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Investigation on Wear Behavior and Chip Formation During Up-Milling and Down-Milling Operations for Inconel 718

M. A. Hadi[a], J. A. Ghani[a*], C. H. Che Haron[a], M. S. Kasim[b]

[a]*Department of Mechanical & Materials Engineering, Faculty of Engineering and Built Environment, University Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia*

[b]*Department of Process, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 75450 Melaka, Malaysia*

*Corresponding author: jaharah@eng.ukm.my

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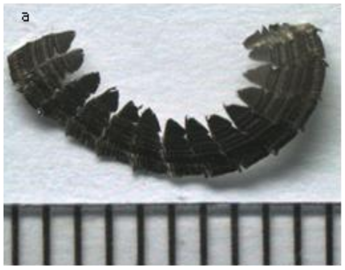


Abstract

A comprehensive study and FEM simulation of ball nose end milling on tool wear behavior and chip formation had been performed on Inconel 718 (nickle-based superalloy) under minimum quantity lubricant (MQL) condition. In this paper, the investigation was focusing on the comparison of up-milling and down-milling operations using a multi-layer TiAlN/AlCrN-coated carbide inserts. A various cutting parameters; depth of cut, feed rate and cutting speed were considered during the evaluation. The experimental results showed that down-milling operation has better results in terms of tool wear compared to up-milling operation. Chipping on cutting tool edge responsible to notch wear with prolong machining. It was observed that the chips formed in up-milling operation were segmented and continuous, meanwhile down-milling operation produced discontinuous type of chips.

Keywords: Inconel 718; FEM; up-milling; down-milling; tool wear; chip formation

Abstrak

Kajian komprehensif dan simulasi FEM terhadap sifat kehausan tip bebola hujung mata mesin larik telah dilakukan keatas bahan Inconel 718 (nickle-based superalloy) dibawah keadaan kuantiti cecair pelincir yang minima (MQL). Dalam laporan ini, pengkajian tertumpu kepada pembandingan proses larik atas (up-milling) dan larik bawah (down-milling) bagi operasi menggunakan pelbagai lapisan TiAlN/AlCrN-bersalut karbida. Pelbagai parameter pemotongan, kedalaman pemotongan, kadar pemotongan dan kelajuan pemotongan/pelarikan telah dijalankan semasa proses penilaian. Hasil kajian mendapati bahawa proses larik bawah mempunyai keputusan yang lebih baik dari segi kehausan peralatan dibandingkan proses larik atas. Cebisan pada perkakasan potong adalah hasil dari takuk kehausan akibat proses pemesinan yang dipanjangkan. Turut diperhatikan, kepingan yang terhasil dari operasi larik atas bersegmen dan berterusan dibandingkan operasi larik bawah yang menghasilkan kepingan yang tidak berterusan.

Kata kunci: Inconel 718; FEM; larik atas; larik bawah; kehausan perkakas; pembentukan cip

■1.0 INTRODUCTION

Inconel 718 is a group of nickel based superalloys which is widely employed in the aerospace industry due to their high-temperature strength, its superior creep and high corrosion resistance. However, Inconel 718 is also well known as a difficult-to-machine material and this cause disadvantages properties during machining process such as poor thermal conductivity, contained high chemical affinity with almost all tools, high strength due to their high-temperature properties and its work harden rapidly [1]. In addition, these properties will lead to severe tool injury; high stress and temperature buildup on the tool face, warping in small parts and rapidly tool wear which resulting shorter tool life [2]. In most cases, the problem encountered during machining Inconel 718 is due to temperature generated which cause tool damage even at low cutting speed and low feed rate [3, 4]. On the other hand, chips are easy to weld on the tool face to form BUE which directly result severe surface damages extending to subsurface levels [3].

Nowaday, the increasing demands for higher quality in machining and manufacturing efficiency have leaded the researchers to put every effort to develop the efficient and the best method to machine Inconel 718. Li *et al*. [2] investigated the tool wear propagation and the cutting force variations in the end milling operation. They have found that significant flank wear was the predominant failure mode affecting the tool life and tool wear was the major reason for the gradual increase of the mean peak force in successive cutting passes. Kasim *et al*.[5] reported that in ball nose end milling, the predominant tool failure for the four round cutting tools are notch wear and flaking near the depth of cut zone where they cause by the repetitive cyclic load. They also claimed that large radial of depth is the main factor affecting the tool wear.

Harshad and Suhas [6] have studied the effect of machining parameters on the quality of surface obtained in a single-pass of ball-end milling cutter. They also reported that maximum surface roughness is measured near the tool tip region on the machined surface, where the minimum surface roughness is obtained in the stable cutting zone. For further investigation on the tool wear, Krain *et al*. [7] have done two phases of experiments to observe the effect of various cutting parameters and also different tool materials and tool geometries; abrasion, adhesion and attrition are the main tool wear mechanisms and BUE is formed when the pressure and chemical affinity are high. The same finding is obtained by Khan *et al*. [8] through their results on finish turning of Inconel 718, where abrasion is the main cause that triggers the dominant wear mode, while workpiece material adhesion is similarly prominent and BUE formation is observed at every parameter level.

Milling process is also known as an interrupted cutting process where the direction of the cutting force is changing due to the tool rotation, and as the tooth enters and leaves the workpiece for every cutting pass [5,9]. This nature resulted in various wear mechanism, cutting temperature and dynamic stability compared to the continuous cutting process. Research carried out by Bouzakis *et al*. [10] has shown that the kinematics of milling process (up-milling or down-milling), have significantly affects the stress distribution during the material removal and also the cutting performance. The results obtained through an experimental study done by Li *et al*. [2], shown that the tool flank wear propagation in the up milling operation is more rapid than that in the down milling operations.

All these studies explained more insight of tool performance in down milling operation of Inconel 718. However, the correlation between cutting performance and kinematics orientation of difficult-to-machine material like Inconel 718 has rarely been studied. The purpose of this paper is to study more comprehensively the tribological behaviours of ball nose end milling in different kinematics direction (up and down) of Inconel 718 with PVD coated TiAlN carbide. Specifically, the wear and tool life are measured in order to assess the effects of up-milling or down-milling on wear mechanism generated.

■2.0 METHODOLOGY

2.1 Workpiece Material and Cutting Tool

The aged-hardened and solution-treated of Inconel 718 alloy with a dimension of 150 x 100 x 50 mm was used as a workpiece material. The hardness of the workpiece was 42 ± 2 HRC. The composition of Inconel 718 are shown in Table 1.

A Sumitomo ball nose type milling cutter with a nominal diameter of 16 mm was attached to a BIG Hi-Power Milling Chuck DV40-HMC20-85 with an overhang length of 60 mm. The insert was tungsten carbide with multi-layer PVD TiAlN/AlCrN grade ACK 300. The cutting tool and tool holder specifications are shown in Table 2.

Table 1 Nominal chemical composition of Inconel 718

Elements	% wt.
Al	0.49
B	0.004
C	0.051
Nb.Ta	5.05
Co	0.3
Cr	18.3
Cu	0.04
Fe	18.7
Mn	0.23
Mo	3.05
Ni	53
P	<0.005
S	<0.002
Si	0.08
Ti	1.05

Table 2 Cutting tool geometry

Items	Value
Insert diameter, Ø	10 mm
Thickness	3.97 µm
Relief angle	11°
Radial rake angle	0°
Axial rake angle	-3°
Approach angle	90°
Number of inserts, n	1

2.2 Tool Wear Measurement and Experiment Parameters

The wear behavior of Inconel 718 during up-milling and down-milling have been investigated. The milling process was interrupted at the specific cutting interval to study the growth of the tool wear for every level of parameter. The tool wear of the insert was observed using a Mitutoyo toolmaker's microscope with 30x magnification and ± 0.003 mm repeatability. After the wear observation and measurement, the insert was used again for the next milling experiment. The experiment was repeated until the tool has met one of the ISO-8688 failure criteria, which are: (i) uniform flank wear of 0.3 mm; (ii) maximum flank wear is 0.5 mm; or (iii) when excessive flanking or fracture happened [11].

For UMO, the tool wear measurement was taken after a single pass of every experiment since in some runs the inserts have already worn out after the first pass. For UMO, the wear data was taken until the twentieth runs for each parameter. The comparison of the tool life was made on the longest time taken during DMO.

For up-milling and down-milling, the cutting parameters were set into three variables which were cutting speed, feed rate and depth of cut. MQL was used as a coolant throughout the experiment with fixed flow rate at 50 ml/h. The details of the machining parameters are provided in Table 3 below.

Table 3 Machining parameters used during the experiment

Cutting parameters	Unit	Values
Cutting speed, v	m/min	100, 120, 140
Feed rate, f_z	mm/tooth	0.1, 0.15, 0.2
DOC	mm	0.5, 0.75, 1.0

■3.0 RESULTS AND DISCUSSION

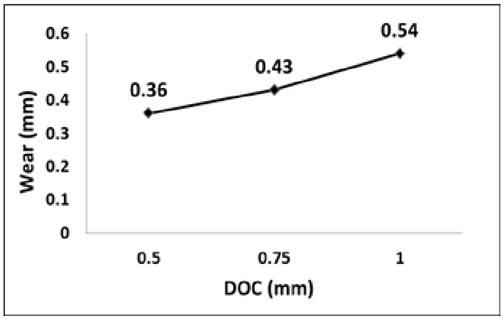
3.1 Tool Wears In Up-Milling Operation (UMO)

In up-milling process, the cutter tends to scoop the metal start from the bottom and goes all the way upwards. In other words, the width of chip will starts from zero and increases. As the cutter encounters minimum chip thickness when it start entering the work piece, rubbing at the beginning of the cut will cause an excessively work hardened layer on the work piece. As a consequence, this condition will generate lower temperature around the cutting edge and chip surface as compared to down milling due to less friction interface between the tool and the chip [12].

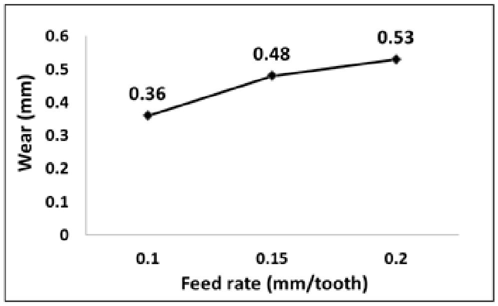
Figure 1(a) (b) and (c) show the effect of cutting parameters on the flank wear. The effect of DOC on tool wear by keeping feed rate and speed constant is shown in Figure 1(a). From Figure 1(a), it is clearly shown that DOC is directly proportional to the tool wear. In single cutting pass measurement, the tool wear increases as the DOC increases. The same finding was obtained by Ali and Salama [13] through their experiment on austenitic stainless steel where they found that as the DOC increases, chip width will also increases and the center of pressure of the chip tend to moves away from the cutting edge, which initiated the crack to occur. At DOC 1 mm, the tool wear meet the maximum flank wear (Vb_{max}) which is 0.5 mm as per ISO-8688 in only one pass.

Figure 1(b) indicates the effect of feed rate on the tool wear by keeping the DOC and speed constant. From the results obtained, feed rate also give a direct proportional relation to the tool wear, where increasing the feed rate will accelerate the tool wear. For feed rate of 0.2 mm/tooth, tool is already worn-out in a single cutting pass with the wear reading of 0.53 mm. This phenomenon is due to BUE formed on flank face that changes the geometry of the tool [14].

From Figure 1(c), the effect of cutting speed is clearly shown that the flank wear is increased with increase of cutting speed. The experiment was done with a constant DOC; 0.5 mm and feed rate; 0.1 mm/tooth. The result also concluded that as the cutting speed is increased, abrasive and adherence of workpiece on the flank face can be clearly seen. In general, this phenomenon is mainly due to the generation of high contact pressure and temperature between workpiece and tool, where most of the wear mechanism of carbide tool is abrasive and adhesive wear [14]. The result as in Figure 2(a) was obtained from the experiment and it shows BUE occurred near the DOC line because of higher stress acting on the cutting edge, while Figure 2(b) show the phenomenon of material adhesion and abrasion wear on the flank face .



(a)



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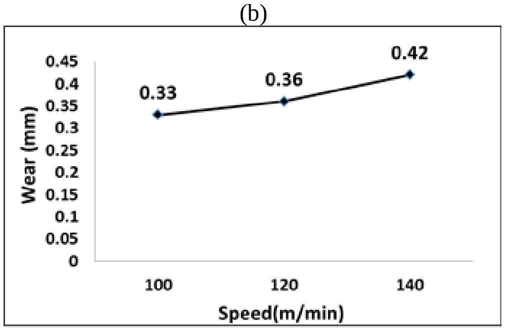
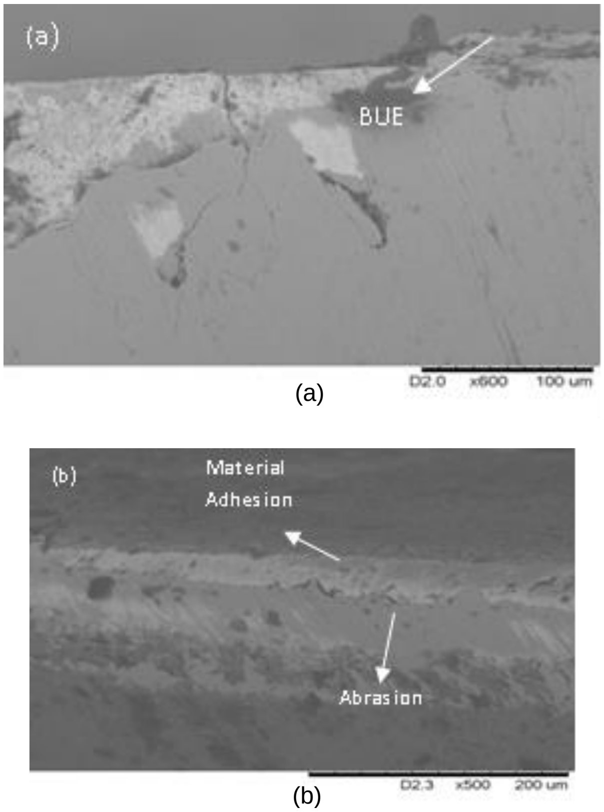


(c)

Figure 1 Up-milling: maximum wear in single cutting pass when (a) DOC are set at 0.5, 0.75 and 1 mm while feed rate and speed are constant at 0. 1 mm/tooth and 120 m/min, (b) feed rate are set at 0.1, 0.15 and 0.2 mm/ tooth while DOC and speed are constant at 0.5 mm and 120 m/min, (c) speed are set at 100, 120 and 140 m/min while DOC and feed rate are constant at 0.5 mm and 0.1 mm/tooth



(a)

(b)

Figure 2 Up-milling (a) BUE (b) Abrasive and adhesive wear

3.2 Tool Wears In Down-Milling Operation (DMO)

As compared to UMO, down-milling process will tend to scoop the metal starting at the top of DOC and goes all the way to the bottom. This scenario will create a high cutting force at the beginning of the cut since the volume of the scoop is higher. Hence, the high impact force can cause chipping (Figure 3a) due to the harden layer on the surface and this will promoting the formation of notch wear (Figure 3b). Localized of notch wear can lead to tool fracture and will be considered as a catastrophic failure.

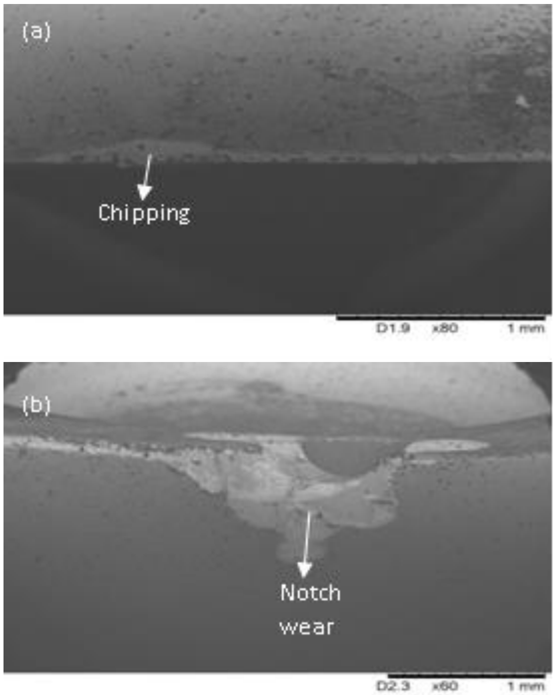
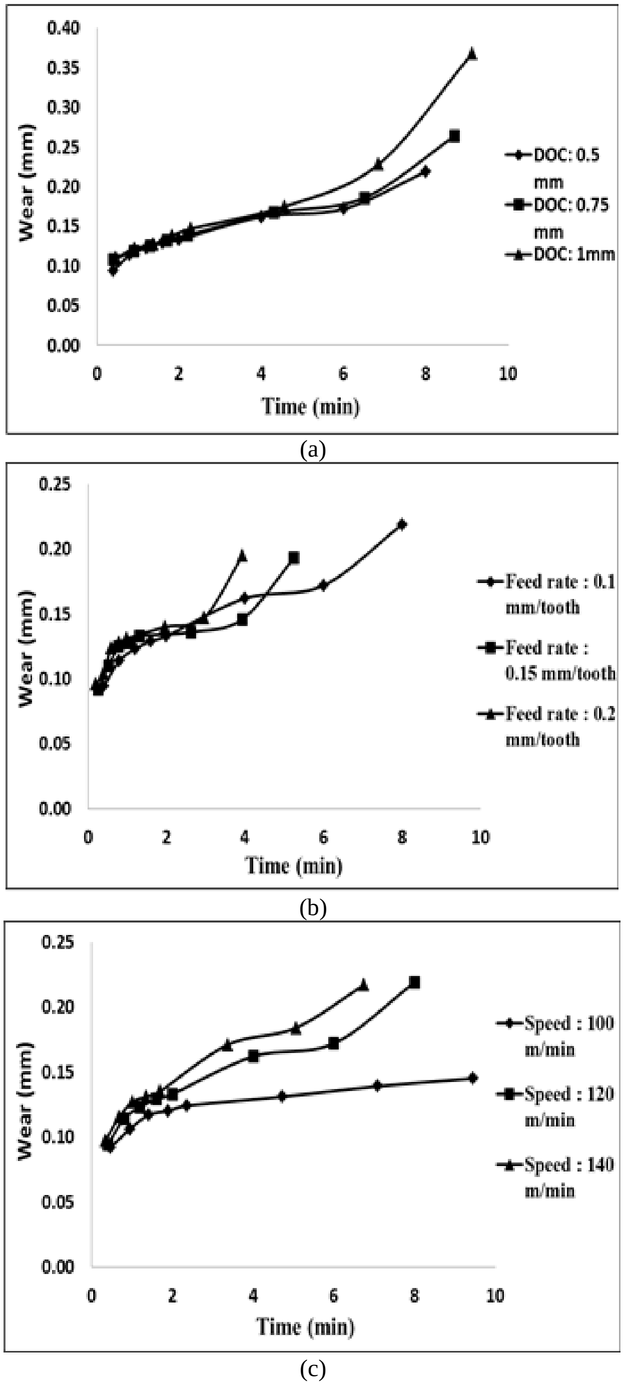


Figure 3 Down-milling (a) Chipping (b) Notch wear

The difference in cutting results during down-milling that due to change of DOC, feed rate and speed over cutting time can be seen in Figure 4(a), (b) and (c). Overall, all the parameters show the improvements in tool wear when the same parameters used in UMOare applied in DMO. From the results in Figure 4(a), the progress of flank wear increases steadily at the initial stage before unevenly progressed after around four minutes of cutting times. This phenomenon is due to chipping and further more will lead to notch wear that caused by the repetitive load [5].

The effect of feed rate during down-milling is observed in Figure 4(b). In general, the progress of the wear has three stages: initial, steady-state and worn-out regions. All the feed rate values started with the increasing of flank wear until they reached almost 1 minute before they gone through steady state region for a certain period of time. For f_z= 0.2 mm/tooth, it took 3 minutes, while for f_z= 0.15 mm/tooth and f_z= 0.1 mm/tooth took 4 minutes and 8 minutes, respectively before the wear drastically increased, leaving the steady state region. As in up-milling, flank wear increases as the feed rate is increased due to the formation of BUE at flank face and increase in the normal contact stress at the tool-chip interface and in the tool-chip contact area. The chipping of the cutting edge leads to tool breakage when the level of normal contact stress reaches the breaking feed of the tool [15].

Figure 4(c) shows the influence of different cutting speed on tool wear under DMO. It can be observed that tool wear is very sensitive to cutting speed. When the speed is low (100 m/min), the tool wear on the flank face is slowly increasing compared to the progress of wear during high speed (140 m/min). This was most likely due to increase of the cutting temperature which resulted in a loss of material strength and increase of its plasticity [16]. In other words, tool tips become easier to worn out cause by high cutting temperature, where abrasive wear marks and workpiece material adhesion have become the prevalent wear mechanisms for all test performed.



(a)

(b)

(c)

Figure 4 Down-milling: maximum wear in twenties cutting pass when (a)DOC are set at 0.5, 0.75 and 1 mm while feed rate and speed are constant at 0.1 mm/tooth and 120 m/min, (b) feed rate are set at 0.1, 0.15 and 0.2 mm/ tooth while DOC and speed are constant at 0.5 mm and 120 m/min, (c) speed are set at 100, 120 and 140 m/min while DOC and feed rate are constant at 0.5 mm and 0.1 mm/tooth

3.3 Chips Formation

During UMO, the low cutting force generated during entrance cutting will tend to cause a vibration during cutting process. In general, an excessive vibration during machining can lead to a poor surface finish, increase tool wear, reduced machine life and limit the productivity [17]. As a result in term of chip morphology for UMO, a segmented chip with a typical saw-tooth shape (Figure 5a) has been shown in order to be linked to high vibration level in UMO. This phenomenon showed that the local rate of heat build-up in the material is large enough that thermal softening overwhelms the effect of strain hardening. Additionally, the segmented chip will result an increase in tool wear and degradation of workpiece surface finish [18].

Based on fact, the chip formation in down-milling is opposite to the chip formation in up-milling. In down-milling process, chips are generally bigger (approximate two times bigger than up-milling) because of the high cutting force during contact and the compressive stresses on the impact of entering which produced thicker chip. Additionally, the impact of high force also prevents the workpiece to encounter from excessive vibration during cutting process. Hence, down-milling can produce a better surface finish as compared to UMO. In the other hand, in down-milling the chip produced was a discontinuous serrated chip as shown in Figure 5b. This type of chip will reduce the tool wear and produce better quality of machined surface.

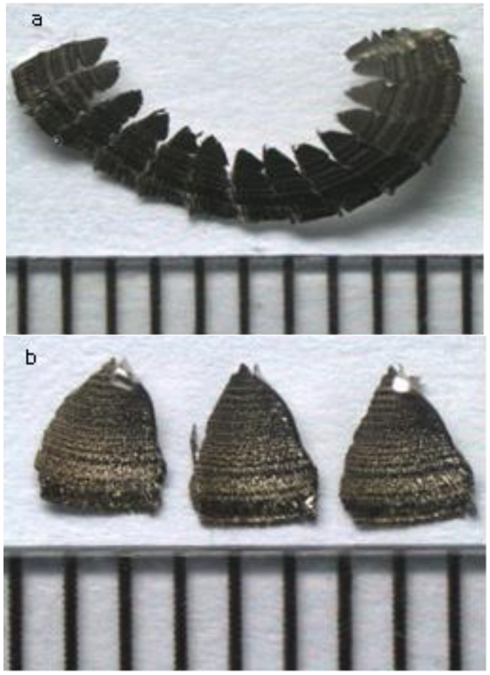


Figure 5 (a) Chip for up-milling (b) Chip for down-milling

3.4 FEM Simulation

Figure 6, depict the form of chips obtained from a simulation done using FEM software ThirdWave AdvantEdge under *v*= 100 m/min, f_z= 0.1 mm/tooth and DOC= 0.5 mm for each cutting process. The simulation results have proved that the chips formation generated during UMO and DMO are parallel with the finding during the experiments. The heat generated at the cutting tool show that the build-up temperature near the tool tip is higher during UMO when compared to DMO.

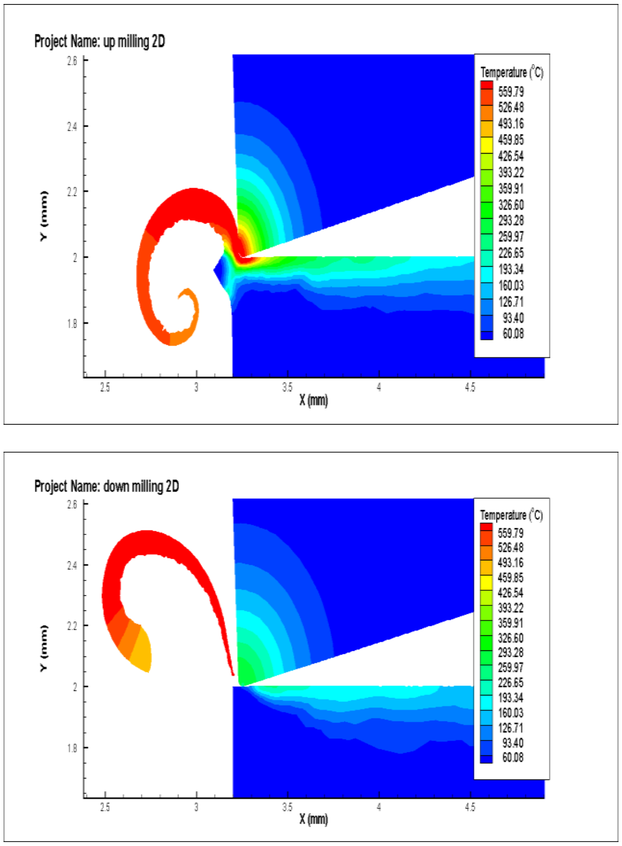


Figure 6 Chip form and temperature distribution during up-milling and down-milling processes

Figure 7 shows the trend of the cutting force versus the times during UMO and DMO. The results proved that the force for UMO is lower at the beginning and increased towards the end of the cut, while in DMO the force start with high value and decreased towards the end of the cut. The difference between these two operations could be explained by the fact that the beginning volume of cut during up-milling process is smaller than down-milling process.

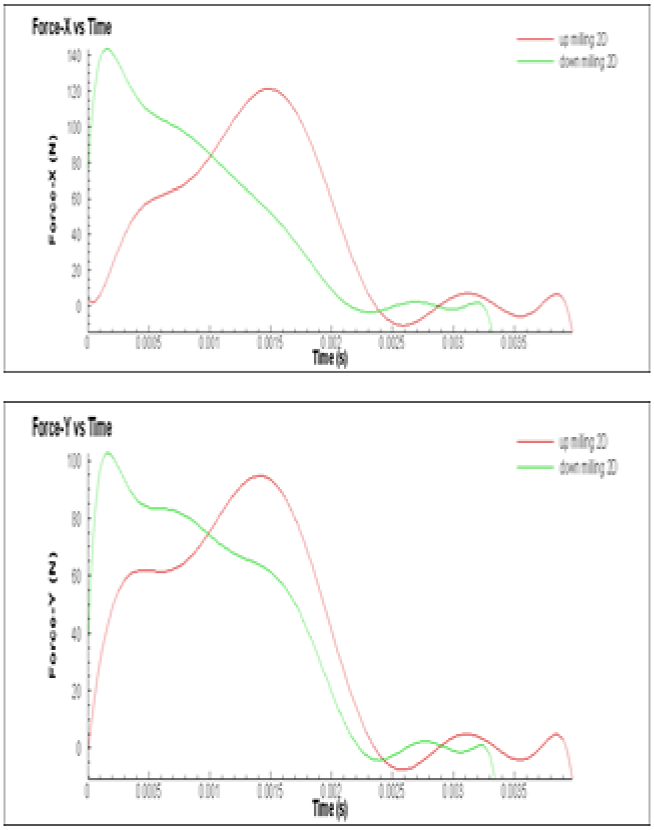


Figure 7 Cutting force in X and Y directions during up-milling and down-milling process

■4.0 CONCLUSION

The article presents the findings on the experiments and the result from FEM simulation during up-milling and down-milling on the effect of DOC, feed rate and cutting speed to the tool wear of TiAlN/AlCrN-coated carbide insert attached to ball nose end milling of Inconel 718. Generally, tool wear is increased with increased DOC, feed rate and cutting speed. It is found that the tool flank wear propagation in the UMO was more rapid compared to DMO. The results also showed that significant pitting and notch wear were the predominant failure mode typically located near the DOC line that affecting the tool performance and tool life. All the three machining parameters have the contributions to notch wear failure where DOC and feed rate affects the volume of material removal and the cutting speed affect the cutting temperature. On the other hand, the chip morphology is different in both operations, where UMO produced a segmented chip with typical saw-tooth shape and DMO produced a discontinuous serrated chip. The cutting force from FEM simulation proved that the entrance force for UMO is higher compared to DMO which is parallel with the theory for both operations.

Nomenclature

BUE	build-up-edge
DOC	depth of cut (mm)
MQL	minimum quantity lubricant
UMO	up-milling operation
DMO	down-milling operation
fz	feed rate (mm/tooth)
v	speed (m/min)
Vbmax	maximum flank wear

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