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Cutting Force Investigation of Trochoidal Milling in Nickel-Based Superalloy

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Abstract

The gas turbine, aerospace and nuclear industries are dependent upon nickel-based superalloys to enable these industries to continue to innovate. Without these materials the industries would fail to achieve new heights of efficiency as the strength and operating temperature requirements continue to climb. Nickel-based superalloys thrive in these elevated temperature applications, where their great resistance to creep and corrosion is coupled with remarkably high strength values. These same characteristics that are invaluable to the final operating environment severely degrade their machinability with high cutting forces and aggressive rate of tool wear.

Although the field of machining research is very well established, when it comes to nickel-based superalloys there is a large amount of that is yet to be understood. Trochoidal milling has been identified to extend tool life and reduce machining time in the milling of aluminums, however in nickel-based superalloys it remains largely unexplored. This work aims to understand the cutting force behavior of milling nickel-based superalloys using this alternative milling technique.

Keywords: Milling, Path Planning, Superalloy, Trochoidal Milling, Cutting Force

1 Introduction

For elevated temperature environments where high strength requirements exist, superalloys are one of the few materials that can be utilized. While there are various forms of superalloys, the most widely adopted are nickel-based superalloys, which account for more than 80% of usage in the aerospace industry (Arunachalam, 2000). These alloys are also heavily utilized in the energy production industry, serving great importance to steam and gas turbines, the automotive industry, and the biomedical industry (M'Saoubi *et al.*, 2008). Serving as the material of choice for gas turbines and jet engine blades and vanes, the materials must withstand hot corrosion and fatigue while demonstrating significant mechanical strength at elevated temperatures, which are routinely above 2000°F (Ezugwu *et al.*, 1999).

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With increasing demand for these alloys it is of great importance to fully understand their machinability. It has been identified by previous researchers that the very properties give these alloys their desirable and unique characteristics at elevated temperatures, negatively impact their machinability, in turn increasing the cost to manufacture components made from them (Arunachalam & Mannan, 2000; Ezugwu *et al.*, 2005). Properties such as rapid work hardening, exaggerated by the austenitic matrix, and low thermal diffusivity work together to greatly reduce the tool life. Although the low thermal diffusivity causes much of the heat generated during the milling process, resulting from the rubbing process and tool work piece friction, back into the tool, the work piece still increases in temperature (Sivasakthivel *et al.*, 2010). In the case of nickel-based superalloys, they are designed to increase in strength and hardness as temperature increase, which works against tool life in the form of increasing stresses on the tool tip (Liao *et al.*, 2008; Ulutan *et al.*, 2011).

With aggressive tool wear it is necessary to understand the types of tool wear that occur during the milling process of nickel-based superalloys in order to better their viability in industry. Today there are no identified exclusive types of tool wear that occur with these alloys, therefore the wear is still due to adhesion, abrasion, and diffusion (Ezugwu, 2005). These mechanisms result in notch wear, flank wear, chipping, and built up edge formation (Thakur, 2009). While many of these mechanisms occur simultaneously, previous researchers have identified two prominent failure modes in the milling of nickel-based superalloys: significant flank wear and notch wear (Li *et al.,* 2006; Thakur, 2009; Krain *et al.,* 2007). Notch wear is of particular interest to many researchers as it leads to catastrophic failure that is difficult to predict in some applications (Coelho *et al.,* 2004). The development of the notch has been thoroughly studied and has been identified to start as pitting, and then over time transforms into localized chipping, which then grows and establishes itself as a notch (Jawaid *et al.,* 2001).

To better the manufacturing of components from superalloys and to reduce their manufacturing costs, reliable tool wear models must be established (Kasim *et al.,* 2013). While Taylor's tool life still serves as the basis for much work, there have been many recent investigations on predicting the cutting forces during milling (Schmitz *et al.*, 2009). Other researchers have found that the predictions must depend on statistical quantities when the main modes of tool wear include chipping (Childs *et al.,* 2000). For nickel-based superalloys there have been empirical updates that have identified the main effects of cutting speeds on tool wear and the overall force profile (Henderson *et al.,* 2010).

To further improve the productivity and the adoption of superalloy components researchers have turned to the tool path. A path that has found success in traditional materials is one that is a linear motion combined with a uniform circular motion termed trochoidal milling (Rauch *et al., 2009*). It is important to note that trochoidal milling is a term adopted by industry to label this cutting motion. The path in itself does not follow the mathematical definition of a trochoid and is more so a repeating circular pattern, however the name prevails. As the tool moves along the circular tool path, the cutting edge of the tool actually follows a true trochoidal pattern due to the combination of the rotational motion translation of the spindle and the translation of the tool itself, which has been established in conventional milling practices (Martellotti, 1941).

There have been modifications of the trochoidal strategy, such as the deployment of double trochoidal milling, where the cutter is engaged twice as much as standard trochoidal milling, therefore reducing the cycle time, but at the cost of higher cutting force (Otkur *et al.*, 2007). In the same study the authors developed a numerical algorithm to predict the engagement of the cutter for given surfaces for face milling operations. Through the prediction of the engagement, the cutting forces were also predicated, however the specific force profile was not thoroughly detailed. Trochoidal milling has been shown to reduce tooling loads and temperatures, in turn creating favorable conditions for extending tool life (Wu *et al.*, 2013).

Trochoidal milling in superalloys has a limited amount of work completed in it, however one study showed that trochoidal milling could machine at least seven times more material than a standard end milling tool path (Pleta *et al.,* 2015). In the same study it was also found that trochoidal milling suffered from the formation of notch wear at the axial depth of cut line, however this study did not examine the cutting forces of the tool path in any capacity.

2 Experimental Design and Setup

All tests in this study utilized Inconel 738 as the test block material, which was cut from a single parent block of material using electrical discharge machining to reduce material variability between tests. The milling was completed on an Okuma GENOS M460-VE three-axis CNC milling machine equipped to measure cutting forces. These forces were measured by a Kistler 9257B piezoelectric dynamometer, which was mounted to the table of the machine and aligned accordingly to measure forces in all three axes. The cutting force signals were amplified utilizing a Kistler amplifier and recorded with Dynoware software. For repeatable force measurements and to ensure accurate alignment for each test, the work piece is mounted directly onto the dynamometer utilizing custom fixturing. All tests were run using the same tool, a two-flute indexable end mill with a 15.875 mm diameter with Sandvik Coromill R390-11T308M-PM-1030 carbide inserts with multilayer TiAlN coating by way of physical vapor deposition (PVD). Flood coolant was applied throughout each test with a concentration of 6.5% as recommended by the supplier.

New, unused inserts where used for each test in this study and at the completion of each test the tool wear was measured using digital microscope photography. The trochoidal slots were milled with a constant slot width of 30 mm, with two levels of cutting speed, three levels of feed and three levels of axial depth of cut which can be seen in Table 1.

Table 1: Milling parameters for trochoidal milling

Parameter	Unit	Low Condition	Medium Condition	High Condition
Cutting Speed	m/min	25	-	50
Feed	mm/rev	0.1	0.2	0.3
Depth of Cut	mm	2.0	5.0	8.0

As mentioned before the trochoidal tool path is best described as a uniform circular motion with a linear motion. The traditional trochoidal path uses a constant feed rate throughout the cut, and at the expense of time continues to follow this federate while continuing in the uniform circular motion while out of cut. This can be seen in Figure 1a, with the portion of the tool path while out of cut represented by the dashed line. In this study the authors propose a time saving method by eliminating the out of cut circular motion and replace it with a rapid linear movement represented by the dashed line in Figure 1b. The tool path is constructed in a way to ensure that the rapid movement only takes place while out of cut and progresses the typical circular feed as the tool enters and exits the work piece. The standard trochoidal milling tool path can be represented through the radius of the planetary motion (R), the position of the tool center with respect to the X and Y axes (θ), and the step over (w), which is the linear index motion, which can be seen in equation 1.

$$\begin{cases} X_c = R\sin\theta + \dfrac{\theta w}{2\pi} \\ Y_c = R\cos\theta \end{cases} \tag{1}$$

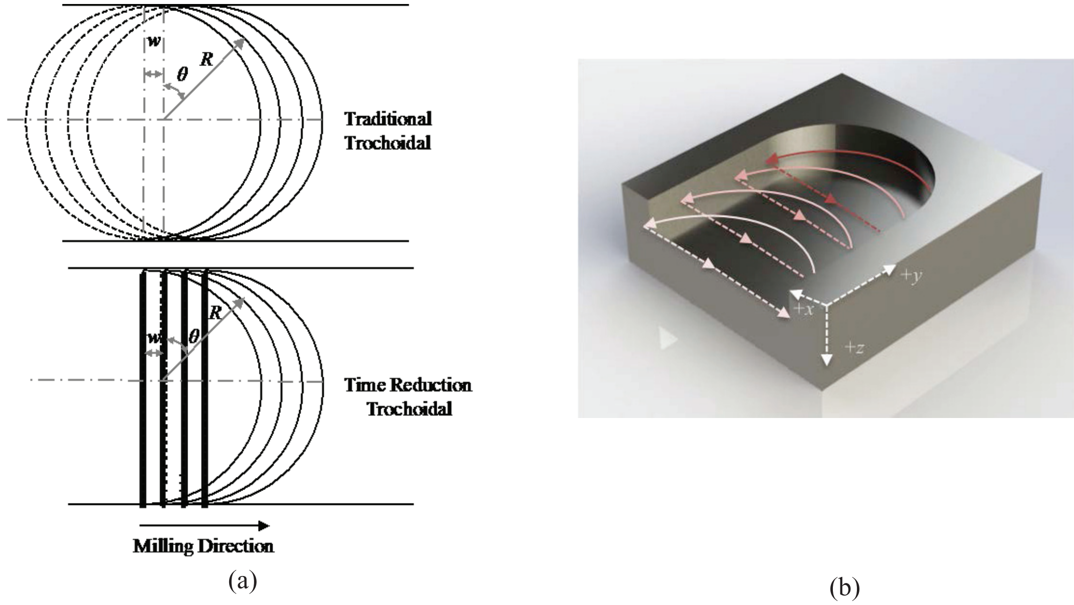

Figure 1: Trochoidal milling tool path: (a) 1D representation of traditional and authors' proposed path (b) 3D representation of authors' proposed path

3 Approach

While the trochoidal tool path has been studied while being deployed in more traditional materials, such as aluminum and steel, there has been very little previous work in nickel-based superalloys. It must be noticed, however, that trochoidal milling has shown promise in milling IN-738, where it was identified that the tool life was prolonged but at the cost of machining time (Pleta, 2014). While this work demonstrated an initial starting point for the exploration of this milling technique, it left much to be understood outside of the effects of milling parameters on output parameters. Therefore, the aim of this paper is to better understand trochoidal milling in nickel-based superalloys by analyzing the machining force for various milling parameters. Furthermore, the effects of machining parameters and machining force are related to a detailed study of the surface finish of the final part.

For each test condition three separate slots were cut in the material, one being a full slot (60 mm), one a half-length slot (30 mm) and a quarter-length slot (15mm). This was done to understand the progression of tool wear during as it relates to slot length, which can also be processed as the volume of material removed (*MR*) with units of mm^3.

4 Results and Discussion

A snapshot of the captured force profile of a trochoidal milling pass can be seen in Figure 2. The captured data here is an excerpt from the full slot trial and displays three trochoidal passes out of the total 113 passes required for a 60 mm slot using a step over of 0.66 mm. The direction of the cutting forces are in the same direction as those which are given in Figure 1. The cyclic nature of the cutting forces is due to a continuously varying radial engagement throughout each trochoidal pass. The radial depth of cut starts at zero, increases to *w* when at the center point of the arc and then decreases to zero again as it exits the arc. This can be seen in Figure 2 where the forces show a cyclic nature, where F_x and F_y are approximately zero at the start and end of each trochoidal pass where the tool is not engaged with the material. It can be gathered that the axial force (F_z) increases as the cutter reaches its maximum axial depth of cut at *w*, and then decrease as the depth of cut does. This behavior remains stable and repeatable throughout the entirety of the process.

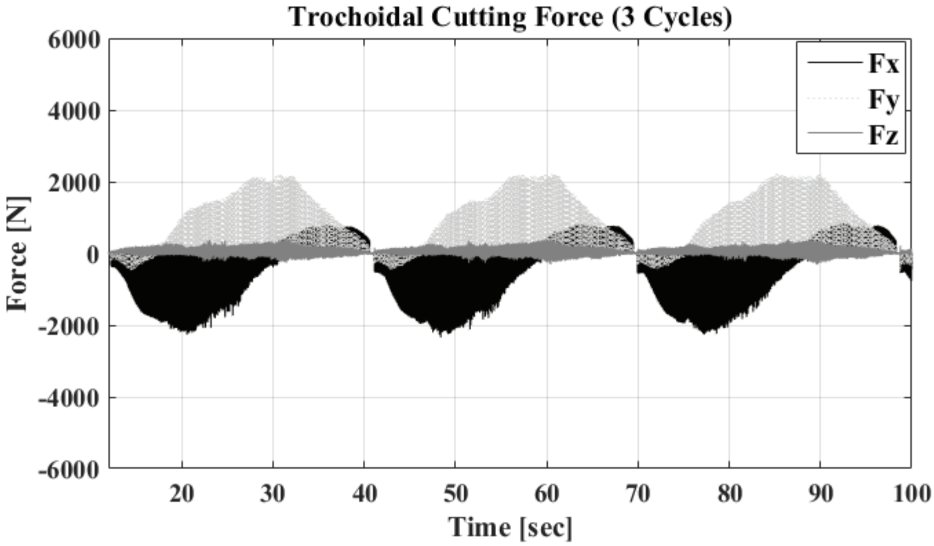

Figure 2: Trochoidal cutting force for slot

When observing the x-component of the force, it builds in the negative direction as it begins cutting against the wall of the slot. After continually decreasing, the x-component reaches it largest negative value and then moves towards zero, which occurs at the center point of the trochoidal arc, and increases in the positive direction. This behavior is the direct result of the milling direction. As the cutter moves throughout the first half of the arc, the cutting edge is imparting force against the slot wall in the negative direction. As the tool reaches the center point of the arc, the forces are then against the slot wall in the positive direction. The y-component of the force follows a similar cyclical trend, where it reaches its maximum value just as it enters the center point of the arc, where it then decrease as the feed direction changes after the center point. Whereas the x-component of the force is a result of the milling direction, the y-component is more dependent on the engagement of the cutter.

The engagement of the cutter is low at both the beginning and end of the trochoidal movement, corresponding to the low y-component of the force in these regions. As the cutter nears the center point of the arc the engagement begins to increase, therefore increasing its force component, where it reaches its maximum at the center point of the arc. A visual display of the engagement can be seen in Figure 3 where all three images were taken at the same scale and magnification on a Zygo white light interferometer. These surface roughness measurements display the cutter path and the engagement. It can be seen in Figure 3a and 3b, that the regions at the beginning of the arc, closest to the left and right slot walls, the engagement is low, whereas Figure 3b shows the center point of the arc, yielding the highest engagement. Analytical modeling of this behavior will be contained in future work.

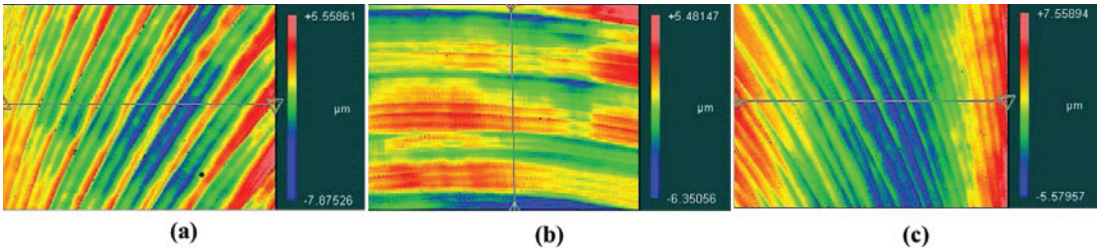

Figure 3: Surface roughness images displaying engagement of tool (a) left most region of arc with low engagement (b) center point of arc with maximum engagement (c) right most region of arc with low engagement

To gain a better understanding of the process Figure 4 was constructed which displays the cutting force over two revolutions of the tool for the two-flute tool. It is apparent from this figure that there is a noticeable amount of run out error between the cutting teeth which account for a 4% difference in maximum F_y and a 14% difference in F_x.

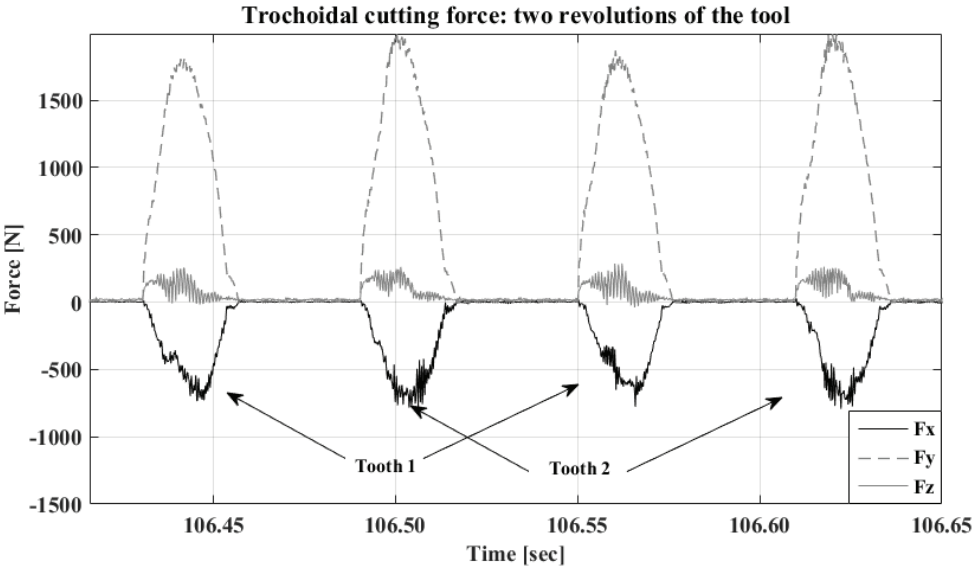

Figure 4: Filtered cutting force for two revolutions of the tool

One of the main advantages of trochoidal milling found by previous researchers was an increase in tool life. By examining force plots throughout the milling of a slot, it was found that the force increase with tool wear, which is a well understood phenomenon which can be seen in Figure 5. In Figure 5, the beginning of the slot chart was constructed after 835mm^3 of material removal and the end of the slot chart was constructed after 14,040mm^3 of material removed. Further observation shows that while F_x exists as a largely negative force in the beginning of the slot, when the tool has little wear. When the tool does incur wear, the x-component of the force undergoes an upward transformation into the positive region. Furthermore, the y-component of the cutting force grows in magnitude in both the negative and positive directions. The resultant force showcases the overall behavior with an upward shift, resulting in a higher average force with the increase in tool wear.

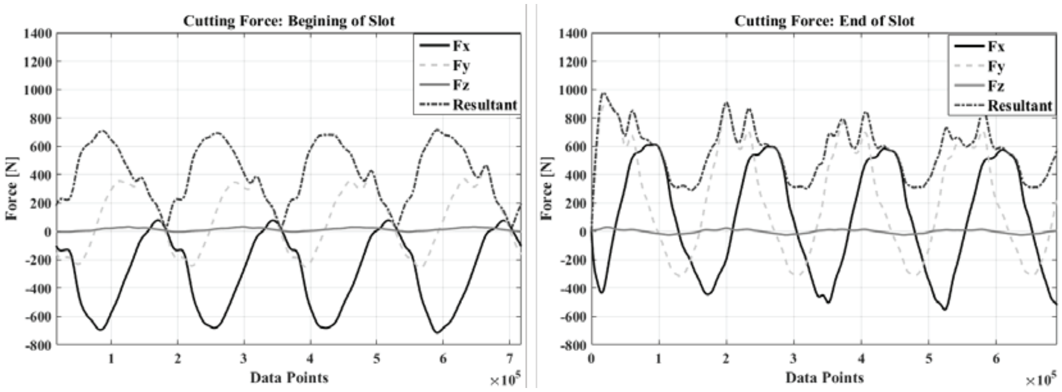

Figure 5: Tool wear influence on cutting force

While the trochoidal tool path exhibits a stable tool wear rate in the conditions above, it has been found that through the development of notch wear in the tool, catastrophic failure can occur. With materials that have better machinability such as aluminums and steels, failure due to notch wear is less severe when compared to superalloys, due to their strength and toughness. Figure 6 captures this behavior occurring at an axial depth of cut of 5 mm with a feed rate of 0.3 mm/rev and a cutting speed of 50 m/min. The standard force increase of the F_y component is typically a 0.5% difference from peak to peak (pass to pass), however in the case of tool failure the difference approaches a 40% difference. The tool failure is most noticeable in the resultant force and F_y, with the other forces only indicating a marginal shift.

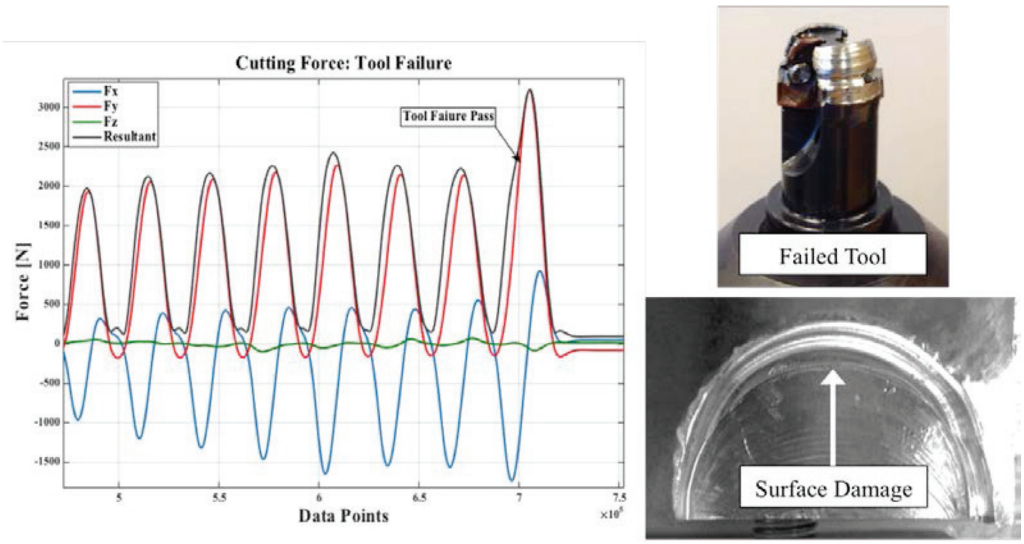

Figure 6: Tool failure identification with material surface damage

5 Conclusions

In this study, the cutting force of trochoidal milling was examined while cutting nickel-based superalloy. It was determined that the cutting force increases over the length of the slot, and does so at a stable rate. This increase in cutting force was determined to be due to the increase in tool wear, which was predominantly flank wear with secondary notch wear. This study also examined catastrophic tool failure, which could be seen with a high variation of the peak-to-peak y-component force. The cutting force profile of trochoidal milling in IN-738 was also analyzed, where it was determined that the x-component of the cutting force results from the feed direction of the tool, whereas the y-component of the force is dependent upon the engagement of the cutter. It was determined that this failure was likely associated with the development of notch wear, leading to tool failure due to the strength of the work piece. Future work will include an analytical engagement model and cutting force model, specifically for IN-738 and a tool wear study to determine at what point in the trochoidal milling process that the formation of notch wear manifests itself.

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