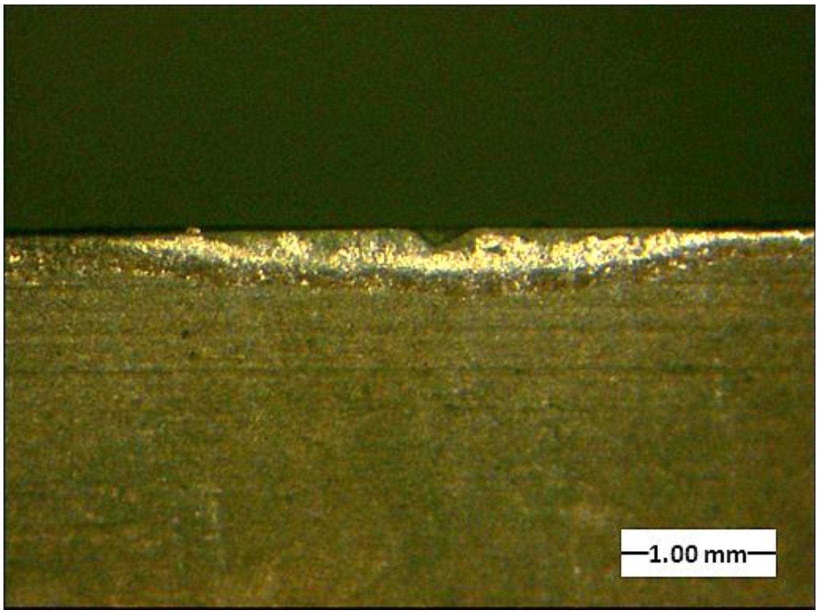

Figure 9: Chipping problem when milling Inconel 718 with a round type TiAlN insert.

The reduction of the tool wear by chilled air was attributed to the reduction in cutting temperature which contributed to reduce abrasion wear by the maintenance of tool hardness and adhesion wear. Gases have relatively poor cooling ability due to their low specific heat and heat conductivity. However, poor cooling ability of compressed gas can be improved by refrigerating it to generate a greater temperature difference between the cutting zone and the incoming gas (Su *et al.*, 2007). In the 15 ^{0}C air-cut machining of difficult-to-cut materials, the chilled air was jetted to the cutting zone at a low temperature and dissipated the heat produced by the cutting process by means of convection. The gradient of the temperature of the cutting tool near the vicinity of the DOC line can be observed, which corresponds to the highest contact area and friction between the cutting tool and the workpiece, as also observed by Lorentzon et al., (2009).

The chilled air is significantly reduced the tool wear because the wear rate depends largely on the temperature, this location exhibits the most severe flank wear along the cutting edge (Figure 8). The rest of the cutting edge wear rate was relatively acceptable because of the effect of chilled air by reducing the temperature at the cutting tool interface. By means, the forced convective heat transfer becomes higher. Although the improvement between the cutting parameters are extremely small (7%), which might be because the difference between one cutting parameter (cutting speeds, 20–40 m/min; feed rates, 0.1–0.2 mm/rev) to each other are relatively small. However, the graph in Figure 7 shows that the use of chilled air is predominant on improving tool wear as the cutting speeds lower, thus prolong the life span of the cutting tool.

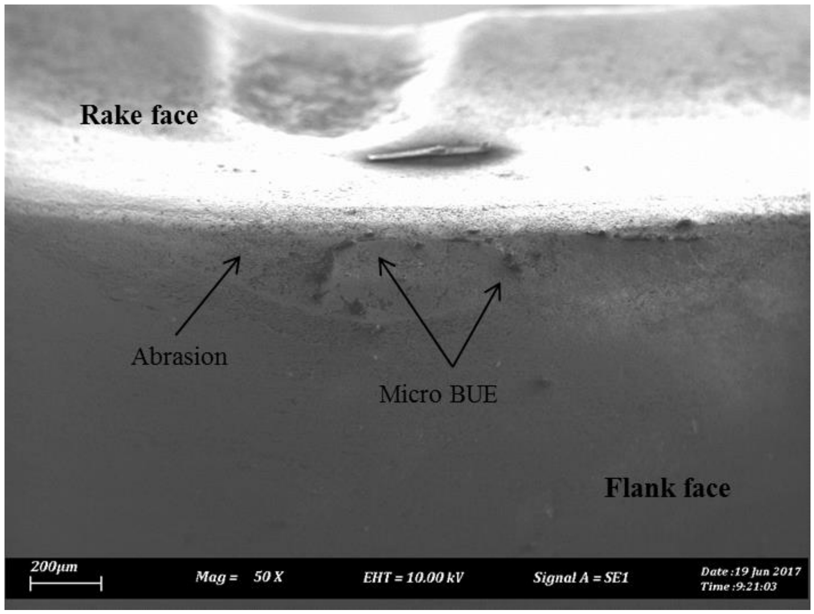

Figure 10: Flank wear at cutting condition, Vc, 20 m/min; 0.1 mm/tooth; dry-cut. Micro BUE form on the flank face near the DOC line.

The findings are significant with Su and his team who had conducted a comparison of three cooling systems (dry machining, MQL and cold compressed air) in a high-speed milling using Nickel-base alloy. As the main conclusion, the machining by implemented air as the cutting fluid was able to extend the tool life up 78% compared with the dry and it was slightly better than the system of MQL (Su *et al.*, 2007). However, there are some authors mentioned, advantages were no found when working at low cutting speeds but, at high cutting speeds the tool wear was significantly reduced. Therefore, compressed air system seems to be a good alternative for machining high-speed (Sarma and Dixit, 2007). By referring to the experiment that runs in high cutting speed, 40 m/min with a feed rate of 0.2 mm/tooth, the comparison made between the dry and air process, there can be seen a high difference of tool life produced from the air process versus the dry. The method that using a chilled air system provide a long tool life during the face milling process of Inconel 718.

4.0 CONCLUSION

The design of experiment such as full factorial method was used to explore the effects such as cutting speed, feed rate, and cutting conditions during face milling of Inconel 718 on tool life (TiAlN). Through variance analysis that has been conducted, it was found that factors which are cutting speed and feed rate are significantly affected whilst cutting conditions is marginally effects on the machining performance. Among that these three factors, it was found that feed rate (fz) was the factor that most affects the response. From the studied, optimization combination with 20 m/min cutting speed and 0.1 mm/tooth of feed rate by implementing chilled air conditions gives the optimum tool life (45.01 min). By means, the air condition helps to improve the dry cutting up to 7%. As the feed increase, the heat will generate in the cutting zone that will cause the deformation of cutting tool edge and significantly the tool will start to wear rapidly. In addition, the use of compressed air as an alternative of the coolant system, it will reduce the high temperature in the cutting zone area and at the same time control the temperature from generating more heat that will cause a plastic deformation of the cutting tool edge.

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