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Tool Life of TiAlN PVD Coated Carbide Tool in High-speed End Milling of Untreated Inconel 718 under Minimum Quantity Lubrication Condition

(Jangka Hayat Perkakas Pemotong Berkabida Bersalut TiAlN Menggunakan Pengisar Hujung untuk Bahan Inconel 718 yang Tidak Dirawat dalam Keadaan Pelinciran Kuantiti Minimum)

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ABSTRACT

This paper presents the tool life of the end milled Inconel 718, which is part of a material that is difficult to be machined. Previous researchers found that tool life in machining aged Inconel 718 is shorter compared with other materials. However, this observation required further investigation. Thus, a raw grade Inconel was proposed in this experiment. The experiments were performed using TiAlN-coated carbide. The studied milling parameters were the cutting speed, V_c, from 90 to 150 m/min; feed rate, f_z, from 0.15 to 0.25 mm/rev; depth of cut, a_p, from 0.3 to 0.5 mm; and radial depth of cut, a_e=1 mm. The application of the cutting fluid used in this experiment was a minimum quantity lubricant, which had the advantage of cooling effectiveness and low consumption of cutting fluid. The results showed that the feed rate, f_z, was the primary factor controlling the tool life. The combination of V_c=115 m/min, f_z=0.15 mm/tooth, as well as a_p=0.5 mm and a_e=0.15 mm gave the longest tool life that served 95.38 min in operation.

Keywords: Ball nose end mill; full factorial; Inconel 718; minimum quantity lubrication

ABSTRAK

Makalah ini membincangkan jangka hayat perkakas pemotong berkabida ketika mengisar hujung bebola bahan Inconel 718. Bahan ini secara umumnya diketahui sebagai salah satu bahan yang sukar dimesin. Kajian terdahulu mendapati pemotongan Inconel 718 yang dikerastua telah memendekkan jangka hayat pemotong. Ini memerlukan kajian lanjut dan Inconel 718 mentah dicadangkan untuk kajian ini. Uji kaji ini dijalankan dengan menggunakan pemotong berkabida bersalut endapan wap fizikal TiAlN. Parameter pemesinan melibatkan kederasan memotong V_c = 90-150 m/min, kadar suapan, f_z = 0.15-0.25 mm/rev dan kedalaman pemotongan sebanyak 0.3-0.5 mm. Mengambil kira keberkesanan kesan penyejukan dan penjimatan, uji kaji ini dijalankan dalam keadaan pelinciran kuantiti minimum. Kajian mendapati kadar suapan adalah faktor utama kesan terhadap jangka hayat. Melalui uji kaji ini, jangka hayat mata alat pemotongan telah direkodkan selama 95.38 min dengan parameter V_c = 115 m/min, f_z = 0.15 mm/gigi dan a_p = 0.5 mm dan a_e= 0.15 mm.

Kata kunci: Faktoran penuh; Inconel 718; pelinciran kuantiti minimum; pengisar hujung bebola

INTRODUCTION

The use of Inconel 718 has increased recently and become very popular in the aerospace industry. This nickel-based alloy is preferred in high-temperature applications for various reasons. First, nickel consists of a face-centered cubic (FCC) crystal structure, which makes nickel both tough and ductile. Nickel is stable in the FCC form from room temperature to its melting point; therefore, nickel does not experience phase transformation that causes expansion and contraction. Second, the diffusion rate of FCC metal is very low and microstructural stability is imparted at elevated temperatures (Reed 2006). As FCC metal can withstand extreme conditions, components made of this material are located at the final stage of the compressor and combustion chamber, whereas the titanium parts are usually located at the early stage of the compression region (air intake) (Reed 2006; Ulutan & Ozel 2011). However, this material possesses disadvantages in machining, including poor thermal conductivity, which causes localized high cutting temperature, increased strength at elevated temperatures and high chemical affinity leading to diffusion wear and work hardening. These properties contribute in shortening the cutting tool life (Kamata & Obikawa 2007). Moreover, the poor machinability of this nickel-based alloy is associated with galling tendency and welding on the tool rake face, as well as the tendency to form a built-up-edge, especially during low speed conditions. Lastly, the presence of hard abrasives and carbides in the microstructures accelerate tool wear (Alauddin et al. 1996; Ezugwu et al. 2005).

Inconel 718 has several grades, but most researchers use the aged grade, AMS 5663. However, this grade is harder than AMS 5662, which is the rawest state of 718 and the softest condition of the AMS group. AMS 5662 can be heat-treated into AMS 5663. The hardness of AMS 5662 is about 20 to 25 HRC, whereas AMS 5663 is about

36 to 44 HRC. Due to the difficulty in machining, some manufacturers prefer to machine their parts in AMS 5662 and later heat-treat these into the specified softness of the material. However, others prefer the opposite method, whereby the machining of the parts is done afterwards. Regardless of the method used, the same outcome of AMS 5663 is achieved (Alloys 2011).

Lubrication is used specifically to remove the chip and reduce the tool tip temperature. Due to environmental constrains, the usage of minimum quantity lubrication (MQL) became popular. The application of oil-based MQL may reduce the oxidation reaction in water during high temperatures. Moreover, from an economic point of view, the use of MQL is cost-effective, wherein the consumption of MQL is about 50 mL/h compared with the 1000 L/min in conventional lubrication. Some people disagree since the conventional coolant may be reused, unlike that of the MQL, which is only used once. However, an ordinary lubrication can only be used for a limited time, which is three to six months and must be replaced (Thepsonthi et al. 2009; Weinert et al. 2004).

Based on the previous studies, the typical wear mechanism observed at the milling end of Inconel 718 with the ball nose tool is the localized flank wear, VB_3. This is the maximum flank wear located near the depth of the cut line and is known as the depth of cut notching (Dudzinski et al. 2004; Krain et al. 2007; Li et al. 2006). Aspinwall et al. (2007) found that the radial depth of cut of more than 2 mm will affect the nature of wear that is dominated by the localized wear (notch wear) rather than the uniform flank wear. However, in their second experiment with a small radial depth of cut, the a_e of 0.2 indicated the absence of notch wear, even under a scanning electron microscope (SEM) analysis. The tool life recorded by Thamizhmanii (2009) was 130 min under an organic MQL condition compared with the results of Krain (2007) which recorded only 7.6 min using semi-synthetic lubrication. Dry machining was done by Alauddin et al. (1995) with a slightly better result of 9.5 min.

Methods

The workpiece material used for this experiment was Inconel 718, which was supplied in raw grade AMS 5662. The chemical compositions of this material include 53 wt. % Ni, 18.30 wt. % Cr, 18.7 wt. % Fe, 5.05 wt. % Nb, 3.05 wt. % Mo, 1.05 wt. % Ti, 0.23 wt. % Mn and C balance. The selected cutting tools were Sumitomo QPMT 10T335PPEN and a physical vapor deposition (PVD) TiAlN coat with fine grain tungsten carbide (10 wt. % Co). The 10 mm dia. insert was attached to the tool holder with a 16 mm diameter, a rake angle of -3°, a radial rake angle of 0° and relief angle of 11°. A tool overhang of 60 mm is maintained throughout the experiment and the measured tool run out has a radial measurement of 10 to 50 μm and an axial measurement of 5 to 30 μm (ISO8688-2 1989). The cutting experiments were performed on a DMC 635 V Eco CNC milling machine with a maximum spindle speed of 8000 revolutions/min. The position of the nozzles are shown in Figure 1.

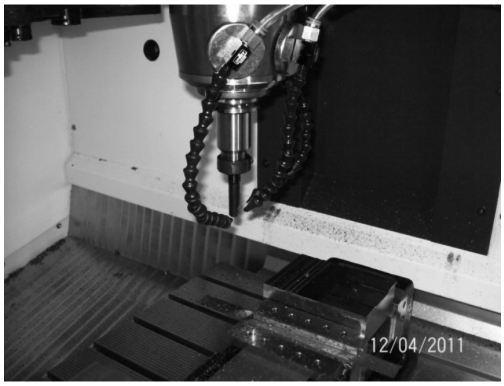

FIGURE 1. Position of MQL nozzles in the high speed milling

Before the experiment, the surface of the Inconel, with a block size of 160 × 100 × 50 mm, underwent a face milling of 0.5 mm to remove any surface irregularities and residual stress resulting from the production. This material is considered stable in ambient and elevated temperatures, thus, oxidation is not considered a critical issue. The hardness of the material was determined before skimming, which resulted in a difference of only 2 HRB. The hardness of Inconel was about 92 HRB when a ball indenter with 16 mm diameter size applied a 100 kg force. All experiments were done under MQL condition at a rate of 20 pulses/min to produce 50 mL/h. Flank wear was measured as wear progressed. Hence, the tool life criterion was dependent on the flank wear, as VB reaches 0.3 mm.

Tool wear was measured using a two-axis toolmaker's microscope attached with a digital micrometer for the x-axis and y-axis in 0.001 mm resolution. Every new layer underwent face milling and the initial and last cuts in the block will be done using a non-test insert to eliminate any influence of previous cutting effect on the work piece. The same set of inserts was used after each measurement. This procedure was based on the experiment done by Balazinski et al. (1995) that used the same set of inserts after each measurement for a longer tool life than using new inserts for every experiment. The tests performed were related to the finishing process, which involved the cutting speed, feed per tooth, as well as axial and radial depth of cut. A list of variable parameters is shown in Table 1.

TABLE 1. Variable parameter and test matrix

Factor	L1	L2
Cutting speed, V_c m/min	115	145
Feed rate, f_z mm/tooth	0.15	0.20
Axial depth of cut, a_p mm	0.50	0.75
Radial depth of cut, a_e mm	0.15	
MQL flow rate, mL/h	50	

Results and Discussion

From the experiment, the longest operation time with TiAlN was 95.38 min and the shortest tool life was 8.59 min as shown in Table 2. Figure 2 shows how the flank wear changes with respect to the cutting time. Based on the progression graph of flank wear, wear can be segregated into three phases: initial breakdown, steady wear rate and failure region. Generally, flank wear grows rapidly at the initial stage and remain constant after 0.150 mm. The growth rapidly increases after 0.270 mm until it reaches the rapid failure region. In general, the feed rate significantly shortens the tool life compared with the other two factors. The shortest tool life was recorded during the combination of high cutting speed and high depth of cut. Most of the failure modes are due to the notch wear. At the initial stage of machining, no significant variation on flank wear was observed. However, the notch wear appeared close to the depth of the cut line after several passes, which became the maximum peak of flank wear. Investigation on the cutting tool indicated that abrasion and chipping were located at the depth of the cut line as shown in Figure 3(a). The maximum effective cutting speed and the maximum cyclic load exerted toward the insert were suspected to contribute to the chipping. In contrast, to that near the tool tip region, the insert experienced lower cutting speed and load, with observed attrition and adhesion. Thus, Figure 3(b) shows the surface of the flank wear was finer near the tool tip region than that at the depth of the cut line.

TABLE 2. Experiment result using the full factorial method

Experiment no.	V_c (m/min)	f_z (mm/tooth)	a_p (mm)	Cutting time (min)	Remark
1	145	0.2	0.75	8.59	Minimum
2	145	0.15	0.5	60.13	
3	115	0.15	0.75	70.28	
4	115	0.2	0.75	46.22	
5	145	0.15	0.75	51.34	
6	115	0.15	0.5	95.38	Maximum
7	115	0.2	0.5	61.16	
8	145	0.2	0.5	49.89	

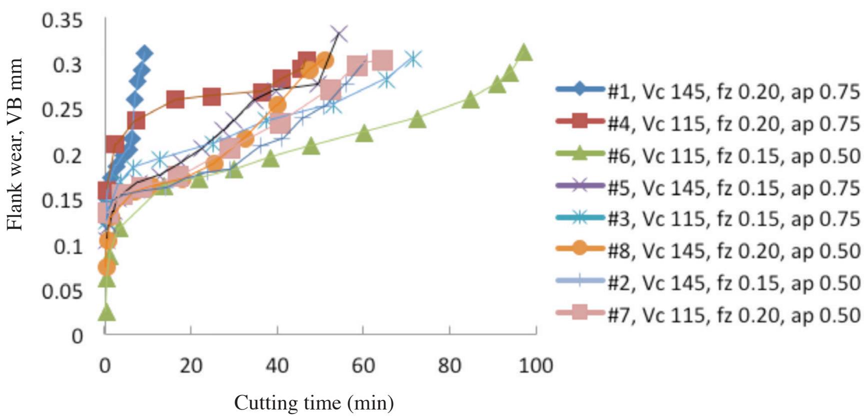

FIGURE 2. Flank wear development of PVD coated in milling Inconel 718, at various parameters

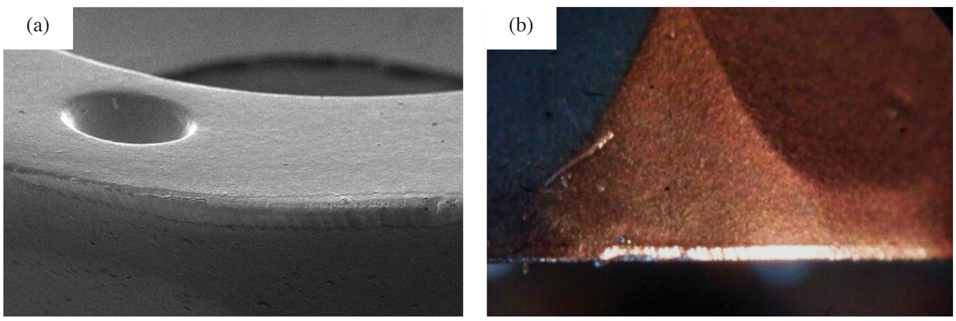

FIGURE 3. Typical tool wear mode during machining Inconel 718 (a) SEM image of chipping, abrasion, adhesion and attrition on cutting edge and rake surface (b) microscope view

The interaction effect of the cutting speed and feed rate is shown in the three-dimensional graph in Figure 4. Increasing the feed rate reduces the tool life at any point of the cutting speed. Figure 5 shows the interaction effect between the axial depth of cut and cutting speed. Increasing the cutting speed and axial depth of the cut reduces tool life. Figure 6 shows the interaction between the feed rate and axial depth of cut. Based on the results, a longer tool life is achieved with the reduction of the machining parameters, feed rate and axial depth of cut.

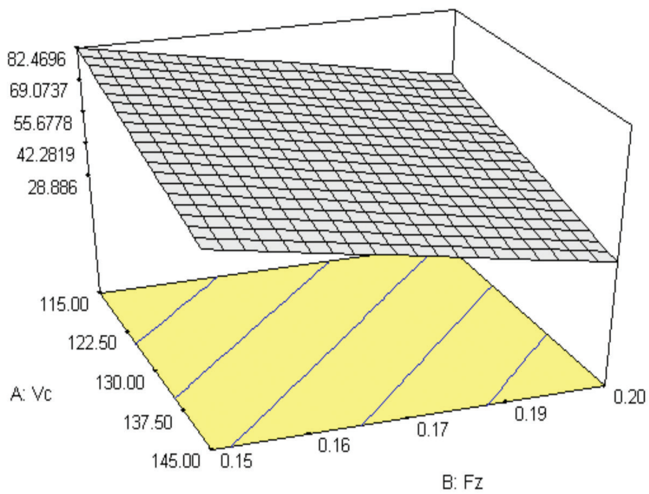

FIGURE 4. Interaction effect between cutting speed and feed rate

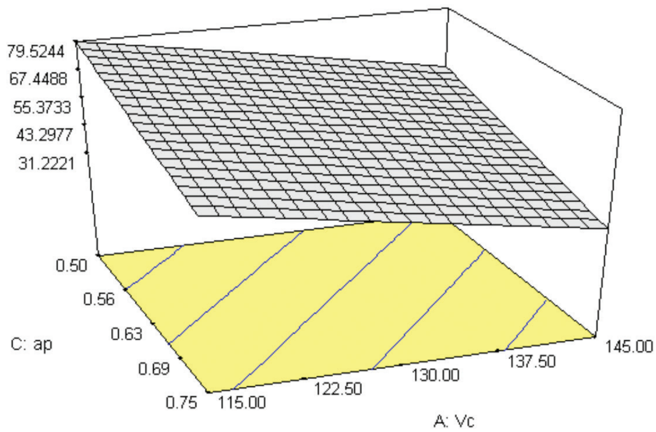

FIGURE 5. Interaction effect between axial depth of cut and cutting speed

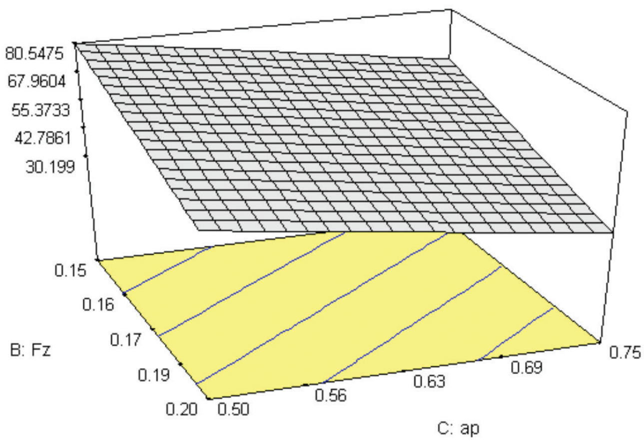

FIGURE 6. Interaction effect between feed rate and axial depth of cut

The analysis of variance (ANOVA) results (Table 3) indicate that the cutting speed, feed rate and axial depth of cut are significant at the 5% level and therefore, have a major effect on tool life. The coefficient of correlation is in accordance with the R^2 of 0.9271 and the adjusted R^2 of 0.8724. The predicted R^2 of 0.7084 is in accordance with the adjusted R^2. An adequate precision of 12.307 indicates an adequate signal that is greater than 4, which is considered desirable.

The regression parameters of the postulated models were estimated using the basic formula of the following linear model:

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3, \quad (1)$$

Then, the linear model for predictive tool life equation is expressed as;

$$T = 320.72396 - 0.85896\, V_c - 556.29804\, f_z - 90.13447\, a_p. \quad (2)$$

The comparison between the observed and calculated data of the mathematical modeling (2) are shown in Figure 7. Considering the objective for this study of determining the longest tool life that can be achieved within the predetermined parameters, the maximum values that can be reached statistically are $V_c = 115$, $f_z = 0.15$, $a_p = 0.50$, $a_e = 0.15$ to obtain a tool life of 93.40 min. Figure 8 shows the point of the longest tool life in the parameter setting.

CONCLUSION

This study demonstrated that TiAlN carbide tool life in the end mill of Inconel 718 were from 11 to 95.38 min. The maximum tool life was achieved when cutting was performed at a Vc of 115 m/min, fz of 0.15 mm/tooth and ap of 0.5 mm. All the factors, namely, cutting speed, feed rate, and depth of cut, determined tool life significantly (p<0.05). However, the feed rate was the statistically dominating factor among the parameters (p = 0.0108; F-value = 20.23). The result showed that the significant localized flank wear, VB3, was the predominant failure mode. Moreover, fine cracking, flaking and coating delamination were also detected. Abrasive wear appeared as the effect with the most contribution in creating flank wear. The other wear mechanism, micro chipping, occurred frequently at the line depth of cut that contributed toward notch wear.

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TABLE 3. ANOVA results for tool life (min)

Response: Tool Life

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F-value	P-value	
Model	3890.92	3	1296.973	16.95343	0.0097	significant
A	1328.055	1	1328.055	17.35972	0.0141	
B	1547.338	1	1547.338	20.22608	0.0108	
C	1015.528	1	1015.528	13.27451	0.0219	
Residual	306.0084	4	76.50211			
Cor Total	4196.929	7				

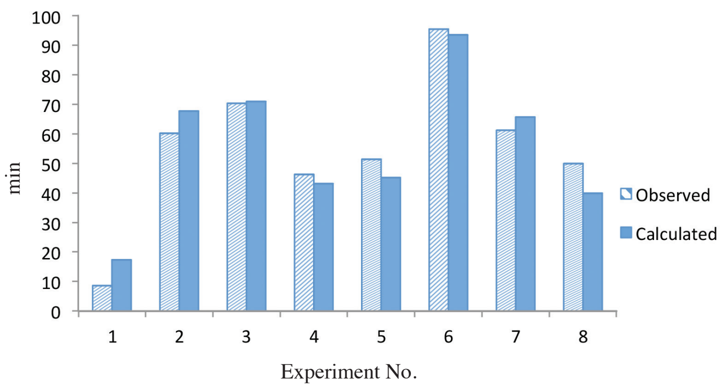

FIGURE 7. Experiment results and confirmation of the equation

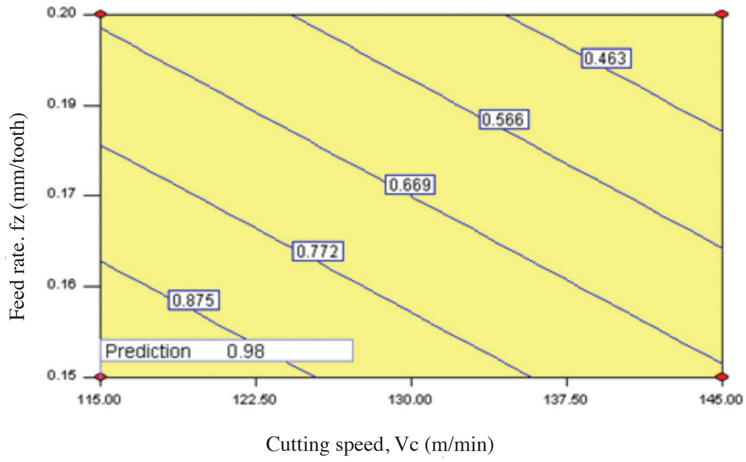

FIGURE 8. Contour plot of the statistically recommended parameters to obtain the longest predicted tool life within the parameter limit, where $a_p = 0.50$ and $a_e = 0.15$

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