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Study on tool wear and wear mechanisms of end milling Nickel-based alloy

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ABSTRACT

Tool wear is a problem when machining Inconel 718. Inconel 718 is known for being a difficult to cut material, this is due to its high strength at high temperatures, low thermal conductivity and high work hardening. This causes cutting tools to experience rapid wear. It is important to understand the wear mechanisms and analyze the causes of wear. The study was done at cutting speeds of 80, 100 and 120m/min and radial depth of cut of 5, 7.5, 10 and 20mm in dry condition. The tool wear and tool wear mechanisms were observed using the tool maker's microscope and scanning electron microscope. The tool wear was found to be more rapid at larger radial depth of cuts at all three cutting speeds. It was also found that the main wear mechanisms present were abrasion, adhesion and attrition.

1.0 INTRODUCTION

Inconel 718 is nickel based alloy, it is used widely in high temperature high load and corrosion resistant environments. Even though it has superior properties, it is known for being a difficult to cut material. Inconel 718 has small thermal conductivity and volume specific heat that causes high cutting temperature (Liao et al., 2008).

This alloy contains a niobium age-hardening addition for increased strength while maintaining ductility. In addition, Inconel 718 is also non-magnetic, oxidation and corrosion resistant and can be used in temperatures ranging from -217°C to 700°C. The uses of Inconel 718 vary in a wide range of fields such as aircraft turbines, oil and gas, cryogenic tankage and also components for liquid rockets. This is due to the good tensile, fatigue, creep and rupture strength (Alauddin et al.,

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1998). Hence, the ability to machine Inconel is heavily demanded in the industry. One of the most common material cutting operation used in the industry is end milling due to the complexity and shape of the parts and the accuracy required in the finished dimensions (Alauddin and Baradie, 1996).

The characteristics that make Inconel 718 highly valued also make them one of the most difficult to machine materials. Various tool materials have been developed in order to increase the machinability of Inconel 718. Some examples are coated tungsten carbide, alumina, whisker-reinforced alumina and cubic boron nitrate but the most widely used is coated tungsten carbide.

Parida and Maity (2018) compared the machinability of nickel based alloys in hot turning (Inconel 718, Inconel 625 and Monel-400), it was found that the cutting force was highest during the machining of Inconel 718 than Inconel 625 and Monel-400. The heating also significantly increased tool life in machining all three materials. In addition, the surface finish of Inconel 718 was better than the other materials in the same cutting condition. Moreover, localization of shear in the chip produces abrasive saw toothed edges which makes swarf handling difficult. These alloys also have a tendency to weld with the tool material at the high temperature generated during machining. The machining temperatures could reach more than 1000°C and streses that could go far beyond 3450MPa in the cutting zone. This leads to accelerated flank wear, cratering and notching depending on the tool material and the cutting conditions used (Choudhury and El-Baradie, 1998). Some of the other reasons that contribute to the poor machinability of nickel base super alloys is the existence of hard carbides in grain boundaries due to elements such as tungsten and molybdenum, very hard compounds which cause severe abrasion on tool and so a deleterious effect on tool wear rate, being especially noticeable when alloys are in the heat treatment state (Polvorosa et al., 2017). Polvorosa et al. (2017) investigated tool wear when machining Waspaloy and Inconel 718 at different coolant pressures using uncoated cemented carbide inserts and found that the flank wear was lower when machining Waspaloy compared to Inconel 718.

Tool damage can be classified into two groups, wear and fracture by means of how its scale and progresses. Unfortunately these two groups of tool damage are not clearly distinguished in practice. The damage of cutting tool edges are influenced by the stress state and temperature at the tool surfaces which in turn depend on cutting mode. Examples of cutting modes are milling, turning, drilling, the cutting conditions or the presence or not of cutting fluid. Wear can be defined as the loss of material which usually progresses continuously on an asperity or micro-contact or in smaller scale down to molecular or atomic removal mechanisms. Fracture or the failure of the cutting tools cover a continuous spectrum of damage scales from micro-wear (micro-chipping) to gross fracture (catastrophic failure) (Grzesik, 2016).

Xavior et al. (2017) assessed the tool wear in turning Inconel 718. It was found that tool wear was greatly influenced by three factors namely thermal softening, diffusion and notching at greater depth of cut and at the edge. D'Addona et al. (2017) investigated High Speed Machining (HSM) while turning of Inconel 718. At high cutting speeds, tool gets worn out at a very fast rate with major tool failure patterns like heavy notching. Cui et al. (2017) studied the tool temperature in end milling considering the flank wear effect. When the flank wear occurred, the dependence of tool temperature on flank wear was evident. But as the flank wear progresses the dependence of temperature on flank wear decreased. The temperature rises slowly until it reaches the peak value and then becomes steady. Altin et al. (2007) investigated the effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools. It was found that flank wear, crater, notching and plastic deformation were the present wear mechanisms. However, flank and notch wear were the dominant wear mechanisms for round inserts while flank and crater are the major wear type of square inserts. The optimum tool life on the other hand was found to be optimum at 250m/min.

There are numerous wear mechanisms but only several are considered important during machining (Huang et al., 2007; Mir and Wani, 2017). Some examples of these wear mechanisms are adhesion, diffusion, abrasion and oxidation. These wear mechanisms are highly dependent on temperature, only adhesion and abrasion are present at low temperatures while at high temperatures the adhesive wear mechanisms give way to diffusion and oxidation (Corrêa et al., 2017). In addition, Huang et al. (2007) reported that wear mechanisms categorized as abrasion, adhesion, diffusion, fatigue and tribo-chemical wear join hands to form tool failure.

Adhesion (Attrition) means the recombination generated when the tool and the workpiece material come into contact with distance of atoms. It is generated by the plastic deformation under sufficient pressure and temperature and it is the so called cold welding phenomenon. Also, it is the result of adhesive force between atoms by the plastic deformation occurred in the actual contact area of friction surface. The adhesive wear when the grain or grain group was taken away by shear or tension is due to the relative motion of adhesion points on these two friction surfaces. Adhesion develops in a process where a built-up edge or irregular material flow is present and microscopic debris are pulled out from the tool surface and dragged along with the flow of the workpiece material, leaving small cavities on the surface of the tool. The image of the worn area produced mainly by adhesion has a rough appearance (developed at the grain level) compared to worn surface produced by diffusion and can be observed through the optical microscope. The presence of adhesion can be indicated from the worn areas with rough surfaces (Corrêa et al., 2017).

The abrasive wear mechanism involves the loss of material by micro-plowing, micro-cutting or micro-chipping caused by particles with high relative hardness. Workpiece materials such as (oxides, carbides, nitrides and carbo-nitrides) can provide these hard particles characterizing a two-body type of abrasion or it can be characterized as three-body type wear , provided from particles originating from the tool which were plucked out by attrition (Trent and Wright, 2000). Abrasive wear is much less likely to be significant wear process with cemented carbides than with high speed steel because of the high hardness of tungsten carbide. There is little positive evidence of abrasion except under conditions where very large amounts of abrasive material are present, as with sand on the surface of castings. The wear of tools used to cut chilled iron rolls, where much cementite and other carbides are present, may be by abrasion but most of the carbides even in alloy cast iron, are less hard than WC and detailed studies of the wear mechanism in this case have not been reported (Krain et al., 2007).

The oxidation wear mechanism is often encountered on the tool during the development of notch wear at the end of the depth of cut region. This wear process is often found when machining heat resistant materials with a high strain hardening coefficient such as nickel, titanium and cobalt alloys. Sliding conditions prevail where this type of wear occurs and the wear mechanisms probably involve adhesion and abrasion as well as the transfer of material and they are strongly influenced by interactions with the atmosphere. Also, studies suggest that oxides form continuously and adhere to the region close to the end of the depth of cut on the tool (Krain et al., 2007).

Corrêa et al. (2017) studied the tool wear mechanisms on carbide tools coated with TiC/TiCN/TiN by CVD during the turning of martensitic S41000 and super-martensitic S41426, results showed that abrasion and diffusion were the prevailing wear mechanisms for martensitic stainless steel and for the super-martensitic stainless steel attrition and abrasion were dominant.

Hao et al. (2011) studied tool wear mechanism in dry machining Inconel 718 with coated cemented carbide tools and found that at lower cutting speeds (20m/min) there are lots of built-up-edge. At high cutting speed (45m/min and 50m/min), the element diffusion between tool and workpiece and oxidation reaction all accelerate the formation and peeling of wear debris.

Imran et al. (2014) investigated dry and wet micro-drilling of nickel base super alloys. It was found that adhesion and diffusion were the main tool-wear mechanisms and adhesion of the coating is the main property that affects the longevity of the coating. Sugihara and Enomoto (2015) found that the problem of high speed machining of Inconel 718 with CBN tool is the thermal wear lead by the high cutting temperature and the diffusion of workpiece material rather than mechanical wear. Tanaka et al. (2016) identified wear mechanisms of two types of PCBN cutting tools in turning of Inconel 718. At low cutting speed, crater wear was found to be exacerbated by cycle of adhesions of workpiece materials and their removals, at 100m/min, diffusion due to high cutting temperature is a dominating factor for promoting crater wear while at 300m/min the factor for exacerbating crater wear changed from mechanical wear to thermal wear. Hao et al. (2011) found that the main cause of tool wear in high speed milling using self – reinforced SiAlON ceramic tool materials was the peeling off of material which is caused by crack nucleation and crack propagation under the cyclic impact load at low cutting speed. Sartori et al. (2016) studied the tool wear mechanisms in dry and cryogenic turning additive manufactured Titanium alloys namely Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM). Crater wear was found in both conditions when machining DMLS material which was the harder material. This suggested the assumption that crater wear depended only on the alloy mechanical properties. The abrasive wear and flank wear were reduced by applying the LN2 and it was found that the EBM alloy presented the best machinability. This study focuses on the effect of radial depth of cut on tool wear propagation and tool wear mechanisms that occur when end milling Inconel 718.

2.0 EXPERIMENTAL PROCEDURE

The parameters that were involved in this study were the cutting speed (V), depth of cut (d) and feed rate (f). The manipulated variables were the radial depth of cut and the cutting speed, while the constant variables were the feed and axial depth of cut. Table 1 shows the respective values of the parameters. The experiments in the dry conditions were named based on their respective parameters using alphabets to avoid confusion. Table 2 shows the experimental identifications.

The experiment was conducted using Mazak Vertical Center (Nexus 410A-II). The workpiece was set up as seen in Figure 1(a). The milling operation used in this study was down-milling. Figure 1(b) illustrates the down milling process from the side view, the tool is illustrated to move in a clockwise position.

The Tool Maker's microscope was used to measure wear on the flank face using the lens with 1X magnification. Figure 3(a) shows the Tool Maker's microscope and Figure 3(b) shows the measured flank face of the tool. The tool wear criteria was based on ISO 8688-2 which is as follows:

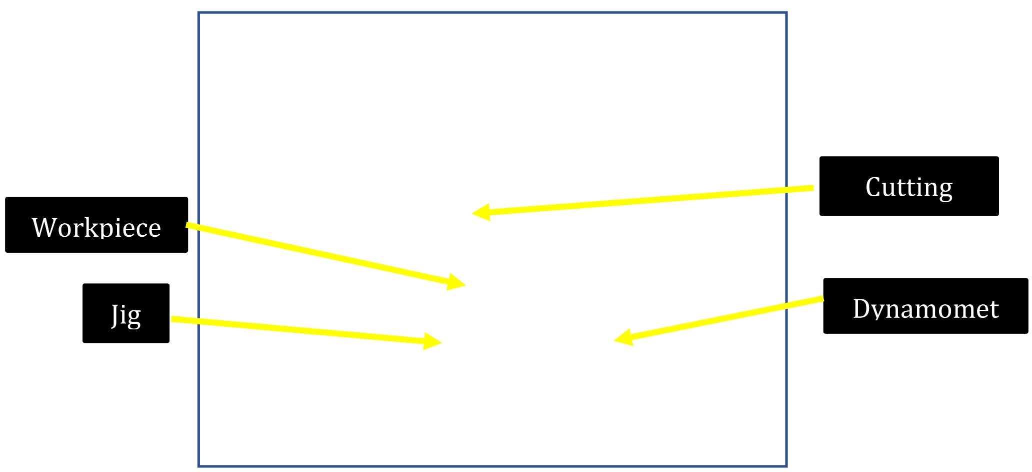
(a) Average uniform flank wear (VB_{ave}) ≥ 0.3mm
(b) Maximum flank wear (VB_{max}) ≥ 0.5mm
(c) Chipping ≥ 0.5mm (localized wear)
(d) Fracture or catastrophic failure

Table 1: Machining parameters.

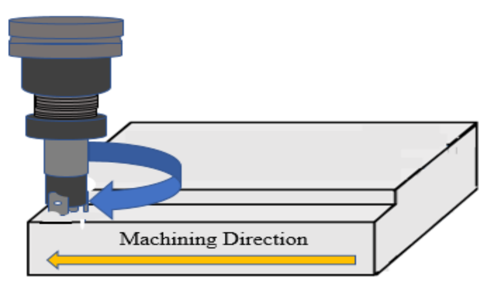
Condition	Parameters
Cutting Speed, V (*m/min*)	80, 100, 120
Feed, f (*mm/tooth*)	0.05
Axial depth of cut, a_p (*mm*)	0.5
Radial depth of cut, a_e (*mm*)	5,7.5,10,20
Tool holder diameter (*mm*)	20
Milling operation	Down milling

Table 2: Experimental Classification of Parameters

Radial DOC	80 m/min	100 m/min	120 m/min
5	A	D	G
7.5	B	E	H
10	C	F	I
20	J	K	L



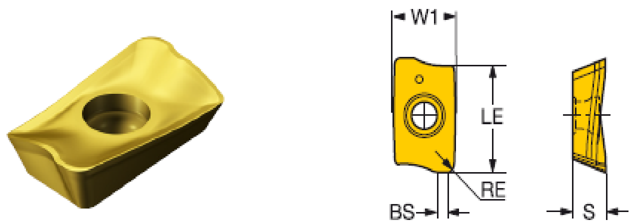
(a)



(b)

Figure 1: (a) Experimental setup (b) Down milling operation (Side View).

The tool specifications were obtained from the Sandvik Coromant catalogue under the ordering code R390-11 T3 08M-PL. The cutting tool can be seen in Figure 2 while the dimensions can be observed in Table 3. The points in which the wear was measured was from 0-0.5mm (Depth of cut) of the flank face as labelled in Figure 3(b).The down milling was performed at 50mm for a single pass, the wear values were taken every 4 passes.



Fifure 2: Cutting tool

Table 3: Cutting tool dimensions.

W1(mm)	LE(mm)	S(mm)	BS(mm)
6.8	10.0	3.59	1.2

(a) (b)

Figure 3: (a) Tool maker's microscope (b) Tool flank face.

3.0 RESULTS AND DISCUSSION

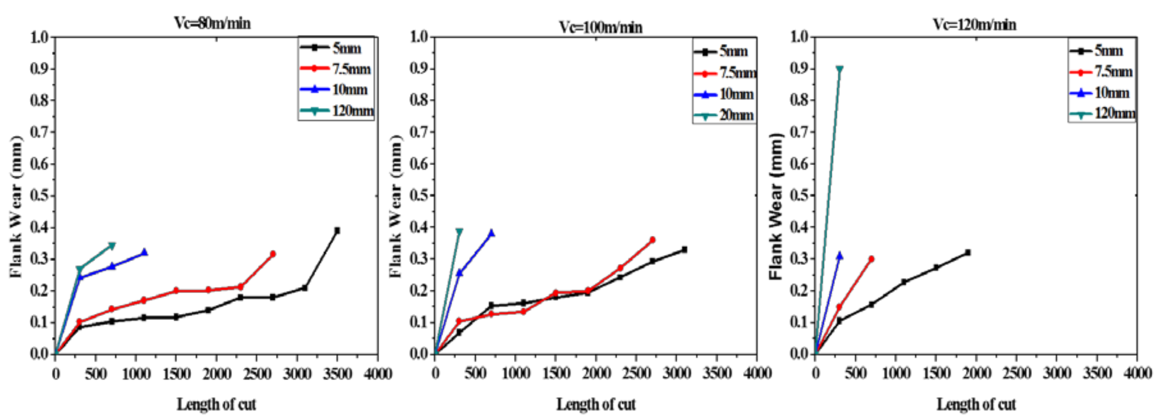
Due to its good performances, i.e., low friction coefficient, high hardness and good temperature properties, the titanium nitride (TiN) and titanium aluminium nitride (TiAlN) coating can greatly improve the life of the carbide tools. The layer of the coating materials is very thin. As long as the removal of coating material does not deteriorate machining quality, the cutting tool without the coating can continue to realize its function until it reaches tool wear criterion. Flank wear of an end mill is common in material cutting operation. Hence, in this work, tool life end point criteria are considered on the basis of the effective cutting time to reach a particular width of flank wear based on ISO 8688 (Alauddin and Baradie, 1996). Figure 4.2 shows the tool wear propagation at speed of 80m/min, 100m/min and 120m/min while Figure 4.3 shows the tool wear mechanisms.

According to the results, the propagation of tool wear under dry cutting condition was more rapid in larger radial depth of cut and much slower in smaller radial depth of cuts. This pattern can be observed at all three cutting speeds. The length for a single cutting pass is 50mm. The tool wear progression for radial depth of cut of 5mm (experiments A, D and G) achieved the longest length of cut at all three cutting speeds. To be exact, 3309.7mm at cutting speed 80m/min, 2680mm at 100m/min and 1722.64 at 120m/min. The tool life of the cutting tool is also longest at radial depth of cut of 5mm at each cutting speed.

The tool wear at radial depth of cut 7.5mm (experiments B, E and H) progresses steadily at cutting speed of 80m/min and 100m/min exceeding 2300mm in length of cut. Meanwhile at cutting speed of 120m/min, the tool only managed to reach 697.06mm in length of cut which is 7 successive cutting passes.

The tool wear at radial depth of cut of 10mm and 20mm (experiments C, J, E, K, I and L) progresses to a flank wear of VBa=0.17mm even before it reaches 200mm length of cut for all cutting speeds. This is a very rapid progression of wear especially when compared to radial depth of cut of 5mm.

The findings can be related to the study conducted by Li et al. (2006). He concluded that the wear propagation was almost linearly related to the cutting time. The curves that describe flank wear can be divided into three different regions. The first region is the break-in period where the flank wear initially increases rapidly and later on gradually reduces to a constant rate. The wear behaves in the form of an exponential curve during this period. The second region is the steady state wear region in which the wear curve can be regarded as linear to the cutting time. The third region is the failure region in which different wear curves produced by different groups of tool-workpiece materials that were machined can be observed.



(a) (b) (c)

Figure 4: Tool wear propagation for different radial depth of cuts at (a) 80 m/min (b) 100 m/min (c) 120 m/min.

In the case of this study, experiments A and B showed the most similarities to the wear curve, the break-in-period was very short but the transition from the steady state region to the failure region could be clearly seen. Furthermore, experiments done in radial depth of cuts of 10mm and 20mm (experiment C, J, F, K, I and L) showed no clear transition into and out of the second region whatsoever as the wear occurred rapidly. The rapid tool wear could also be due to the austenitic nature of nickel alloys in face centered cubic (FCC) structure which presents a tendency to strain hardening. Thus previous passes of tool produce a rubbing effect on the part surface, hardening a thin layer of the surface that wears the tool cutting edge in successive passes (Polvorosa et al., 2017).

Figure 5 shows the SEM images for the flank face and rake face of the cutting tool. It was observed that the wear mechanisms that were present in end milling Inconel 718 were mainly abrasion and adhesion. Abrasive and adhesive wear are wear modes generated under plastic contact. In the case of plastic contact between similar materials, the contact interface has adhesive bonding strength. When fracture is supposed to be essentially brought about as the result of strong adhesion at the contact interface. The resultant wear is called adhesive wear, without particularizing about the fracture mode. On the other hand, in the case of plastic contact between hard and sharp material and relatively soft material, the harder material penetrates the softer one. When the fracture is supposed to be brought about in the manner of micro-cutting by the indented material, the resultant wear is called abrasive wear, also without particularizing about adhesive forces and fracture modes (Bhushan, 1999) .

Li et al. (2006) also conducted a study on the end milling of Inconel 718 using coated carbide inserts, the experimental results obtained also show that the dominant tool wear and damage were flank wear and chipping. D'Addona et al. (2017) mentioned in the review that welding and adhesion of workpiece material onto the rake face and flank face are the dominating wear modes when dry cutting Inconel 718. Çelik et al. (2017) reported that flaking occurred on the rake face due to the increase in cutting temperature, weakening the bonding between the coating and the base material. In addition, abrasive wear was caused by the rubbing action between cutting tool and the workpiece which removes the tool material to create deep scratches and scores on the worn surface. The adhesive wear is due to high temperature and pressure during cutting which causes welding to occur between the clean fresh surface of the chip and the rake surface (Bhatt et al., 2010). A crack was also observed to occur on the flank face at radial depth of cut of 7.5mm and cutting speed 100m/min, the cracks that occurred on the rake face from the study by Sugihara and Enomoto (2015) was due to the unstable adhesion layer that repetitively falls off and reforms during the cutting process, while Grzesik (2016) mentioned that thermal cracking was caused by cyclic heating and cooling associated with interrupted cutting (thermo mechanical fatigue), such as milling, creates high temperature gradients at the cutting edge. Hence, we can say that the cracking that occurs in this study occurred due to repetitive and continuous load variations during the cutting process.

Chipping that occurred in this study may have resulted from the adhesive wear. Another reason that could have led to chipping was the high temperature at the cutting edge made the cutting edge weak and consequently lead to the chipping of the cutting tool (Sugihara and Enomoto, 2015). The BUE formation is commonly associated to the mechanical adhesion forces at the tool-workpiece interface. The instability of the BUE during the machining process which periodically breaks taking off small lumps of the tool material eventually causes chipping of the tool edge (Sartori et al., 2016).

The gross fracture (catastrophic) as seen in radial depth of cut of 10mm and cutting speed 100m/min represents bulk breakage caused by heavy cutting conditions. Wear on the rake face characterized by the formation of crater or BUE resulted from the action of the chip sliding along the tool chip contact. Meanwhile, the wear on the flank face which is abrasion is formed from the rubbing action of the newly generated workpiece surface (Grzesik, 2016). Overall, the main wear mechanisms that were found in all parameters were abrasion and adhesion.

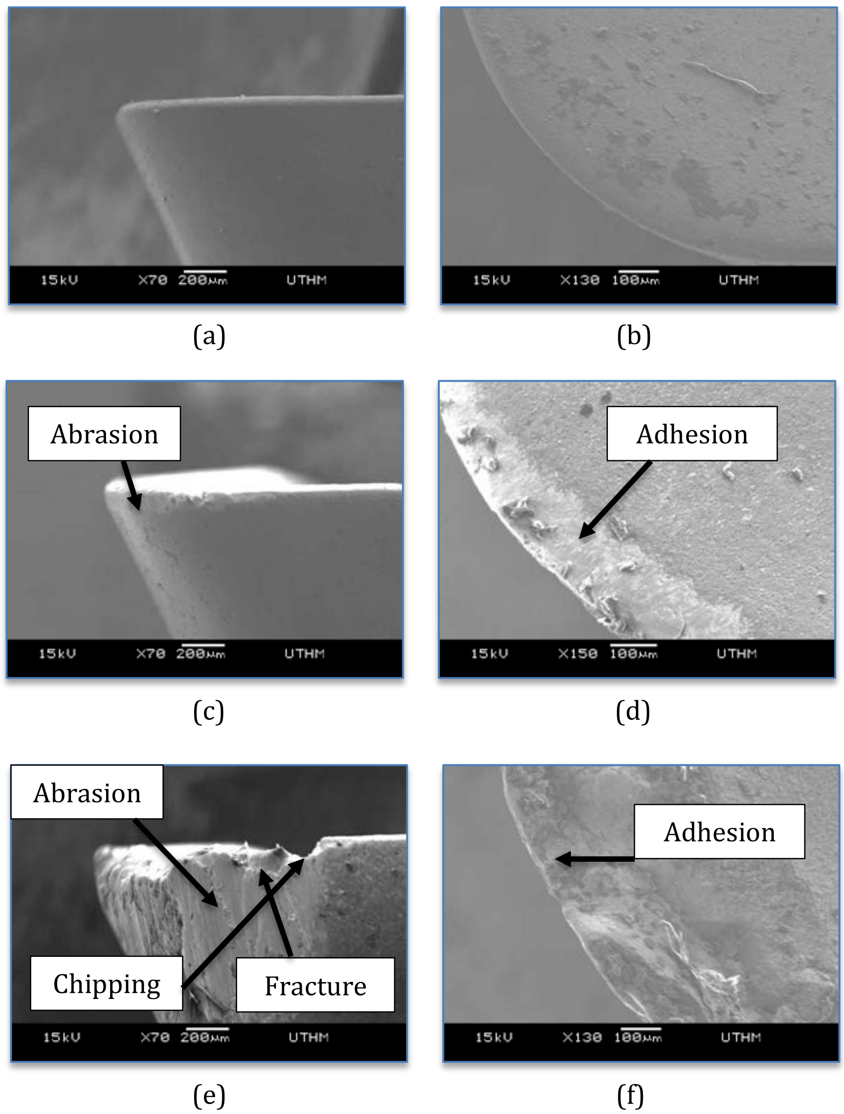


Figure 5: Fresh Inserts (a) Flank Face of Fresh Insert (b) Rake Face of Fresh Insert (c) Flank Face V=80m/min, a_e=5mm (d) Rake Face V=80m/min, a_e=5mm (e) Flank Face V=120m/min, a_e=20mm (f) Rake Face V=120m/min, a_e=20mm

4.0 CONCLUSION

In this paper, the authors studied the effects of radial depth of cut at different cutting speeds on tool wear propagation. At each cutting speed, the tool wear propagation was most rapid at radial depth of cut of 20mm followed by radial depth of cut of 10mm and 7.5mm and radial depth of cut of 5mm was the slowest. The fastest tool wear propagation occurred at a speed of 120 m/min and radial depth of cut of 20mm while the slowest tool wear propagation occurred at cutting speed of 80 m/min with radial depth of cut of 5mm.

The main wear mechanisms that were identified when machining Inconel 718 were abrasion and adhesion. The dominant failure mode was found to be chipping of the tool material. The severity of the adhesion and abrasion with regards to radial depth of cuts and cutting speeds could be clearly seen from Figure 5. It can be clearly seen that adhesion and abrasion were more severe at larger radial depth of cuts and cutting speed.

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