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Abram Pleta
Clemson University

Durul Ulutan
Clemson University

Laine Mears
Clemson University, mears@clemson.edu

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An Investigation of Alternative Path Planning Strategies for Machining of Nickel-Based Superalloys

Abram Pleta*, Durul Ulutan, and Laine Mears
Clemson University International Center for Automotive Research, Greenville, SC.
apleta@clemson.edu, dulutan@clemson.edu, mears@clemson.edu

Abstract

Nickel-based superalloys play a crucial role in elevated temperature applications where high strength and high resistance to corrosion and creep resistance are required. These environments are largely found in the aerospace, nuclear power and gas turbine industries. Due to the properties that make them suitable for their end use they remain a challenge to manufacture. In the machining of nickel-based superalloys high cutting forces and tool wear occur greatly reducing their machinability. Although there have been multiple recent studies on the machining of such alloys, the field remains vastly unexplored. A limited amount of research has been done in tool path methods, as most previous research focuses on finding optimal machining parameters to curtail the difficulties in machining while keeping the tool path constant. An alternative tool path, trochoidal milling, has been identified to combat the difficulties in machining superalloys and combines linear motion with uniform circular motion, reducing chip load in exchange for increased machining time. Although this method has been shown to reduce flank wear on tools it suffers from notch wear at the depth of cut line.

In this study the authors propose and evaluate a new tool path termed variable depth milling (VDM) to reduce or eliminate the occurrence of notch wear in nickel-based superalloys. In this method the axial depth of cut is varied across the tool in a linear fashion, progressing from a maximum depth of cut value to zero in an upward ramping fashion. This work characterizes the effects of trochoidal milling and variable depth milling techniques and compares them against a traditional milling technique, end milling. In order to compare these alternative tool path approaches directly to end milling the authors utilize relatively new metrics to provide a more representative comparison of productivity and efficiency characteristics: volumetric material removal per unit tool wear (MR/VB) and the material removal rate per unit tool wear (MRR/VB). It was found that trochoidal milling was superior to end milling in terms of productivity, where trochoidal could machine at least seven times more material than end milling with the same amount of tool wear with similar efficiency as end milling. It was demonstrated that VDM eliminated the formation of notch wear in the cutting tool at the expense of a slight decrease in productivity and efficiency.

Keywords: Milling, Path Planning, Superalloy, Trochoidal Milling, Variable Depth Milling, Notch Wear

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[*] Corresponding author

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1 Introduction

Nickel-based superalloys are designed for use in extreme environments where high corrosion and creep resistance are required, and high strength needs to be maintained even at elevated temperatures. These environments are largely found in the aircraft, nuclear power, and gas turbine industries where nickel-based superalloys play a crucial role (Ulutan & Ozel, 2011) As the metallurgy of the alloys is getting progressively better for their operational environments, they are getting more difficult to machine (Nowotnik, 2008; Ranganath *et al.,* 2009). The demand for nickel-based superalloys is not slowing, especially with the growth of the aircraft and gas turbine markets, thus necessitating a cost-effective method to manufacture high quality components (M'Saoubi *et al.,* 2008; Guo *et al.,* 2009).

Advancing the manufacturability of such alloys has large impacts on the industry as 45-50% of the total material required in the manufacturing of an aircraft engine is nickel-based superalloys (Ezugwu *et al.,* 1999). Material properties such as rapid work hardening of the material due to the austenitic matrix, low thermal diffusivity and high amount of carbide particles, leading to high tool wear, make nickel-based superalloys extremely difficult to machine (Ezugwu *et al.*, 1992).

Although the manufacturing challenges persist in these alloys, milling remains as the most common manufacturing method (Arunachalam *et al.*, 2000). A significant amount of heat is generated in milling due to the rubbing process, as well as the friction between the workpiece and the tool (Sivasakthivel *et al.*, 2010). When milling nickel-based superalloys, this heat generation is further intensified by the low thermal diffusivity of the material therefore increasing the problems encountered in milling (Shaw, 2005). Despite low thermal diffusivity, the workpiece still increases in temperature, and in the case of nickel-based superalloys, the hardness increases with temperature (Liao *et al.*, 2008). Rapid work hardening of the material results from microstructural alterations of the machined subsurface where excessive strain takes place, and the austenitic matrix. This increases the stress on the tool tip, leading to high tool wear and increasing difficulty to make sequential cuts (Ulutan *et al.*, 2011; Axinte *et al.*, 2006).

Of the various types of tool wear that occur in milling, notching is of great importance when dealing with nickel-based superalloys, as this type of tool wear causes catastrophic or instantaneous tool failure. The dominant factors in the manifestation of notch wear are the welding and adhesion of the workpiece material onto the cutting tool which causes removal of the tool coating and the tool substrate (Li *et al.*, 2002). Researchers also found that built up edge (BUE) is formed by high pressure and chemical affinity of the tool (Krain *et al.*, 2007).

Notch wear manifests itself as pitting in its early stages. Through multiple tool rotation cycles, the pitting is worsened and initiates localized chipping, in turn leading to notch wear (Jawaid *et al.*, 2001). With BUE formation and changes in the tool geometry, the friction at the cutting edge of the tool increases, leading to an increase in cutting temperature. This further weakens the bond between the tool coating and the tool substrate material leading to high amounts of wear (Jawaid *et al.*, 2001). Fragments of the tool can sometimes be dislodged as the BUE breaks off, acting as a mechanism of wear (Jawaid *et al.*, 2001). Other researchers have identified pitting transforming into notch wear when milling, and that it occurs on both the flank and rake faces of the tool near the depth of cut (DoC) line (Sharman *et al.*, 2001; Krain *et al.*, 2007; Kasim *et al.*, 2013).

Due to the increase in demand for nickel-based superalloys, many researchers have begun to develop models to predict the behavior of milling these materials. Milling itself is difficult to model due to the multi-tooth interrupted chipping, non-uniform chip loading and the variation of the cutting force direction (Zhang *et al.*, 2009). Models were developed to predict the cutting forces during milling (Schmitz *et al.*, 2009), and empirical updates to these models were used in assistance to apply them to slot and end-milling processes in superalloys, concluding that the increase in the average cutting forces in time can be attributed to tool wear and that cutting speed had a significant effect on overall tool wear and force trends (Henderson *et al.*, 2010). These trends were related to the chip formation mechanisms. The resultant cutting force also increased with increasing axial depth of cut and feed rate.

With greater understanding of the mechanisms of tool wear and cutting force in standard machining operations in nickel-based superalloys, researchers have begun to investigate nontraditional milling tool paths. Paths such as trochoidal milling have been introduced to better meet the challenges that difficult-to-machine materials present such as high cutting forces and rapid tool wear. The trochoidal tool path is a combination of uniform circular motion with uniform linear motion and can be seen in Figure 1(Rauch *et al.*, 2009). Researchers have found that tool loads and cutting temperature are greatly reduced when utilizing trochoidal milling in place of conventional milling (Wu *et al.*, 2013). Despite findings that show higher cycle times in trochoidal milling, it has been demonstrated to reduce cutting forces, especially in critical cutting regions such as sharp corners and narrow slots (Ibaraki *et al.*, 2003) and (Ibaraki *et al.*, 2010).

Researchers have also studied the time optimization of the trochoidal tool path. To this end, they introduced a double trochoidal path that doubles the time that the tool is engaged in the part therefore reducing the cycle time, but at the cost of increased cutting forces (Otkur *et al.*, 2007). They also introduced numerical algorithms that are able to predict cutting forces for the trochoidal path. A limited amount of work has been completed with trochoidal milling in nickel-based superalloys; however in a previous work by the authors, it was found that while the efficiency of trochoidal milling was slightly less than that of end milling, the productivity of the process was far superior (Pleta *et al.*, 2014).

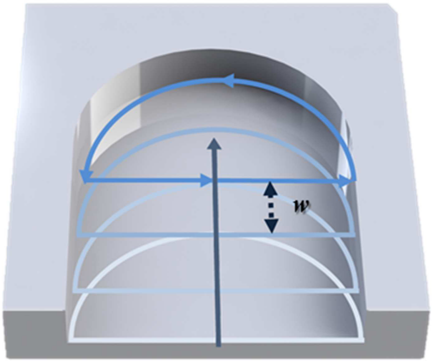

Figure 1: Trochoidal milling tool path

The trochoidal milling tests exhibited lower average flank wear (*VB*) than end milling for a given volumetric material removed, however the tools also exhibited notch wear at the depth of cut line. In an effort to reduce the notch wear, an alternative tool path method termed Variable Depth Milling (VDM) is proposed in this study, where the focus is to understand the effects of machining parameters on trochoidal and variable depth milling tool paths to allow for tool path optimization strategies. To do so, this work is comprised of two parts: The first part provides an analysis on trochoidal milling and a comparison of it to standard end milling with respect to alternative productivity and efficiency metrics. The second part of the study provides a detailed analysis on the effects of VDM parameters and their relation to standard machining outputs.

To better understand the effects of alternative tool path parameters, trochoidal and variable depth, their machining outputs, namely resultant force, tool wear and surface roughness are investigated. In this study, the occurrence of notch wear in the tool is of specific interest. Additionally, the productivity and efficiency of each process is investigated utilizing new metrics of comparison.

Normalizing the total material removed (MR_{tot}) and the total material removal rate (MRR_{tot}) with average flank wear (VB) allows for a better description of productivity and efficiency, respectively. Standardizing these commonly used metrics with tool wear provide a better means to understand nonconventional tool paths in milling, and makes optimization of conflicting manufacturing objectives such as efficiency and tool life much easier.

2 Experimental Design and Setup

All tests in this study were completed on a gamma-prime strengthened nickel-based superalloy. The workpieces have dimensions of 80 x 60 mm, and were cut from the same block to reduce material variability. The tests were run on an Okuma GENOS M460-VE three-axis CNC milling machine. A three-axis piezoelectric dynamometer (Kistler 9257B) is mounted on the table of the machine and measures the cutting forces in all three axes. The cutting force signals are amplified with a Kistler amplifier and subsequently recorded using Dynoware software. To allow for repeatable alignment of the experimental workpieces, they are mounted on the dynamometer utilizing custom fixturing. The surface roughness for each test was completed utilizing a Mahr profilometer taking multiple measurements for each test to gather data for an average surface roughness value. Through the use of digital microscope photographs, the average flank wear (VB) was measured along the cutting edge of each insert. Fresh unworn inserts were utilized for each test in this study.

Standard end-milling and variable depth milling tests were run using a constant radial depth of cut of 9.5 mm, corresponding to 60% tool engagement, for each 60 mm linear path cut. Eight different cutting conditions were investigated constituting of two levels of three parameters with a full design of experiments structure (Table 1). The ramping tool path for each variable depth milling test was held constant for each condition of axial depth of cut. Similarly, trochoidal milling tests were completed at similar (but suitable for trochoidal milling) sets of parameters (Table 2). The width of the trochoidal slot was kept constant at 30 mm and the stepover distance w (Figure 1) was kept constant at 0.66 mm.

Table 1: Milling Parameters for End Milling and Variable Depth Milling

Parameter	Unit	Low Condition	High Condition
Cutting Speed	m/min	25	50
Feed	mm/rev	0.05	0.1
Depth of Cut	mm	0.25	0.5

Table 2: Trochoidal Milling Parameters

Parameter	Unit	Low Condition	High Condition
Cutting Speed	m/min	25	50
Feed	mm/rev	0.1	0.3
Depth of Cut	mm	2	8

For all tests in this study, Sandvik Coromill R390-11T308M-PM-1030 carbide inserts with multilayer TiAlN coating using physical vapor deposition (PVD) were utilized. They were mounted on a two flute indexable tool holder with a diameter of 15.875 mm. Flood coolant was used throughout all tests as advised by the insert manufacturer.

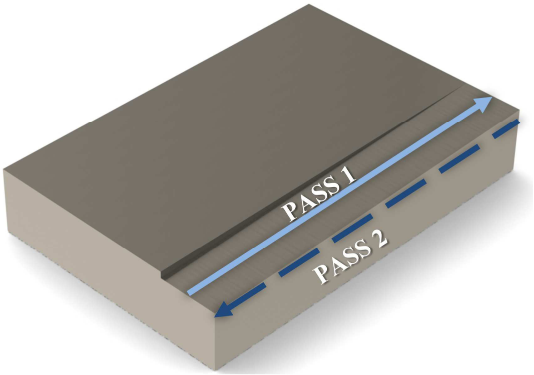

Figure 2: Variable depth milling tool path

3 Approach

The motivation of the trochoidal portion of this study was to investigate its potential to improve upon standard machining methods in nickel-based superalloys by greatly extending tool life. To compare this nontraditional tool path method to a standard milling technique, specifically end milling, the authors are utilizing recently established metrics of comparison for efficiency and productivity (Pleta *et al.*, 2014). These metrics were established to be able to compare machining process with different machining parameters.

To better describe the productivity and efficiency of the process, the authors propose the use of the recently established metrics: total material removed per unit of tool wear (MR_{tot}/VB) and the total material removal rate per unit of tool wear (MRR_{tot}/VB). These standardize commonly used metrics with tool wear and provide a better means to understand this nonconventional method of milling and make a comparison between different techniques that have distinctive machining characteristics. It should be mentioned that the tool wear (VB) measurement is taken at the completion of each test, which in turn corresponds to the amount of material removed (MR) at that point. It does not serve as a measure of the progression of tool wear in this study, but rather the amount of material that can be removed and the rate in which it is done per amount of wear.

The second part of this study was completed to better understand the effects of variable depth milling machining parameters on a gamma-prime strengthened nickel-based superalloy. The machining outputs of this study are focused on tool wear, surface roughness and resultant force. Also of interest are the productivity and efficiency metrics previously proposed by the authors.

The tool path for this portion of the investigation is a straightforward, yet effective solution to reduce the amount of notch wear in milling nickel-based superalloys. The first pass starts at the axial depth of cut and feeds through the material at a constant feed rate, ramping upward to gradually decrease the depth of cut until the tool reaches the top surface of the block at the far end of the block (Figure 2). This way, the upper triangular portion of the slot is removed in the first part of the pass. Once the tool exits the workpiece, it is lowered back to the original depth of cut and moved in the opposite feed direction to remove the lower triangular portion of the slot. It is again set to the axial depth of cut value and progresses at a constant feed and constant z-level until it exits the workpiece, with the depth of cut gradually decreasing to zero. When analyzing the results of the VDM machining operation, resultant force values for both portions of the pass are reported; resultant force 1 (upward ramping) and resultant force 2 (return pass). The maximum machining force during the cuts is reported as the induced force in this process; however, doing so means the force values are comparable to end milling tests and not representative of the full capability of the VDM process.

4 Results and Discussion

4.1 Trochoidal Milling

This part of the study focuses on trochoidal milling characterization and its comparison to standard end milling with respect to productivity and efficiency metrics. Through the use of a full design of experiments (Table 2), it was found that an increase in the axial depth of cut had the greatest effect on machining outputs (Table 3): The resultant cutting force increased by 336% and effects of similar magnitude were observed in both MR_{tot}/VB and MRR_{tot}/VB, increasing from 33 to 144 mm^3/µm (332% increase), and from 0.8 to 3.1 mm^3/min/µm (273% increase) respectively. Increases in MR_{tot}/VB indicate that a higher volume of material can be removed per tool, which results in a reduction in tooling costs. Depth of cut also had a significant effect on surface roughness (R_a), with an increase in DoC corresponding to a 56% increase although feed was the most significant parameter resulting in an 88% increase. These results can be seen in Figure 3.

Table 3: Trochoidal milling effects on machining output parameters

Machining Parameter	Effect of DoC	Effect of Cutting Speed	Effect of Feed
Resultant Machining Force	*336%*	*68%*	*184%*
MR_{tot}/VB	*332%*	*-25%*	*-28%*
MRR_{tot}/VB	*273%*	*30%*	*82%*
R_a	*56%*	*-8%*	*88%*

The feed also has a significant impact on the resultant force, representing a 184% increase from the low to the high condition. It was resulted that through an increase in depth of cut, the efficiency (MRR_{tot}/VB) and the productivity (MR_{tot}/VB) can be greatly increased if the process can tolerate an increase in force and a small increase in surface roughness. End milling test were completed (Table 1) to compare the trochoidal milling approach against. In terms of productivity, trochoidal milling proved to be superior to end milling with MR_{tot}/VB values ranging from 33 to 144mm^3/µm, whereas end milling ranged from 1.9 to 3.8mm^3/µm. It can be gathered that with the same tool, trochoidal milling can be used to machine at least seven times more material than end milling with the same amount of tool wear. The efficiency of trochoidal milling is comparable to that of end milling with MRR_{tot}/VB values in a much closer range than productivity. Trochoidal MRR_{tot}/VB values were in the range of 0.8 to 3.12mm^3/min/µm, while end milling resulted in the range of 1.7 to 3.7mm^3/min/µm.

While trochoidal milling extends overall tool life, it should be noted that it is sensitive to notch wear on the insert, especially at higher levels of axial depth of cut. This was the result of chip welding and chip hammering while undergoing the milling process. Utilizing high speed imaging, the chip welding and hammering were captured in Figure 4, where the chips are outlined in each image. Chips were observed to attach to the cutting face of the tool and remain attached for multiple revolutions of the tool, and then be ejected only to be replaced by another chip. Due to the strength and toughness of nickel-based superalloys, notch wear can cause catastrophic tool failure, providing the impetus to find an alternative tool path to reduce or eliminate the development of notch wear.

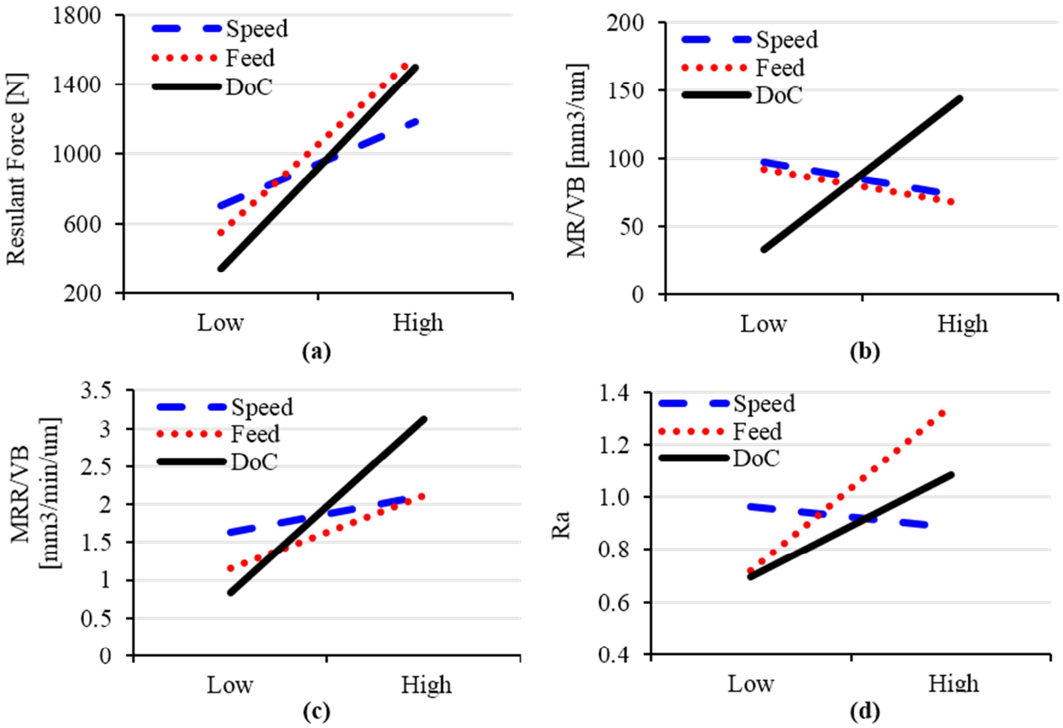

Figure 3: Trochoidal milling effects on (a) resultant force (b) MR/VB (c) MRR/VB (d) Ra

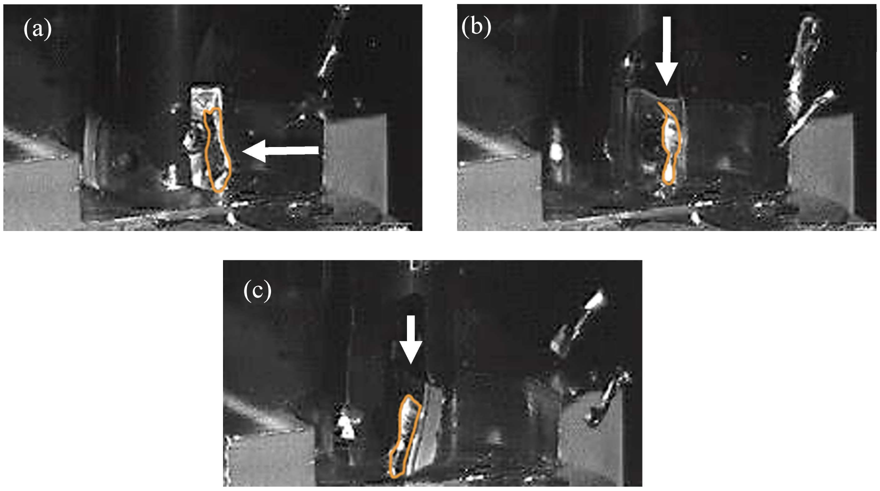

Figure 4: (a) Chip welding to tool inserts causing smearing and notch wear (b) after 45° of rotation (c) after 90° of rotation

4.2 Variable Depth Milling Characterization

Similar to trochoidal milling, the largest effect on machining outputs is due to an increase in the axial depth of cut (Table 4). The resultant cutting force for the two portions of a pass increased by 47% and 46%, respectively (Figure 5a) with increasing depth of cut. The cutting force on the return pass is reduced to the lack of ramping in the tool path. As previously described, the tool remains at a constant z-depth as it progresses across the block. This eliminates high forces that occur at the tool tip that the first pass incurs while ramping upward. Surface roughness increased by only 11% from 0.22 to 0.25 25 due to the increase in force resulting from the increase in depth of cut. The efficiency of the process (MRR_{tot}/VB) increased by 35% with an increase in depth of cut, however speed and feed were more influential. The most prominent influence of increasing depth of cut was doubling (1.78 to 3.53mm^3/µm) the productivity metric MR_{tot}/VB (Figure 5b). With a minor increase in force and an even smaller increase in surface roughness, the productivity and efficiency of the process increases by as much as 99% through an increase in the depth of cut.

Table 4: Variable depth milling effects on machining output parameters

Machining Parameter	% change with DoC	% change with Speed	% change with Feed
Resultant Cutting Force 1	*47%*	*10%*	*8%*
Resultant Cutting Force 2	*46%*	*-1%*	*-2%*
MR_{tot}/VB	*99%*	*-11%*	*-12%*
MRR_{tot}/VB	*35%*	*41%*	*36%*
R_a	*11%*	*4%*	*2%*

Cutting speed and feed have little effect on resultant force 1 (upward ramping) with a 10% and 8% increase, respectively (Figure 5a). Alternatively, it is demonstrated in Figure 5 that increasing cutting speed and feed did not change resultant force 2 significantly. The productivity of the process (MR_{tot}/VB) is also reduced by 11% with respect to cutting speed and 12% with respect to feed (Figure 5b). The most significant influence of cutting speed and feed is represented in Figure 5c, which shows increases to the efficiency of the process with increases of 41% and 36% respectively. From these results, it can be gathered that an increase in cutting speed and feed will improve the efficiency of the process by as much as 41%, however it will result in a corresponding reduction in productivity by 12% coupled with a small increase in surface roughness (Table 4).

To better understand VDM it was compared to a standard end milling process utilizing the same cutting feeds, speeds and axial depths of cut. Variable depth milling exhibited lower resultant forces than in end milling, in both pass one and two, with decreases of 41% and 56% respectively. This is due to the reduced depth of cut value for the VDM tool path that changes over the length of cut. Average flank wear increased by 12% with a corresponding decrease in surface roughness of 9%. With an increase in average flank wear both productivity and efficiency suffered, decreasing by 11% overall. Although the efficiency and productivity are reduced the process was shown to eliminate notch wear that occurred in the end milling tests, therefore reducing the probability of catastrophic tool failure that corresponds with notch wear in superalloy machining.

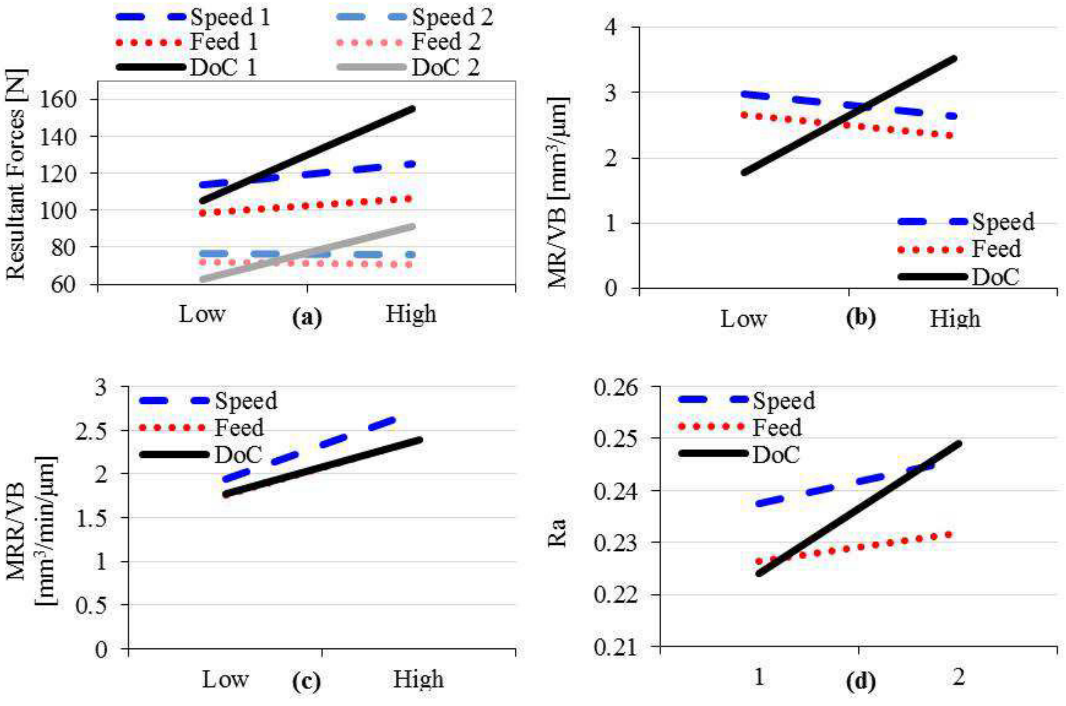

Figure 5: VDM Parameter Effects on (a) resultant force (b) MR/VB (c)MRR/VB (d) Ra

5 Conclusions

In this study, an investigation into the benefits of alterative tool path methods in nickel-based superalloys, namely trochoidal and variable depth, has been presented. It was shown that trochoidal milling was superior to end milling in terms of productivity, where trochoidal could machine at least seven times more material than end milling with the same amount of tool wear with similar efficiency as end milling. Trochoidal, however suffered from the formation of notch wear in the tool, leading to the development of variable depth milling. It was demonstrated that VDM eliminated the formation of notch wear in the cutting tool at the expense of a slight decrease in productivity and efficiency when comparing it against standard end milling.

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