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The effect of cutting force and tool wear in milling INCONEL 718

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Abstract. 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. These excellent properties makes Inconel 718 suitable for high temperature applications. This paper presents a study on the effects of the radial depth of cut on the cutting force variations and tool wear propagation in the first cut using TiAlN coated inserts as the cutting tool. The machining operation conducted was side milling at cutting speeds of 80m/min, 100m/min and 120 m/min. The results obtained shows that the cutting forces and tool wear increase with increasing radial depth of cut.

1. Introduction

Inconel 718 is a nickel based superalloy that is commonly used in the aerospace industry. This is due to its high temperature strength, superior creep and high corrosion resistance. What makes it useful in its applications also makes it well known as a difficult-to-machine material which causes disadvantages properties during machining processes such as poor thermal conductivity, high chemical affinity almost with all tools, high work hardening and high strength at high temperatures. Consequently, this will lead to lead to severe tool damage, accelerate tool wear and shortens tool life [1]. During machining, the cutting edge is stressed by very high heat treatment and high pressure which depend on the hardness of the material. This causes the most problems during the machining and influences the type and style of the tool wear [2]. The reason behind the difficulty in machining Inconel 718 are due to high work hardening at machining strain rates (becomes more difficult to machine after each cutting pass), abrasiveness, tough, gummy and strong tendency to weld on tool and form built-up-edge, low thermal properties leading to high cutting temperatures and tendency for maximum tool face temperature to be close to the tool tip [3][4].

End milling is a type of face milling operation usually used for facing, profiling and slotting operations. The problem for milling machine maintenance has now been minimized with the use of inserted teeth milling cutters. In addition, the versatility of the CNC milling machines or machining centers has made it a workhorse in the part fabricating industries [5]. The aerospace industry is an example, the shape and complexity of the parts, including the accuracy required in the finished dimensions has made it place heavy demand on the end milling process [3].

Alauddin et al. [6] studied the influence of machining conditions (speed, feed and axial depth of cut) on the average cutting forces for half immersion end milling in the up- and down milling operations. They found that the cutting forces increased with increasing feed and axial depth of cut for up- and down milling while the cutting force decreases with increasing speed for both up- and down milling. Li et al. [7] studied the effect of tool wear during end milling Inconel 718 on the surface integrity and fatigue life of Inconel 718, they found that all the milled surfaces had roughness of less than 0.4µm and the majority of surface roughness was less than 0.25µm. Higher tool wear produced less surface roughness. Kasim et al. [8] reported that notch is the predominant failure mode during end milling of Inconel 718
and the two components that affected notch wear are the radial depth of cut (RDOC) and cutting speed. Ali et al. [9] studied new SiAlON based ceramic milling tools (α/β-SiALON and its TiN reinforced composite) and the tests were performed at a high machining time of 36 minutes and speed of 585 m/min, results showed that the addition of TiN particulates into SiAlON had a positive effect on the resistance to the formation of diffusion zones when it was in contact with Inconel 718 alloy at high temperatures (>1000°C). Some of the reports also mentioned on the effect of coated carbide tools when drilling Inconel 718 [10, 11, 12].

Nowadays, a number of tool materials have been developed in an attempt to increase machinability, examples of these cutting tools are coated tungsten carbide, alumina (Al₂O₃) and SiC whisker-reinforced alumina and cubic boron nitrate (CBN). Coated tungsten carbide (WC) is the most commonly used but there is little published material available regarding the milling of Inconel 718. This paper focuses on the effects of the radial depth of cut on the cutting force and the tool wear in the first cut in milling Inconel 718.

2. Experimental setup

The parameters in this study are the cutting speed ($V$), radial and axial depth of cut ($a_e$, $a_p$) and also the feed ($f$) as shown in Table 1.

| Parameters                        | Values  |
|-----------------------------------|---------|
| Cutting Speed, $V_c$ (m/min)      | 80, 100, 120 |
| Feed (mm/tooth)                   | 0.05    |
| Radial Depth of Cut, $a_e$ (mm)   | 5, 7.5, 10, 20 |
| Axial Depth of Cut, $a_p$ (mm)    | 0.5     |
| Tool Holder Diameter (mm)         | 20      |
| Milling Operation                 | Down Milling |

The cutting tool used in this study was Sandvik Coromant TiAlN coated carbide insert. The inserts were placed on 20 mm diameter holders with three inserts on a single holder. The tool overhang of 65 mm was maintained throughout experiment. The Inconel 718 work samples used for the side milling experiments were of 130 mm x 50 mm x 16 mm dimensions. The table below shows the composition of Inconel 718 by wt. %.

| Element | Ni | Cr | Nb+Ta | Mo | Al | Si | Mn | Fe |
|---------|----|----|-------|----|----|----|----|----|
| % wt    | 52 | 19 | 5     | 3.05 | 0.5 | 0.3 | 0.2 | 18.5 |

In this study, the flank wear is measured at the depth of cut length on the flank face using the Tool Maker’s Microscope with 1X magnification. The cutting force was measured using the Kistler 9254 Dynamometer. In this study, the dynamometer measures the cutting force exerted by the cutting tool during the first cut. The dynamometer work table detects the force of the cutting tool when the cutting tool starts to cut the work piece, it will transmit a signal to the amplifier that passes and converts the signal into the value of the cutting force, the value was displayed on the computer using the dyno software. The output was be displayed in the form of a graph of cutting force versus time. The cutting force was taken for the first pass at 50 mm length for a single pass.

3. Results and discussions

3.1 Effects of Radial Depth of Cut on Resultant Cutting Force
The measured experimental resultant cutting forces were plotted against cutting speeds for different radial depth of cuts for the first cut. From figure 1, it is observed that the resultant cutting force increase with increasing radial depth of cut for each cutting speed. At cutting speed of 80m/min, the cutting force at radial depth of cut of 5mm was 26.44N, the value of cutting force increases to 40.61N and 59.10N at radial depth of cut of 7.5 and 10mm before it spikes to 153.96N at radial depth of cut of 20mm.

At cutting speed of 100m/min the value of cutting force at radial depth of cut of 5mm was 30.55N. As the radial depth of was increased to 7.5mm, the cutting force increases slightly to 39.42N. A significant change in cutting force was then seen when it reached 87.03N at radial depth of cut of 10mm and 117.29N at radial depth of cut of 20mm.

![Figure 1](image)

**Figure 1.** Graph of cutting force against Cutting speed at different radial depth of cut

The values for cutting forces at cutting speed of 120m/min for radial depth of cut of 5 and 7.5mm were 26.8N and 36.13N. The value at radial depth of 20mm was the largest among all parameters which was at 164.1N. The increase of cutting force with increasing radial depth of cut is due to the size of cut per tooth increases as the radial depth of cut increases [11]. In addition, the findings are similar to that of Kasim et al. [12] that states, the increase in cutting force due to increasing radial depth of cut is because of the small entry angle of wider radial depth of cut which results in higher tangential force while the narrow radial depth of cut has wider entry angle which results in lower tangential force. The tangential force in the experiment was also found to be only slightly different to the resultant force. The results obtained due to the effects of cutting speed are comparable to the study of Liao et al. [13], it was reported that in slot milling at 124m/min there is only small amount of chip flow out of the cutting zone. Most of the chips are pushed to the side of the slot and they are piece-wisely stacked. The chips welded on both sides of the slot retarding chip flow and cutting temperature will increase because the heat generated cannot be dissipated with the chips. At this moment, the cutting force will increase rapidly. The lowest cutting force on the other hand was obtained at cutting speed 101.8m/min, this was resulted from the smaller material removal rate that causes the rate of temperature rise to decrease. This reduced the strain hardening to an extent.

This explains why the cutting force in full immersion for this study was highest at 120m/min and lowest at 100m/min. Hence, it is essential to maintain cutting speed within the range of 90-110m/min so that even if softening of work material occurs on one hand, carbide tool can still retain its cutting ability. It is also mentioned by Liao et al. [13] that for side milling which can be related with radial depth of cuts of 5, 7.5 and 10 mm in this study, there is not much variation of chip type for speeds in the range of 33.9-101.8m/min and the force is quite stable. The chip starts to become disintegrated again at cutting speed of 135.7m/min and only starts to weld together at the speed of 147m/min.

### 3.2 Effects of Radial Depth of Cut on Cutting Force Components
Figure 2 shows the values for the cutting force components (F_x, F_y and F_z) for the radial depth of cut of 5, 7.5, 10 and 20mm. The cutting force components for radial depth of cut of 5 mm, 7.5 mm and 10 mm shows that the highest cutting force obtained is F_y followed by the F_z and lastly F_x. The reason being in down milling, the force in the y-component is the sum of two resolved components in the cutter system of cutting forces [6]. This result is similar to that of Alauddin et al. [6] in his study of cutting forces in end milling Inconel 718 in which the cutting forces in down milling operations increases with increasing axial depth of cut.

For radial depth of cut of 5mm (figure 2 (a)), the highest value for F_y is at cutting speed of 100m/min while the values for F_x and F_z at this cutting speed is the lowest. The values for F_y at speeds of 80m/min and 120m/min are similar ranging from 18.9-20.24N, the same can be said for F_x whose values range are between 7.2-9.4N and F_z between 15.8-16N.

For radial depth of cut of 7.5mm (figure 2(b)), the largest value for F_y is 30.5N at cutting speed of 80 m/min the values for F_y at 100 m/min and 120m/min only differs slightly within the range of 27.9-28.2N. The value for F_z at in this depth is highest at cutting speed of 100 m/min and lowest is at cutting speed 120m/min at a value of 22.3N, it can also be seen in figure 2(c) that the values for F_z and F_y are identical at each cutting speed.

For radial depth of cut of 10mm, we can observe from Figure 2 (c) that for F_x, F_y and F_z, the highest cutting force obtained is at cutting speed of 100m/min while the lowest cutting force is at cutting speed of 80m/min.
For radial depth of cut of 20mm, the dominant cutting force is at $F_z$, followed by $F_x$ and $F_y$ has the lowest values of cutting force as observed in Figure 2 (c). The highest value for $F_z$ is at cutting speed of 80m/min at 129.8 N, it decreases to 83.3 N at cutting speed of 100m/min and as the cutting speed is increased to 120m/min, the value of $F_z$ increases to 107.5 N. $F_x$ decreases slightly as the cutting speed increases from 80m/min to 120m/min before it reaches the highest value of $F_x$ (101.9N) at cutting speed of 120m/min. The increase of cutting force in $F_z$ and $F_x$ is also due to the same reason why the resultant cutting force in full immersion from the previous section is so high. Most of the chips are pushed to the side of the slot and they are piece-wisely stacked. The chips welded on both sides of the slot retarding chip flow and cutting temperature will increase because the heat generated cannot be dissipated with the chips. This causes the tool to exert more cutting force in order to maintain its cutting path.

3.3 Tool Wear

Figure 3 shows the effect of cutting parameter on the flank wear in the first cut. The effect of radial depth of cut on tool wear can be observed by keeping the feed rate constant and compare it in the same cutting speed. At each cutting speed, we can clearly see the increase in flank wear as the radial depth of cut is increased at each cutting speed. At cutting speed of 80m/min, the flank wear increases from the value of 0.063mm at radial depth of cut of 5mm up to 0.175mm at radial depth of cut at 20mm. The same can be said for the cutting speed of 100m/min where the flank wear starts at 0.057mm at radial depth of cut of 5mm to 0.172mm at radial depth of cut of 20mm. The flank wear at cutting speed of 120m/min and radial depth of cut of 5mm is at 0.068 which is the highest at the radial depth of cut of 5mm and the flank wear at 20mm is at 0.151mm which is the lowest for radial depth of cut of 20mm compared to the other cutting speed. The findings are similar to that of Hadi et al.[1] in his comparison between tool wear in up and down milling operations and concluded that tool wear increases with increased depth of cut.

![Figure 3: Tool Wear of first cut at each cutting speed at each radial depth of cut](image)

5. Conclusions

There are several conclusions based on the study conducted

1. The cutting force increases with increasing radial depth of cut. The maximum cutting force obtained is at cutting speed of 120m/min and radial depth of cut of 20mm.
2. The highest force component in down milling is the $y$-component for radial depth of cut of 5mm to 10mm.
3. Tool wear increases with increasing radial depth of cut with the maximum wear occurring at parameters 80m/min and radial depth of cut of 20mm at a value of 0.175mm.
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