Investigation of Burr formation and Surface roughness in Micro milling of Inconel 718 alloy

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Declaration

I certify that this research work titled "*Investigation of Burr formation and Surface roughness in Micro milling of Inconel 718 alloy*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged/referred.

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Acknowledgment

I would like to thank my parents and teachers for guiding me through this work. They were the ones to help me out every time I felt difficulty. I acknowledge their patience. They have contributed the most to my study.

Dedicated to my parents for their support

Abstract

Industry, particularly aviation, has seen remarkable technological advancement in recent years. More micro-scale manufacturing capabilities, notably micro-milling capabilities, are required for high precision machined microparts with complex features in order to obtain the necessary yet exact dimensional accuracy and surface finish. In this study, the influence of feed rate, cutting velocity, depth of cut, and four various types of tools with (AlTiN-, TiSiN-, nACo-coatings, and uncoated) on burr formation, tool wear and surface roughness during micromachining of Inconel 718 was investigated using digital microscope and statistical techniques. On a CNC milling machine, machining experiments were carried out at high speed with a feed rate below the cutting-edge radius for a 10 mm cutting length with a carbide tool of 0.5 mm diameter. The depth of cut was shown to be the most important element in burr creation, whereas cutting velocity was found to be the most important component in surface roughness. Due to the difference in coefficient of friction, cutting tool coating had no effect on either surface roughness or burr development. The depth of cut and feed rate influenced the kinds of burr generated during micro-milling of Inconel 718 while cutting velocity had no effect. It was also determined that the surface finish achieved by high-speed machining is equal to that achieved by transition and low-speed machining and that the burr width discovered during high-speed machining confirmation trials was likewise within an acceptable range.

Key Words: *Inconel 718, micromachining, micro-milling, surface roughness, burr formation, tool coating*

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CHAPTER 1: INTRODUCTION

The continuous advancement of technology, particularly in the aviation industry, necessitates the development of production processes. For instance, engineers are working to improve the efficiency of aircraft engines. As a material for aircraft engine parts such as the blades, disc, and others, Inconel 718 has been employed. Because of its great strength, corrosion resistance, and creep resistance at high temperatures, Inconel 718 is used for more than just aviation engines. It may also be found in rocket and gas turbine parts. Inconel 718 is made up of nickel, chromium, iron, and other elements that make it extremely durable. As a result, the manufacturing process for Inconel 718 will need to be studied further due to the material's poor machinability. Inconel 718 has been optimized for electrochemical micro-machining. Electrochemical machining has also been used to drill Inconel 718. However, micromachining Inconel 718 remains a challenge [1].

Miniaturization of industrial components with many functionalities and acceptable dimensional precision is in high demand. Micromachining is a method of mass fabricating small parts and components. Micromachining is defined in various ways. It is a material removal method that produces small and detailed 3D shapes ranging from 1 to 0.99 nm in size [2,3]. Demand for micro parts and components has surged in recent years. Printing heads and micropumps drug delivery systems are examples of such elements.

The production of small parts necessitates the use of more accurate tooling and procedures that are more precise, reliable, and reproducible. In addition to laser manufacturing, ultrasonic photolithography, and ion-beam machining, several researchers have looked at various manufacturing methods for micro-components [4-7]. In mechanical micromachining, the rate of material removal is one of the key challenges. There are distinct physical and cutting mechanisms "size effect" phenomena in the macro-machining realm that make this apparent. Due to the wide range of sectors in which Inconel alloys are used, it is one of the most extensively studied materials in the open literature [8,9]. This is possible because nickel-based micro-components may be micro-milled to achieve the appropriate design.

In order to improve machining performance when working with Inconel 718, a variety of aids are employed, including various coatings, coolants, machining settings, and laser-assisted machining for preheating the workpiece in order to soften it and make it simpler to mill [10-13]. Compared to traditional machining, the and specific cutting energy improved. High speed micromachining of

Inconel 718 at 48 m/s by Irfan et al. [14] examined the coating's impact of on tool wear and surface roughness. When it comes to tool wear and the creation of Built-Up Edges (BUE), TiAlN +WC/C coatings and Diamond-Like Coatings (DLC) perform well. The DLC-coated tool had the lowest surface roughness, followed by tools with AlTiN coating and TiAlN + WC/C-coating ones. Lower feed rates and smaller depths of cut results in high tool wear. Tool condition, cutting parameters machining vibrations, and the production of BUE all affect the surface roughness, according to Xiaohong Lu and colleagues [15]. Surface roughness decreased at first, but then began to rise as cutting duration increased. It was found that tool coatings affected cutting force and tool wear as well as machining quality in the micro milling of Ti6Al4V alloy by K. Aslantas et al. [16]. Cutting force rises as a result of increased tool wear, which in turn lowers machining quality. For micro milling Ti6Al4V, T. Ozel et al. [17] evaluate the machining and wear quality of a tool with cBN-coating to that of an untreated tool and found that the tool with cBN-coating outperformed the uncoated tool. During micro-milling of hardened tool steel, A. Aramcharoen et al. [18] studied how different coatings on tools affected the wear of the tool. Coatings such as TiN were found to have better wear resistance than TiAlN in terms of edge chipping and flank wear, whereas TiAlN caused more burr development than the uncoated tool, a finding that was not pursued further.

As a result, Abd Rahman et al. [10] came to the conclusion that cutting speed affected surface roughness more than depth of cut or feed rate. Minimal Quantity Lubrication (MQL) is more consistent and stable than dry machining in the micromachining of Inconel 718, according to Abd Rahman et al. Due to the increased tool and workpiece contact area through a dry cutting operation, the tool wear is much higher than during a wet machining process [19].

Researchers have studied several features of input parameters to improve the quality of the machined surface during micro-machining procedures. It was A. Attanasio et al research's that concentrated on the impact of microstructure on the final quality of machining (burr production), tool wear and cutting forces. By examining surface uniformity, Zhanwen Sun and Suet To [2-] sought to improve machining quality by examining input cutting parameters such, feed rate, spindle speed, depth of cut, and tool wear. Spindle speed tilt angle has been shown to reduce burr formation and surface roughness in micro-machining, according to a study by Jan C. Aurich et al [21].

A variety of tool coatings were used by various researchers in order to prolong tool life and ensure compatibility with a wide range of materials during micro milling techniques, according to the published research. Nevertheless, the impact of different tool coatings on machining quality was never investigated because tool wear was overlooked in the research. As a consequence of minimal tool vibration and less burr development at higher cutting speeds, the majority of previous studies focused on high cutting speeds, whereas just a few of studies looked at the quality of micro machined components at lower cutting velocity. When comparing the two, a low-speed machining system is easier to come by and more cost-effective. Thus, this study intends to fill a void in the literature and explore the influence of low cutting velocity on the surface roughness and production of burrs less than the cutting-edge radius.

1.1 Aim of research work

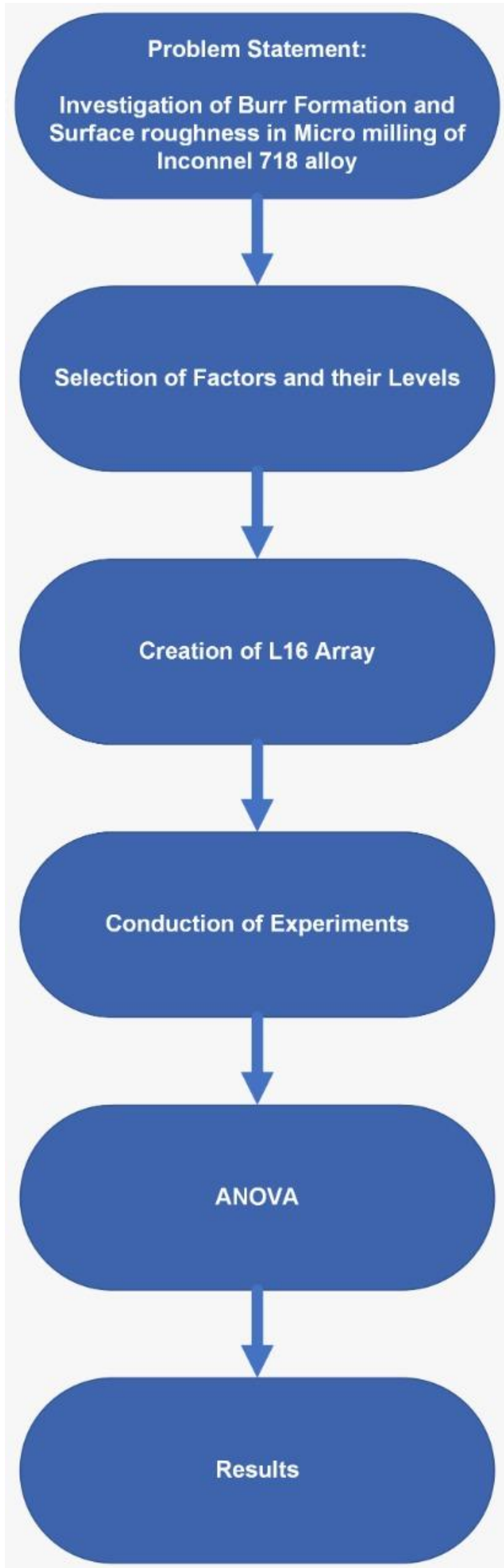
The objective of this work is to enhance the quality of manufacturing for aerospace-grade materials by minimizing bur formation and surface roughness. This will give optimized conditions for the high-quality manufacturing of hard materials like Ni-based superalloys. The following are the study's main objectives:

- Examine the possibility of micro-milling nickel alloys under a variety of processing regimes.
- Examining the impact of various tool coatings on milling performance.
- Evaluation of the integrity of the workpiece's surface.

1.2 Application of work

This work is a national need of the defense industry. This work has a wide range of applications as; jet engines, turbine blades, power plants, aircraft engines, automotive industries, electronics, etc.

1.3 Research Methodology



1.4 Thesis Layout

Chapter 1 gives the introduction of the topic and briefly describes the aim, area of application, and research methodology of the study.

Chapter 2 discusses the process of reviewing previous literature on the subject and presents the findings.

Chapter 3 describes the experimental process, methodology, and design of the experiment. Also, discuss the different cutting parameters in detail.

Chapter 4 presents the experimental results as well as ANOVA results and their discussion

Chapter 5 concludes the Thesis. It focuses on the conclusions of the study and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

In this chapter, prior research articles on important overview of the machining process, tool geometry parameters, machining of nickel alloys, and difficulties in micro-milling processes are discussed. In addition, research is being done on workpiece surface integrity and the application of various tool coatings for tool life improvement in the micro-machining of nickel-based alloys. In light of the above literature assessment, further research is needed to fill in the gaps in our knowledge.

2.1 Micromachining: An Overview

The aerospace, medicinal, electronics, and automotive industries have all seen an increase in demand for high-precision miniaturized components. Chip formation method, tool sharpness, minimum chip thickness [22,23], vibrations, excessive forces, and difficulties in measuring reliable and repeatable procedures for correct analysis are all issues associated with micromachining. All of these variables could have an impact on machining efficiency. As a result, it has been suggested that mechanical micromachining cannot benefit from simple downscaling. Furthermore, every potential influence that governs micro machining phenomena must be investigated [24,25].

Micro and macro machining differ significantly in terms of the cutting mechanism. The Merchant sharp edge radius cutting model was used in traditional machining to detect the dominating shear plane and friction at the tool rake face. In micromachining, the size effect can be defined as the ratio of the chip thickness to the tool edge radius [26,27]. Deviations from proportional extrapolated values are used to describe scaling geometric parameters The size impact can be explained by a tiny, undeformed chip thickness. Consideration of wasted energies throughout the micromachining process is critical. It has long been documented that the majority of the heat generated during macroscale metal machining with continuous chip production is removed by the chip (about 80%). With the thermal mass of the chip decreasing as the depth of cut decreases, shearing in the shear zone and rake face friction could not account for the observed energy. For cut depths less than a few micrometers, tool flank face rubbing caused by elastic recovery of the workpiece material and ploughing resulted by the tool edge radius played a greater role in mechanical energy dissipation.[25, 28].

It's critical to know how rake angles affect cutting performance while doing micromachining with thin, undeformed chips. Rake angles have an impact on cutting forces and energy in micromachining because the rounded component of the tool cuts the workpiece [29,30]. Actual and efficient rake angles, respectively, were attributed to regulate cutting phenomena at greater and lower uncut chip thicknesses. An extremely negative tool rake angle could have a significant impact on the shear angle, causing the shear angle to drop as the rake angle becomes more extreme. If the shear angle is reduced with an effective rake angle, cutting forces that contribute to the size impact could be increased. Adverse rake angles not just to increase cutting pressures, but also enhance plastic deformation and extrusion in front of the cutting edge [31,32]. Additionally, conventional milling with a positive rake had a thrust force-to-cutting force ratio of less than 1. While this ratio was bigger than one with negative rake angles, demonstrating a resemblance between grinding and machining, this resulted in stronger specific cutting parameters. The plastic deformation of the workpiece's subsurface is attributed to these greater cutting forces, which are considered the most important. The tool's cutting-edge radius and flank face friction are also factors in plastic deformation. In addition, the huge cutting-edge radius was a major contributor to the extremely negative rake angles. Minority causes were discovered to be caused by the friction between the machined surface and the flank face [33]. Thermal stresses were also reported to result in a higher effective rake angle and friction on the flank face due to increased plastic deformation in micromachining. The material flow and thermo-mechanical behavior grew more complicated under such strong plastic deformation conditions [34].

Liu et al found that the bulk of micromachining research is experimental in nature [35]. In order to better understand diverse micromachining processes, further experiments in the realm of ultra-precision machining are needed. Because of this, it's critical to comprehend cutting processes in micro-milling via the lens of micro-machining science. The surface-to-volume ratio increases as size decreases, so more attention should be paid to tool wear processes, and surface and subsurface characterization of micromachined workpieces.

2.2 Superalloys based on nickel: an overview

Alloys produced for high-temperature applications have been referred to as "superalloys." A super alloy's most important characteristics include the capacity to bear stress close to the melting point, long-term mechanical degradation resistance, and harsh working conditions. Yield stress and ultimate tensile strength are examples of static qualities [36]. Fracture toughness is also a static property. As a result, nickel-based superalloys appeared as the best material in high-temperature applications, particularly in the exhaust stream of gasoline, turbines, jet engines [37]. Nickel-based superalloys are shown in Figure. 2.1 to have excellent creep and stress rupture resistance. The aluminum, titanium, and magnesium alloys utilized in aircraft construction are relatively lightweight.

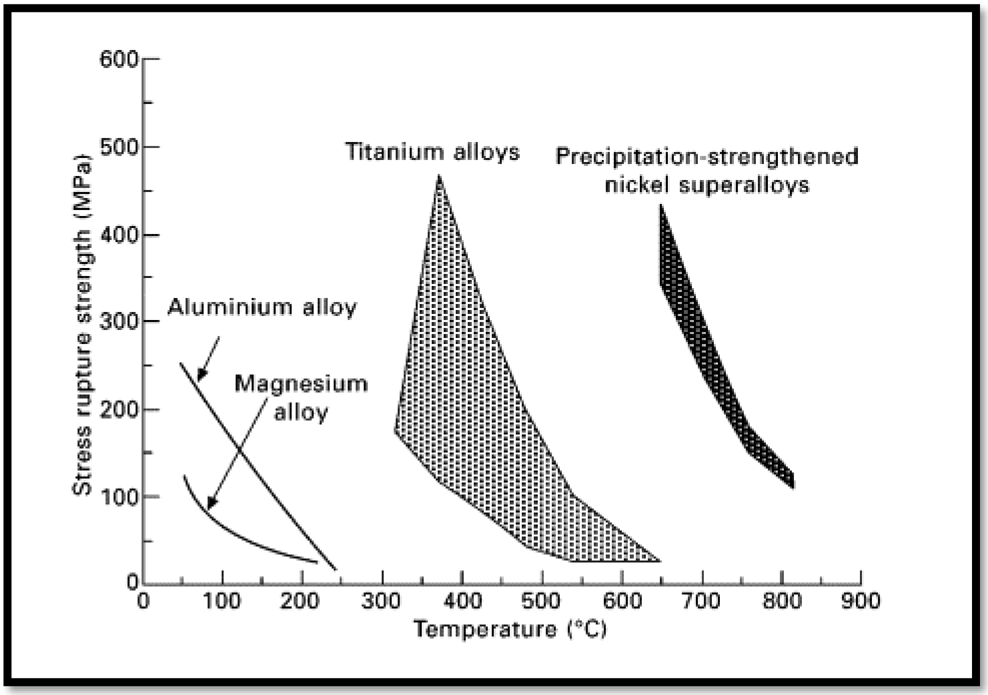


Figure 2.1; Stress rupture curves for various aerospace alloys [38]

Nickel superalloys have a nickel content of about 50% by weight. Chromium (10–20 percent), titanium and aluminum (up to 8 percent combined), and cobalt (5–15 percent) are among the most common alloying elements in many of the superalloys. Small amounts of molybdenum, tungsten, and carbon are also present. Several jet engine nickel-based superalloys are enumerated in Table 2.1.

Table 2.1; Composition of various nickel-based alloys [38]

	Composition									
Alloy	Ni	Fe	Cr	Mo	W	Co	Nb	Al	C	Other
Astroloy	55.0	–	15.0	5.3		17.0	–	4.0	0.06	
Hastelloy X	49.0	18.5	22.0	9.0	0.6	1.5	3.6	2.0	0.1	
Inconel 625	61.0	2.5	21.5	9.0	–	–	–	0.2	0.15	<0.25 Cu
Nimonic 75	75.0	2.5	19.5	–	–	–	–	0.15	<0.08	1 V
Inconel 100	60.0	<0.6	10.0	3.0	–	15.0	–	5.5	<0.08	2.9 (Nb+Ta)
Inconel 706	41.5	37.5	16.0	–	–	–	5.1	0.2	0.12	<0.15 Cu
Inconel 716	52.5	18.5	19.0	3.0	–	–	5.2	0.5	0.05	0.1 Zr
Inconel 792	61.0	3.5	12.4	1.9	3.8	9.0	–	3.5	0.04	
Inconel 901	42.7	34	13.5	6.2	–	–	–	0.2	0.16	0.3 V
Discaloy	26.0	55	13.5	2.9	–	–	3.5	0.2	0.15	0.5 Zr
Rene 95	61.0	<0.3	14.0	3.5	3.5	8.0	–	3.5	0.14	
Rene 104	52.0	–	13.1	3.8	1.9	182	1.4	3.5	0.03	2.7 Ta
SX PWA1480	64.0	–	10.0	–	4.0	5.0	–	5.0		2 Hf
DS PWA1422	60.0	–	10.0	–	12.5	10.0		5.0		

Inconel 718 is one of the most often utilized austenitic nickel-chromium-based superalloys in the oil and gas sector. In high temperatures, Inconel 718 is extremely strong and corrosion resistant. High-temperature mechanical qualities of Inconel 718 make it suitable for a variety of uses, including aerospace and automotive, as well as biomedical [39,40]. It is difficult to mill nickel alloy because of its low heat conductivity, which encourages built-up edge when machined, hardness, and strong affinity to tool materials. During machining, Inconel 718's limited heat conductivity causes a large rise in cut temperature, that limits the tool life.

Turbine discs and blades have traditionally been made of nickel-based superalloys. Nickel-based superalloy Inconel 718 has become a popular choice for high-temperature applications among commercially available superalloys. Other applications include gas turbine engines for ships, industries, and vehicles, rocket engine parts, nuclear power plants, turbine casing engine mounts, rocket motors, pumps, and chemical equipment [41].

2.2.1 Machinability of Inconel 718

Many aero-engines use nickel-based superalloys i.e., Inconel 718 due to their high thermal strength, outstanding fatigue resistance, and corrosion resistance. Their exceptional hardness and limited thermal conductivity make machining these metals problematic. The existence of hard abrasives in the microstructure and the possibility of reaction with the tool material worsen the machining challenges even more. As a result, the material's high tensile and yield strength can be attributed to the formation of precipitate hardening of its secondary phase strengthening (Ni3Nb).

During machining, rapid strain hardening of these alloys may result in high cutting temperatures and forces. Machined nickel alloys put twice as much stress on cutting tools as steels do at almost the same cutting speed [42,43]. It was stated that nickel superalloys were machined at speeds of up to 300m/s at temperatures as high as 1000 °C [44]. All of these factors can have a significant impact on the tool life and surface integrity of the machined parts.

2.2.2 Chip Formation

To effectively anticipate the cutting forces, it is necessary to understand the mechanics of micro-chip generation, which is largely nonlinear in nature. For different materials, the thinnest possible chip cannot be created because of the material's inherent properties. As a result, the feed rate must be equivalent to or better than the lowest chip thickness [45]. An estimation of the fluctuation in chip thickness h (Ø) may be made by using csin (Ø) as the feed rate and angle of immersion. Micro milling, on the other hand, does not allow for this kind of estimation. A large negative rake angle is caused by the narrow tool’s cutting edge, the small DOC, and the low feed rate. Micromachining is also prone to ploughing phenomena, which tend to increase the workpiece's elastic recovery and surface roughness [46,47].

2.2.3 Tool Wear

Many previous studies on micro milling have based on the creation of wear of tool and its effect on quality of machining. A tiny depth of cut results in a significant frictional increase among the tool and workpiece, that leads to rise in temperature and wear of tool during micromachining procedures. As a result, the cutting-edge radius of the tool rises, lowering component quality and increasing the rate of tool wear [26]. Tansel et al. [48] established a technique to assess the wear of micromachining tools by using cutting force and wear data; machining steel caused quicker tool wear rates than aluminum, according to the researchers. When it comes to tool wear, Weule et al. [49] found that material is a major factor. When micromachining Inconel 718, different forms of tool coating can be employed to extend tool life [14]. Tool wear can be reduced, and surface quality improved by applying a low-friction coating on the tool [30]. It's possible to extend the life of a tool by decreasing the temperature of the cutting edge with cryogenic tooling.

2.2.4 Surface Integrity

These nickel-based superalloys are some of the most challenging to manufacture in order to meet both production and quality standards. Additionally, the aerospace industry is compelled to maintain quality requirements on machined parts due to safety regulations. Because nickel alloys are crucial components in aero-engines, surface integrity has been an important concern in nickel alloy machining [50]. The relationship between a produced surface's topographical, mechanical, chemical, and metallurgical qualities and its functional performance was characterized as "surface integrity". Almost all traditional and new machining methods introduce surface alterations, and these modifications are dependent on how harsh or soft the circumstances are [51]. Nickel alloys are known to suffer from plastic deformation, cracks, substantial variations in microhardness, residual stresses, and microstructure alterations on the machined surface when conventional machining is used. Aerospace industry surfaces must be studied for their mechanical and metallurgical properties that might influence fatigue strength, stress-corrosion resistance, and the lifetime of the machined component. Electrical discharge machining (EDM) has been shown to reduce fatigue strengths of Waspalloy, 410 SS, and commercially pure titanium by approximately half when compared to mechanical milling [52].

2.3 Tool coating

Tool wear has been reduced in nickel-based superalloys through the use of coated carbide tools. Coated carbide tools increased productivity [53]. However, in order to select the best coating material for a given application, it is necessary to know the fundamental requirements. Figure 2.2 [54] illustrates three regions of primary relevance in the application of a coating for a certain application. Adhesion, substrate-coating layer interaction, and strain generated by thermal expansion fluctuations should all be considered at the tool substrate-coating layer interface. Material composition and microstructure of the coating layer must also be taken into account. Coating qualities including strength, hardness, thermal stability, and internal stress are determined by this. It was made clear that the microstructure of the coating material was dependent on the elements present and the manufacturing parameters employed. As a last consideration, the coating's interaction with the workpiece material can be determined by the coating's surface layer. Adequate adhesion between the tool substrate and the coating is critical to the performance of an effective coating, especially in areas of high loading intensity. In addition, the substrate must be rigid and strong enough to hold the coating without distortion. However, increasing the coating's hardness and strength means sacrificing its toughness and adhesion. When a coating is stiffer than the substrate, stress might build up within it, according to Kramer's explanations. In general, the stress level rises as the load increases, and the disparity in the modulus of elasticity between two materials grows. This results in less stress on the substrate, because the rigidity of WC is greater than that of TiC coating, which is exactly what we wanted. For this reason, an identical TiC coating on an HSS substrate will be more susceptible to damage because of the substrate's reduced rigidity. Coating adhesion cracks occur when coating adhesion is greater than the adhesion strength between coating and substrate. This increases stress on the substrate. Stresses from the tool and coating system are also a factor. If the substrate's coefficient of thermal expansion is larger than the coating's, the stresses will be tensile. The coating will experience compressive stresses if the coefficient is too high [55]. Chemical stability and inertness in relation to the workpiece are important requirements for successful coatings in addition to appropriate adherence. The secondary goals of employing the coating on cutting tools were fine grain structure, good oxidation resistance, surface morphology, high-temperature hardness, controlled compressive residual stresses, and thermal conductivity.

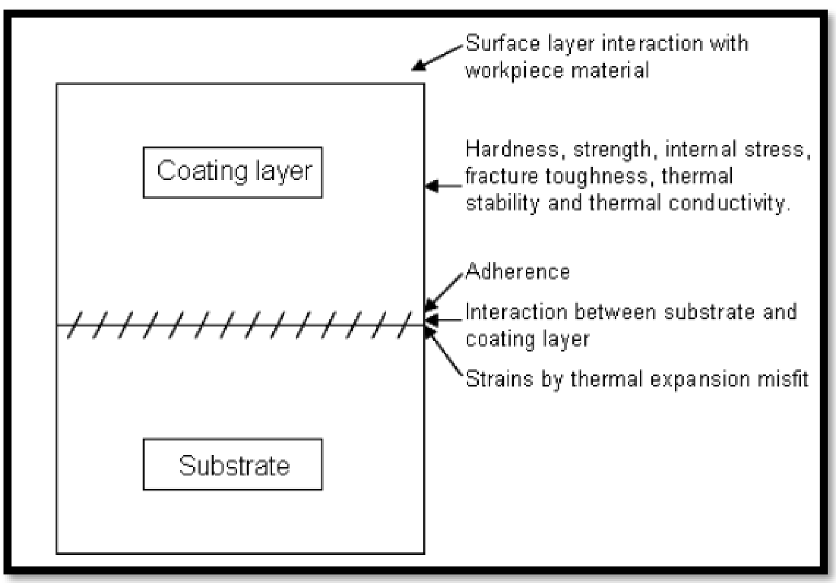


Figure 2.2; Basic parameters for selecting a coating [54].

According to Beake et al [56], cutting tool coating performance can be determined by a number of factors. The relative cutting performance in different ranges of applications was determined by factors such as hot hardness, plasticity index (ratio of hardness to elastic modulus) at room and increased temperatures, and fatigue fracture resistance. It was discovered that plastic index and tool life have a connection that could not be explained solely by hardness. It was also discovered that the choice of the coating was based on specific applications, such as turning and milling. Using the plastic index, for example, turned and milled operations showed that the adhesive fatigue mechanism of milling may be accurately predicted. The degree of flexibility is less important in turning than it is in other types of cutting where the degree of hardness is vital. Longer tool life can be achieved by combining high hot hardness with enhanced plasticity in end milling, but in high-speed turning, hot hardness was the deciding factor. According to Donald and Quinto [55], the workpiece's fracture strength and hardness determine the amount of force required to plastically deform it in the form of a chip, while its elongation or fracture strain determines the final chip shape. There are several elements that influence the functional qualities of an applied coating for a particular workpiece and application, rather than just a single parameter like hardness. The requirements are also specific to the application.

Hardness and oxidation resistance have traditionally been the primary considerations when selecting coatings for applications. Even if it were possible, this method would be inapplicable in all cutting tool scenarios [57]. Fox- Robinvich recommended a methodical technique for selecting coatings, which included examining mechanical qualities, oxidation resistance microstructure, and service characteristics in specific working settings.

High strength at high temperatures, low thermal conductivity, strong shear, work hardening, and adhesion tool wear behavior are all characteristics of nickel-based superalloys that can be machinable. Good thermal conductivity is required in this application to disperse energy first from the cutting zone, especially during drilling. It is therefore imperative that an abrasion-resistant coating be applied to the workpiece at high temperatures, as well as an oxidation-resistant coating [55,57]. Coatings that are more plastic and impact fracture-resistant can help reduce the amount of wear that occurs as a result of attrition wear.

Several papers on the analysis of coatings in machining nickel-based superalloys were provided, however, the majority of the study focuses on turning. In the literature, there was no evaluation of coatings in the drilling of nickel alloys. Distinct nickel alloy cutting procedures necessitate the use of different coatings. The use of TiAlN multilayer[13], TiN/TiAlN [14], and TiN/TiAlN multilayer [15] coatings in nickel-based superalloys drilling have been reported, but these coatings must be evaluated in order to select the best coating for this specific drilling application.

CHAPTER 3: DESIGN OF EXPERIMENT AND METHODOLOGY

This chapter presents the experimental investigation of the micro-milling process on nickel-based superalloy i.e., Inconel 718. This work was investigated under various machining parameters i.e., cutting velocity, feed rate, and depth of cut (DOC). The tool coating and machining parameter effects on surface finish/roughness and burr formation as well as tool wear are also studied using an optical microscope. The schematic process flow diagram of this research is given in Figure 3.1.

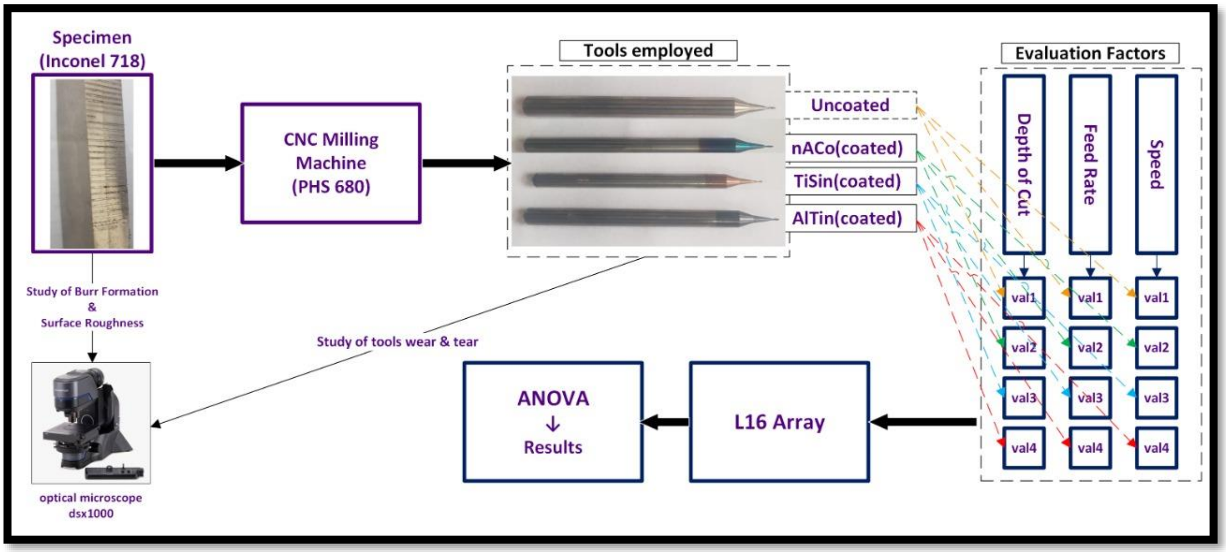


Figure 3.1; Schematic process flow diagram

3.1 CNC Machine setup and detail

The micro-milling studies were carried out on nickel-based superalloy i.e., Inconel 718 with CNC Milling Machine (PARPAS PHS-680), Figure 3.2. The workpiece surface was first leveled by using a carbide end mill that had a diameter of 12 mm. Then, the surface was used as a reference. For precise z-axis measurements, a tool pre-setter was employed. Table 3.1 provides the experimental parameters for these tests.

Table 3.1; Experimental setup and parameters

Material of workpiece	**Inconel 718**
Cutting length	10 mm
Flutes number	2
Dimeter of tool	0.5 mm
Type of Milling	Full immersion

Electric discharge machining (EDM) was used to prepare the workpiece's dimensions, which were 146 mm ×10 mm× 22 mm. In order to minimize tool wear and tear, and 10mm slot of the cutting length was set for the experiments. Figure 3.3 shows the slot spacing, which was 2 millimeters.

Figure 3.2; Pictorial view of CNC Milling machine

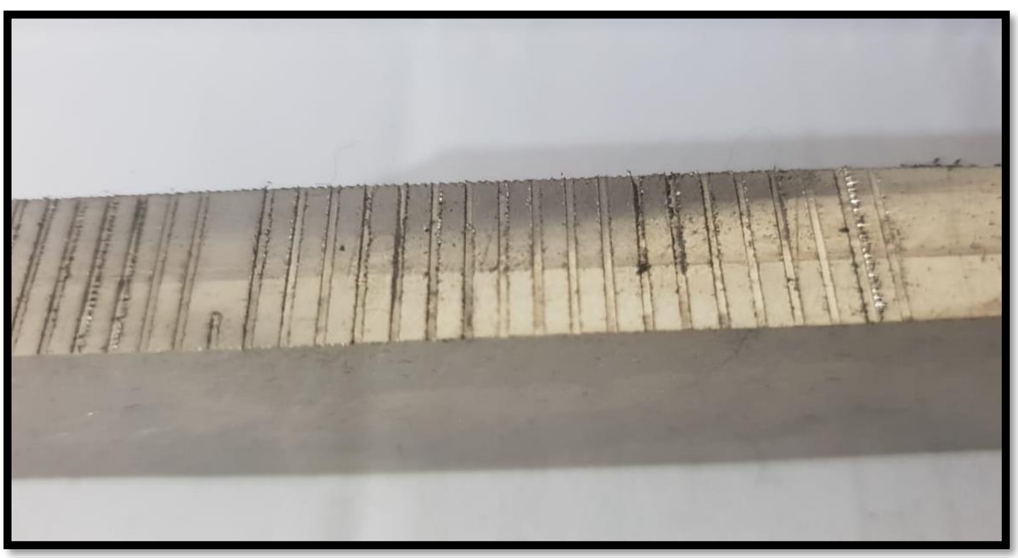


Figure 3.3; Milled workpiece sample pictorial view

3.2 Design of Experiment

The effects of four variables on burr formation, tool wear and surface finish/ roughness were examined. These variables are;

a) Four various tool coatings
b) Four levels of depth of cut
c) Four levels of feed rate
d) Four levels of cutting-speed

The machining variable's details are enlisted in Table 3.2.

Using the ANOVA method and the Taguchi method, we were able to establish the factors that have the greatest impact on surface roughness and burr formation in this study. There are only a limited number of experiments used to study a wide variety of factors. For reproducibility's sake, all sixteen of these tests were performed twice.

Table 3.2; Machining variable details

Variables	**Unit**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Coatings	-	Un Coated	nACo	TiSiN	AlTiN
Depth of cut	µm	30	50	70	90
Feed rate	µm/tooth	0.25	0.50	0.75	1.00
Cutting speed	m/min	9	14	29	24

3.3 Workpiece preparation and characteristics

The first step was to grind and polish the material. Kalling's waterless itching agent was used for about 5 seconds before being washed away with water. Using a digital microscope (Olympus DXS-1000) and the ASTM standard method, the average grain size was determined to be 23.4 µm. The Vickers hardness of Inconel 718 was determined using a Vickers Microhardness tester and was 361 HV.

Figure 3.4, Digital microscope (Olympus DSX-1000)

3.4 Cutting tool specifications

Wedge-shaped cutting tool constructed of tungsten carbide steel with 0.06-inch (0.5-mm) diameter. Images of the cutting tools used in this work are shown in Figure 3.4. Microtools with nACo, AlTiN, and TiSiN coated cutting edges had an average cutting-edge radius of 1.5 µm, 1.3 µm, 1.21 µm, and 3.0 µm, respectively. Run out of all the tools were measured between 0.02 mm to 0.09mm.

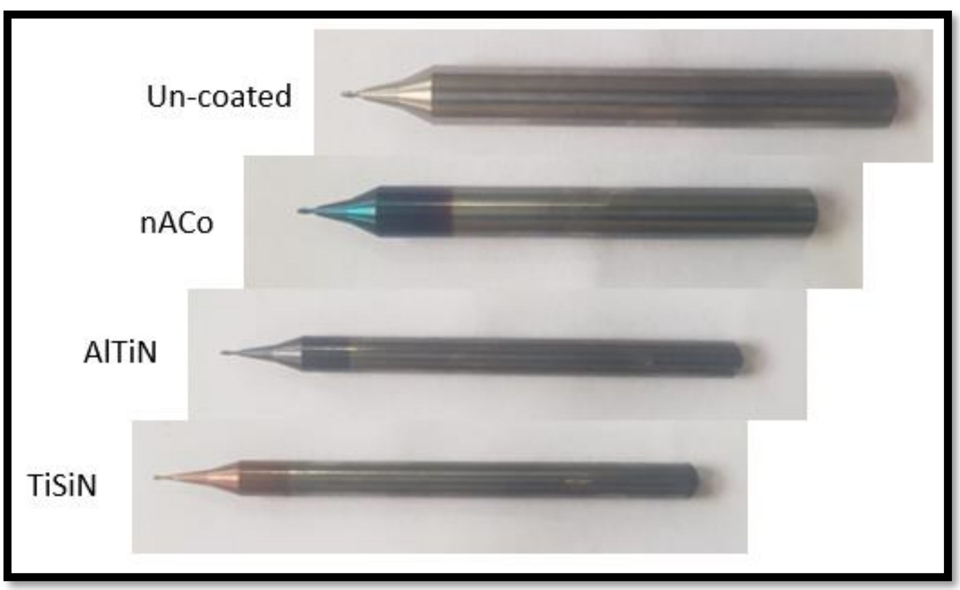


Figure 3.5; Pictorial view of different microtools used in the current study

3.5 Burr formation measurement

Burrs can form in a variety of sites, including the top, bottom, entrance, and exit burrs. During burr analysis, In the current work, the focus was on the top and down burr height, width, which was measured using a digital microscope (DXS-1000) at different magnifications based on the burr width, and height.

3.6 Surface roughness measurement

The digital microscope (DXS-1000) was used to study the surface roughness of all slots since it enables the determination of micro-surface roughness in micro-milling operations. At the beginning of the machined slots, we measured the surface roughness to see if tool wear had an impact on the final result. Micrometers are the units used to measure surface roughness. ISO-4287 is the standard for measuring surface roughness.

3.7 Methodology

In this study, ANOVA method was applied to determine the effect of every factor on surface roughness analysis and burr formation, and the Taguchi method has been used to determine the best criteria for minimizing burr formation and surface roughness. According to the type of data, the S/N ratio might be calculated differently. Three formulas are employed to calculate the S/N ratio—the lower, more nominal, and greater to an acceptable value. S/N ratios have been calculated using smaller values of burr width, and this is because smaller values are necessary for this study.

$$\frac{S}{N} ratio = -10 \log_{10}\left(\sum_{i=1}^{n} Y_i^2 / n\right) \qquad (i)$$

It was determined the mean S/N ratio at each level, and the optimal parameters were chosen by selecting those with a maximum mean S/N ratio.

CHAPTER 4: RESULTS AND DISCUSSION

In spite of the restricted tool life, the micromachining of nickel-based superalloys has the potential to produce high-quality components. There is still a need for custom-designed milling and drilling tools for specific applications, despite recent breakthroughs in micro-milling. In micro-milling Inconel 718 superalloys, this study examined the impact of various tool coatings, cutting parameters on tool life, bur formation, surface roughness, and workpiece surface integrity. Analyzing the statistical relevance of the milling on tool-wear, surface roughness, and burr size was done using the ANOVA method. The mechanism of burr development in Inconel 718 was studied using material microstructure analyses to support the findings. Studies of microstructural damage to the machined surface measured surface and subsurface integrity were examined. This chapter presents the details of the results obtained from this study and discussion.

4.1 Results

4.1.1 ANOVA Results

It was decided to run an ANOVA to govern the percentage impact of the various parameters on the outcomes. For the surface roughness, burr development, and tool wear, Tables 4.1 to 4.6 exhibit ANOVA findings that reveal which cutting parameters had the most impact.

Table 4.1; ANOVA results for surface roughness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
Speed	3	0.008855	39.30%	0.008855	0.002952	6.74	0.003	Significant
Feed	3	0.000531	15.36%	0.000531	0.000177	0.40	0.049	Significant
DOC	3	0.000697	3.09%	0.000697	0.000232	0.53	0.667	Insignificant
Coating	3	0.004132	21.34%	0.004132	0.001377	3.15	0.031	Significant
Error	19	0.008317	20.91%	0.008317	0.000438	-	-	-
Lack-of-Fit	3	0.001791	7.95%	0.001791	0.000597	1.46	0.262	-
Pure Error	16	0.006526	28.96%	0.006526	0.000408	-	-	-
Total	31	0.022532	100.00%	-	-	-	-	-

Table 4.2; ANOVA results for bur formation width (down milling)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance

Speed	3	41700	22.27%	41700	13900	1.72	0.041	Significant
Feed	3	74234	19.06%	74234	24745	3.05	0.049	Significant
DOC	3	31444	32.50%	31444	10481	1.29	0.020	Significant
Coating	3	68662	7.56%	68662	22887	2.82	0.198	Insignificant
Error	19	153943	18.61%	153943	8102	-	-	-
Lack-of-Fit	3	38577	10.43%	38577	12859	1.78	0.191	-
Pure Error	16	115366	31.18%	115366	7210	-	-	-
Total	31	369983	100.00%	-	-	-	-	-

Table 4.3; ANOVA results for bur formation height (down milling)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
Speed	3	91308	25.80%	91308	30436	2.16	0.039	Significant
Feed	3	40119	21.94%	40119	13373	0.95	0.044	Significant
DOC	3	81095	19.03%	81095	27032	1.92	0.049	Significant
Coating	3	97214	6.82%	97214	32405	2.30	0.437	Insignificant
Error	19	268187	26.41%	268187	14115	-	-	-
Lack-of-Fit	3	71179	12.32%	71179	23726	1.93	0.166	-
Pure Error	16	197008	34.09%	197008	12313	-	-	-
Total	31	577923	100.00%	-	-	-	-	-

Table 4.4; ANOVA results for bur formation width (up milling)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
Speed	3	1857	10.71%	1857	618.8	0.06	0.230	Insignificant
Feed	3	52664	20.06%	52664	17554.6	1.67	0.049	Significant
DOC	3	901	30.34%	901	300.4	0.03	0.016	Significant
Coating	3	7607	2.90%	7607	2535.7	0.24	0.466	Insignificant
Error	19	199465	35.99%	199465	10498.2	-	-	-
Lack-of-Fit	3	18345	6.99%	18345	6114.9	0.54	0.662	-
Pure Error	16	181120	69.00%	181120	11320.0	-	-	-
Total	31	262494	100.00%	-	-	-	-	-

Table 4.5; ANOVA results for bur formation height (up milling)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
Speed	3	1024	15.16%	1024	341.4	0.13	0.172	Insignificant

Feed	3	9227	20.49%	9227	3075.7	1.13	0.046	Significant
DOC	3	18101	30.58%	18101	6033.7	2.22	0.021	Significant
Coating	3	7960	4.05%	7960	2653.3	0.98	0.361	Insignificant
Error	19	51631	28.71%	51631	2717.4	-	-	-
Lack-of-Fit	3	13338	15.17%	13338	4446.0	1.86	0.177	-
Pure Error	16	38293	43.54%	38293	2393.3	-	-	-
Total	31	87943	100.00%	-	-	-	-	-

Table 4.6; ANOVA results for tool wear

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
Speed	3	1051.3	20.27%	948.5	316.18	3.50	0.037	Significant
Feed	3	504.0	9.72%	439.8	146.61	1.62	0.219	Insignificant
DOC	3	768.4	14.82%	858.2	286.08	3.17	0.050	Significant
Coating	3	1237.1	23.86%	1237.1	412.36	4.57	0.015	Significant
Error	18	1624.5	31.33%	1624.5	90.25	-	-	-
Lack-of-Fit	3	301.4	5.81%	301.4	100.48	1.14	0.365	
Pure Error	15	1323.1	25.52%	1323.1	88.21	-	-	-
Total	30	5185.3	100.00%	-	-	-	-	-

4.1.2 Experimental results

The results reported from the experiment for Burr width, burr height, surface roughness, and tool wear are all displayed in Table 4.7. There were multiple runs of each experiment, and the average of those runs was used in the study. The results from the first and second runs differed significantly, mostly due to differences in machine noise, tool quality, human error during measuring, and setting the DOC. Due to the enhanced sensitivity of micromachining procedures, small mistakes and noise have a substantial influence on the findings.

Table 4.7; Experimental design using L16 array and burr formation, tool wear, surface roughness

Trail		Input Parameters				Output Parameters (um)						
		Speed	Feed	DOC	Coating	Burr Height		Burr Width		Surface Roughness	Tool Wear	
		V_c (m/min)	f_z (um/tooth)	a_p (um)	(t_c)	Left	Right	Left	Right		Flute 1	Flute 2
Run 1	1	9	0.25	30	nACo	86.128	262.403	218.413	560.167	0.059	90.334	100.136
	2	9	0.5	50	AlTiN	56.414	417.613	270.575	473.983	0.037	31.771	34.347
	3	9	0.75	70	TiSiN	251.747	219.736	650.049	403.683	0.035	51.289	46.885
	4	9	1	90	Uncoated	90.175	218.132	306.687	237.734	0.043	Tool Damage	
	5	14	0.25	50	TiSiN	51.642	451.017	210.437	515.621	0.074	60.674	52.952
	6	14	0.5	30	Uncoated	99.211	172.141	228.17	226.356	0.049	44.294	32.943
	7	14	0.75	90	nACo	94.613	163.593	273.504	362.552	0.073	Tool Damage	
	8	14	1	70	AlTiN	135.57	98.263	397.715	247.718	0.051	42.569	41.782
	9	19	0.25	70	Uncoated	141.336	256.026	185.573	434.421	0.065	Tool Damage	
	10	19	0.5	90	TiSiN	81.741	315.855	386.71	375.989	0.072	42.497	47.96
	11	19	0.75	30	AlTiN	78.777	385.27	280.425	314.183	0.048	54.233	55.085
	12	19	1	50	nACo	86.942	96.512	337.228	171.922	0.046	50.822	49.55
	13	24	0.25	90	AlTiN	46.358	328.854	293.971	437.448	0.071	24.662	29.146
	14	24	0.5	70	nACo	128.374	267.073	298.751	252.469	0.071	29.647	42.83
	15	24	0.75	50	Uncoated	102.557	489.501	328.26	277.863	0.106	43.129	42.704
	16	24	1	30	TiSiN	246.965	351.128	429.231	617.487	0.141	Tool Damage	
Run 2	1	9	0.25	30	nACo	110.875	269.711	350.082	381.435	0.075	100.78	58.928
	2	9	0.5	50	AlTiN	158.148	463.897	317.229	485.915	0.089	51.243	45.387
	3	9	0.75	70	TiSiN	99.344	211.59	197.656	284.953	0.101	80.158	62.24
	4	9	1	90	Uncoated	81.693	638.981	262.37	365.851	0.104	30.745	41.008
	5	14	0.25	50	TiSiN	55.702	372.484	280.607	429.432	0.098	68.751	48.682
	6	14	0.5	30	Uncoated	249.916	151.097	366.381	350.063	0.058	35.871	34.773
	7	14	0.75	90	nACo	133.414	200.584	426.729	303.168	0.057	20.131	38.431
	8	14	1	70	AlTiN	107.917	126.474	321.155	197.603	0.048	28.193	26.719
	9	19	0.25	70	Uncoated	101.144	277.834	316.988	224.72	0.067	38.434	37.15
	10	19	0.5	90	TiSiN	130.111	376.536	294.162	388.951	0.061	45.021	36.235
	11	19	0.75	30	AlTiN	116.507	126.438	380.225	247.243	0.051	32.577	45.386
	12	19	1	50	nACo	92.047	74.982	424.49	258.925	0.059	51.243	46.851
	13	24	0.25	90	AlTiN	79.703	442.548	226.965	386.622	0.075	50.876	36.603
	14	24	0.5	70	nACo	63.048	184.069	219.154	319.625	0.097	38.431	43.985
	15	24	0.75	50	Uncoated	103.076	156.707	382.709	235.496	0.113	33.777	35.91
	16	24	1	30	TiSiN	166.079	411.81	269.423	344.937	0.134	40.996	47.401

4.2 Discussion

Machining parameters affect aspects of surface quality, such as surface roughness and burr formation, as well as tool wear. On the basis of ANOVA and experimental result, detailed discussion of various machining parameter on surface roughness, burr formation and tool wear are given in this section.

4.2.1 Surface Roughness

Machined metals' surface roughness is affected by factors such as cutting-edge radius and tool coating, as well as factors like cutting speed and depth-of-cut. Increasing the cutting-edge radius and decreasing the feed rate both have an impact on tool wear.

The influence of various tool coatings and cutting parameters on surface finish/roughness, is depicted in Figure 4.1. Inconel 718 micro-machining with a 10 mm cutting length yielded the lowest surface roughness values when using AlTiN coated tools, according to the main effect plot. An increase in cutting temperature may have been induced by an increase in the coefficient of friction [82]. As a result of a greater cutting temperature and a lower feed/tooth radius, most of the material removal happens through chip deformation. While surface roughness is reduced without grooves, friction between tool and workpiece increases burr development and facilitates chip deformation. As a result, cutting at a greater velocity with an AlTiN coated tool produced the lowest possible surface roughness. Compared to AlTiN-coated tools, nACo-coated tools demonstrated the second-best results for surface roughness. Surface roughness values were observed to be higher in TiSiN coated tools. Increased surface roughness was reported on the tool with AlTiN coating than on the uncoated, nACo and tool with AlTiN coatings, which may be related to the higher BUE forms on those surfaces.

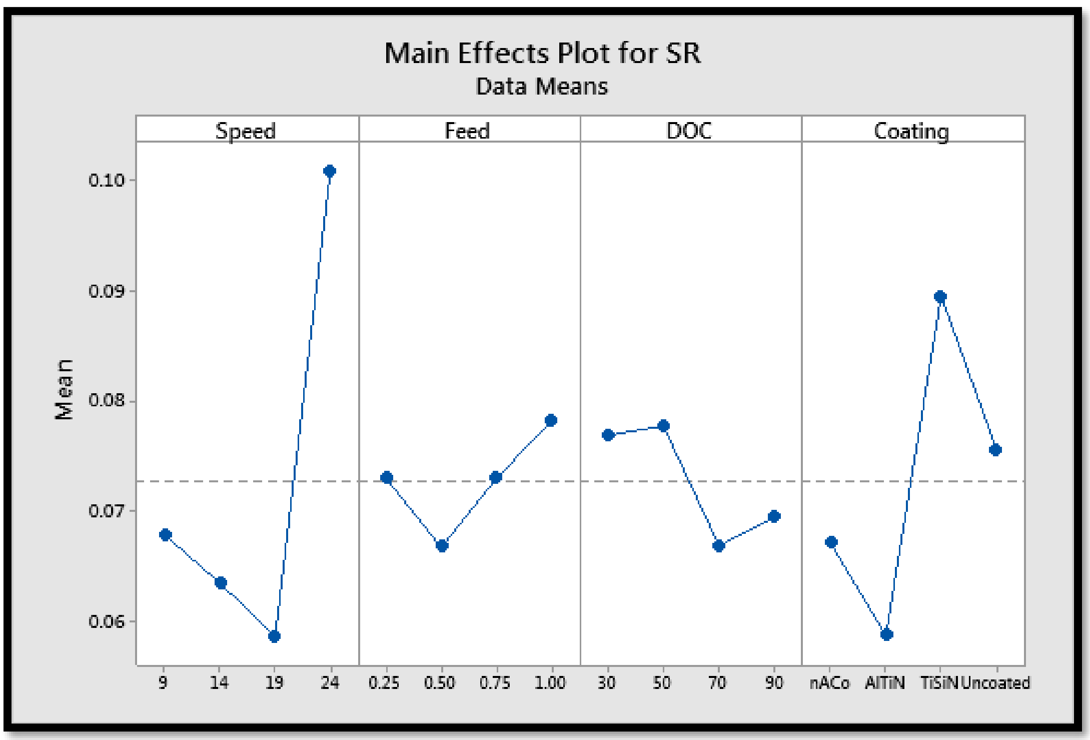


Figure 4.1; Surface roughness as a function of tool coating and cutting parameter

As the cutting edge of a tool comes into contact with a piece of material, the friction increases, resulting in a rise in temperature. Surface roughness values rise as a result of the increased cutting force and tool vibration [10,15]. An excellent surface quality can be produced up to a minimal chip thickness with increasing cutting force [32]. However, the surface roughness grows below that limit. Inconel 718 has a minimal chip thickness of 18% to 23% of the cutting-edge radius. Deforming the workpiece below the required chip thickness results in built-up edges and poor surface quality since appropriate chips aren't formed. This results in.

Workpiece velocity relative to the cutting tool is referred to as feed rate. It is faster to machine with a higher feed rate. Tool wear from a rushed machining process might degrade the surface quality. Feed per tooth is directly proportional to feeding rate. Feed/tooth is the amount of material that each tooth of the cutting tool is capable of cutting. Because the cross-sectional area of the chip was expanding, the cutting load in the machining process was also increasing. When the cutting process is disrupted as a result of tool wear, it will have a negative impact on the surface finish. The rate of tool wear will rise as feed/tooth is increased. Increasing feed rate from 0.5 to 0.1 µm/tooth resulted in increased surface roughness as demonstrated in figure 4.1.

In terms of surface finish, the tool's cutting-edge radius is one of the most critical factors [58]. For the coated tools i.e AlTiN and nACo, the cutting-edge radius is around 1.2 µm, whereas the tool coated with TiSiN has a radius of roughly 3 µm, which is slightly larger. Because of this, the minimal chip thickness was found to be 0.17 µm/tooth for TiSiN, and 0.28 µm/tooth for AlTiN, and nACo coated tools. The tool with TiSiN coating has feed rate equals the minimal chip thickness, whereas tool with AlTiN and nACo's coatings has feed rate above the minimal chip thickness and one is lower it for the coated tools made of TiSiN and nACo. To achieve good surface roughness, it is better to micro-mill on the thinnest chips possible, since this reduces surface deformation and hence improves surface clarity, as opposed to milling on a thicker or thinner chip [58]. This may also explain why tools of TiSiN coated have reduced surface finish values.

The analysis of variance (ANOVA) data on surface roughness showed that cutting speed is the most significant component, accounting for 39 percent of the total flexibility as reported by the literature. As cutting speed increases, the temperature rises, which in turn affects the roughness of the surface. [59]. One of the most important factors in surface roughness is depth of cut, which accounts for more than 30 percent of the overall range. Surface finish/roughness was influenced less by coating type and feed rate, with each accounting for 21 percent and 15 percent, respectively.

The tool coating had a far lesser impact on surface roughness than cutting velocity. A lesser effect on heat generation was attributed to the tool coating's lower coefficient of friction. As a result, there is no influence the coating has on the cutting mechanism in any other respect. Research shows that the DOC don't have a major impact on surface roughness and can't be detected because of the contradictory results [10]. Surface roughness was shown to be more attributable to an enhanced ploughing effect at very small depths of cut, but as the DOC increased, the ploughing impact decreased and appropriate cutting occurred, resulting in a decrease in surface roughness [32]. Several theories were put forward as to why the roughness of the surface had decreased. According to [10,15], surface quality deteriorated due to an increase in cutting force and vibration.

4.2.2 Burr formation analysis

The burr width was used as a response variable in an ANOVA for the burr study. According to our findings and those of other researchers [86], the down milling operation produced the majority of the burr generated during the experiment. During the burr analysis, researchers are focusing their attention on the very top burr. Each slot's maximum burr width and height was determined using a digital microscope.

The primary plot depicting the influence of right and left burr width and height can be shown in Figure 4.2 and 4.3. For micromachining of Inconel 718, burrs were most likely to be created when the cutting length was set at 10 millimeters, as shown in the plot above. It was found that left burr values, both in width and height on tools nACo-coated were greater than those on AlTiN-coated tools, but lower than those on tools coated in TiSiN and uncoated tool. While right burr values on AlTiN coated tool was greater than those of nACo and uncoated tool. The TiSiN coated tool had a larger cutting-edge radius than the other tools, which resulted in higher burr formation values both in height and width. Micro milling requires precise control of the cutting-edge radius, according to this study. In large part, this is because increased cutting-edge radius resulted in most of the cutting occurring under the minimal chip thickness required. As a result, cutting pressures and distortion were increased, resulting in a wider burr width.

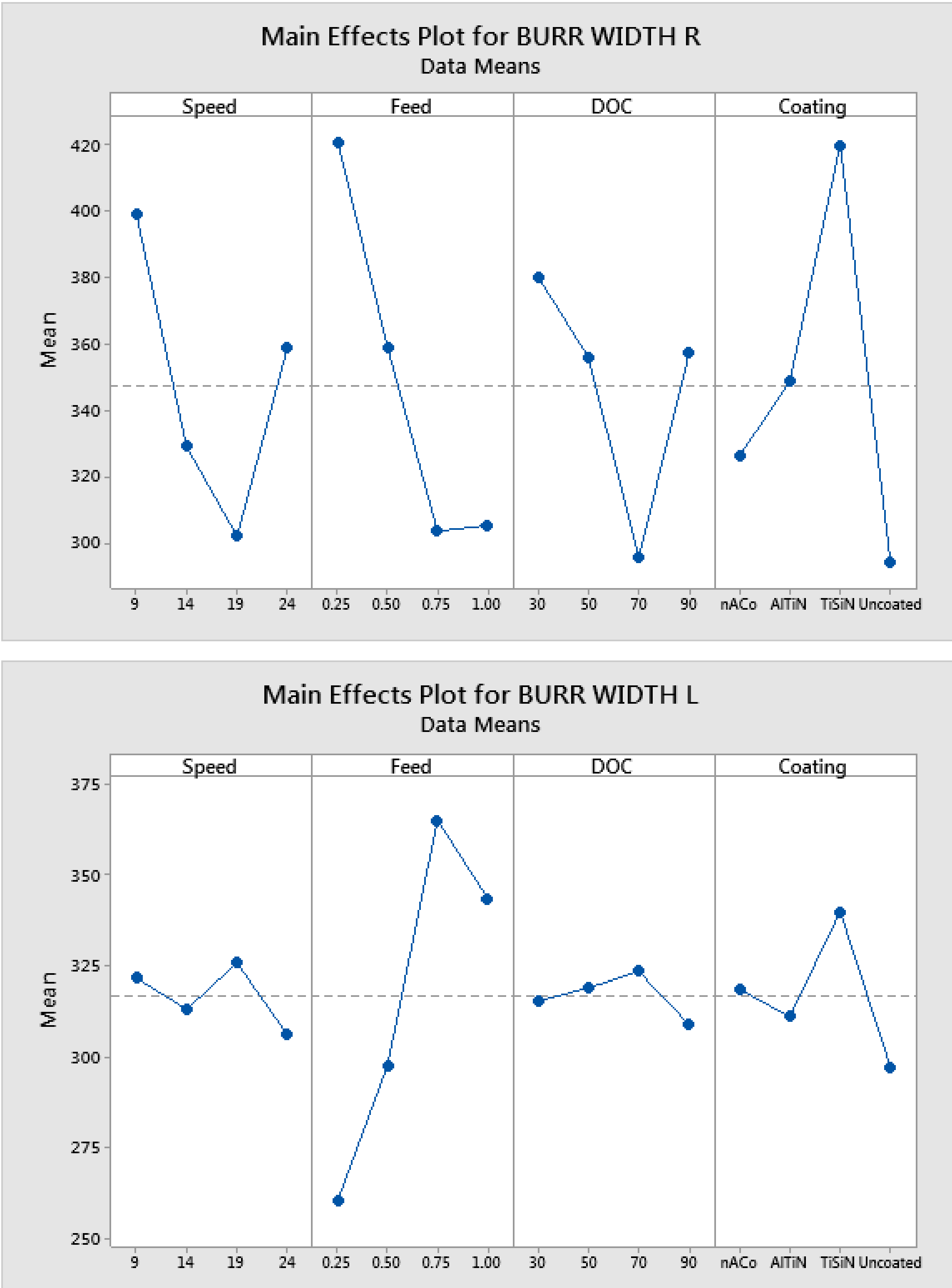
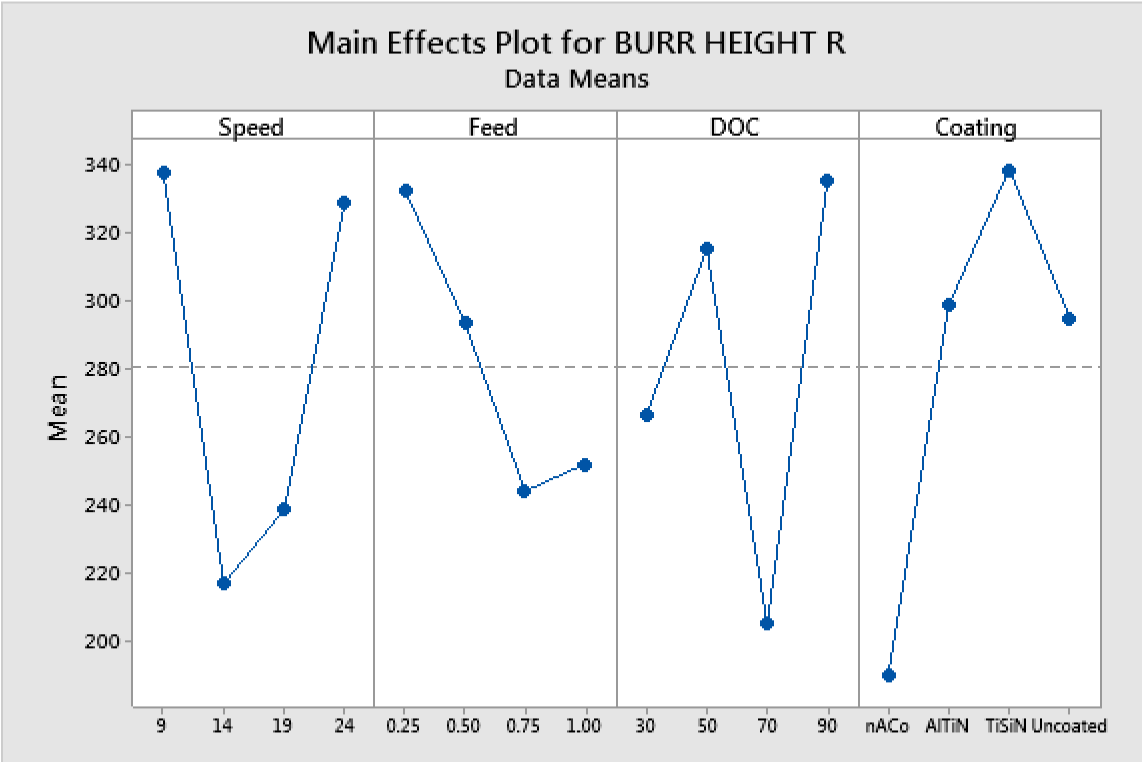


Figure 4.2; The main effect plot for right and left burr width



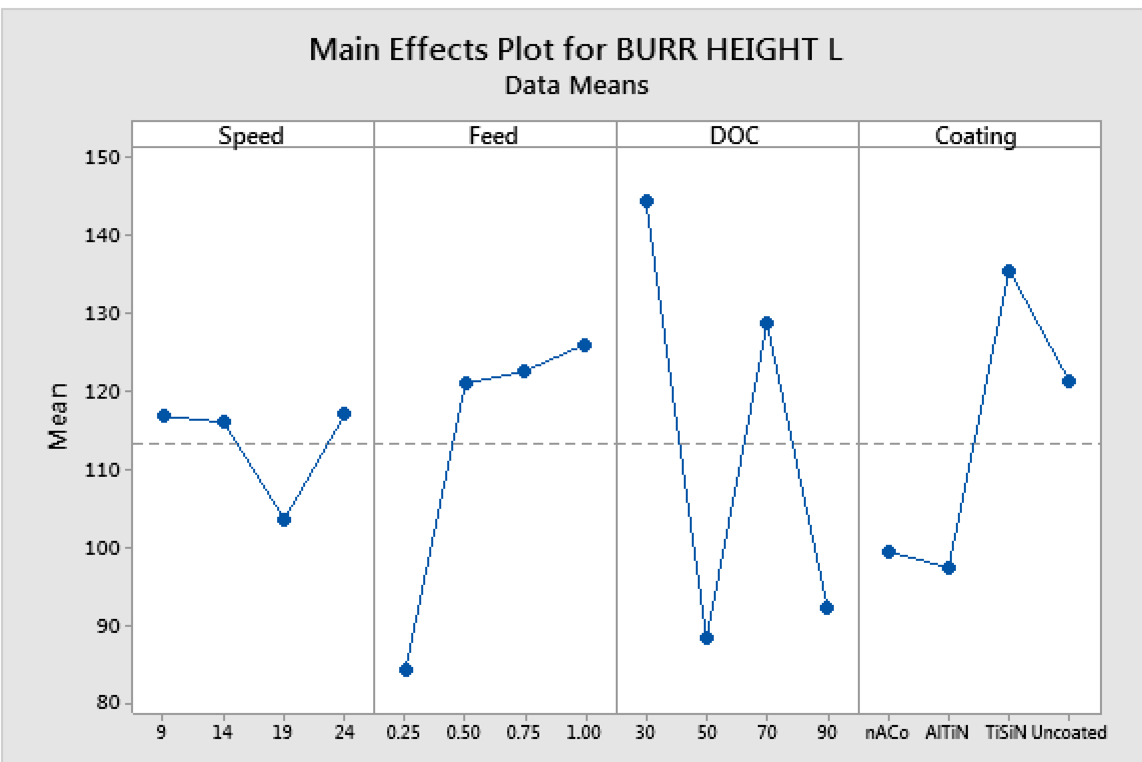


Figure 4.3; The main effect plot for right and left burr height

In an ANOVA study on burr development, researchers found that the DOC was the most important factor in the production of burrs. Overall, this factor was responsible for 32 percent of the variation. As far as burr formation is concerned, cutting speed came in second with a 22 percent share of the total variability. The burr formation contributions were only 19 percent affected by the feed rate. Tools coatings was realized to have no bearing on the final product.

According to Figure 4.2 and 4.3, it was realized that the burr width reduced with increasing cut depth when micromachining Inconel 718. The association between the two variables was used to come to this conclusion. Uncut chips can be easily chipped off since burr is an uncut form of the chip. This makes it easier to chip off the worked piece at a higher depth of cut than at a lower depth of cut, which reduces burr formation. Burr is a form of chip that has not been sliced.

Additionally, it was determined that increasing the cutting speed led in a larger burr as various cutting speeds lead to considerable variations in cut temperature. A broader burr is produced by machining at higher speed because the workpiece deforms more due to higher temperatures between the tool edge and workpiece. The tool with TiSiN-coating had a higher coefficient of friction, which aided to distort the material as the temperature rose, resulting in more burr development [59]. As the feed rate increased, it was discovered that the burr breadth first grew, and then decreased. There were findings that burr width reduced with rise in the feed-to-cutting-edge radius.

4.2.3 Tool Wear

The finished product quality and the accuracy of the machining process are both adversely affected by tool wear, which is an irreversible process. The wear of tool down at a rate directly proportional to the hardness of the workpiece material. According to Wang et al. [60], various machining factors have an impact on the final product. An experimental machining operation's wear progression is compared to the wear progression that occurred during the wear mode. This helps determine how different machining factors affect wear progression. During testing, it was discovered that the micro end mills wore out rapidly and that the predominant wear mode may be divided into three distinct stages: primary, secondary, and tertiary. As seen in figure 4.4, fast cutting speeds and moderate feed rates can reduce abrasive wear in the beginning. As a result of irreversible wear on tools, higher temperatures in the cutting zone can cause volumetric gain, which can lead to the workpiece material adhering to the tool's cutting face, reducing the tool's hardness, and increasing its wear rate. The hardness of the workpiece and the machining parameters used during the machining process affect the effective tool life of a cutting tool. Cutting tool wear is influenced directly by machining factors, such as feed rate, cutting velocity, DOC, and spindle speed, according to data from an experimental evaluation. Nonuniform abrasion of the active cutting edge, tool cutting face, and tool flank is responsible for the high tool wear rates.

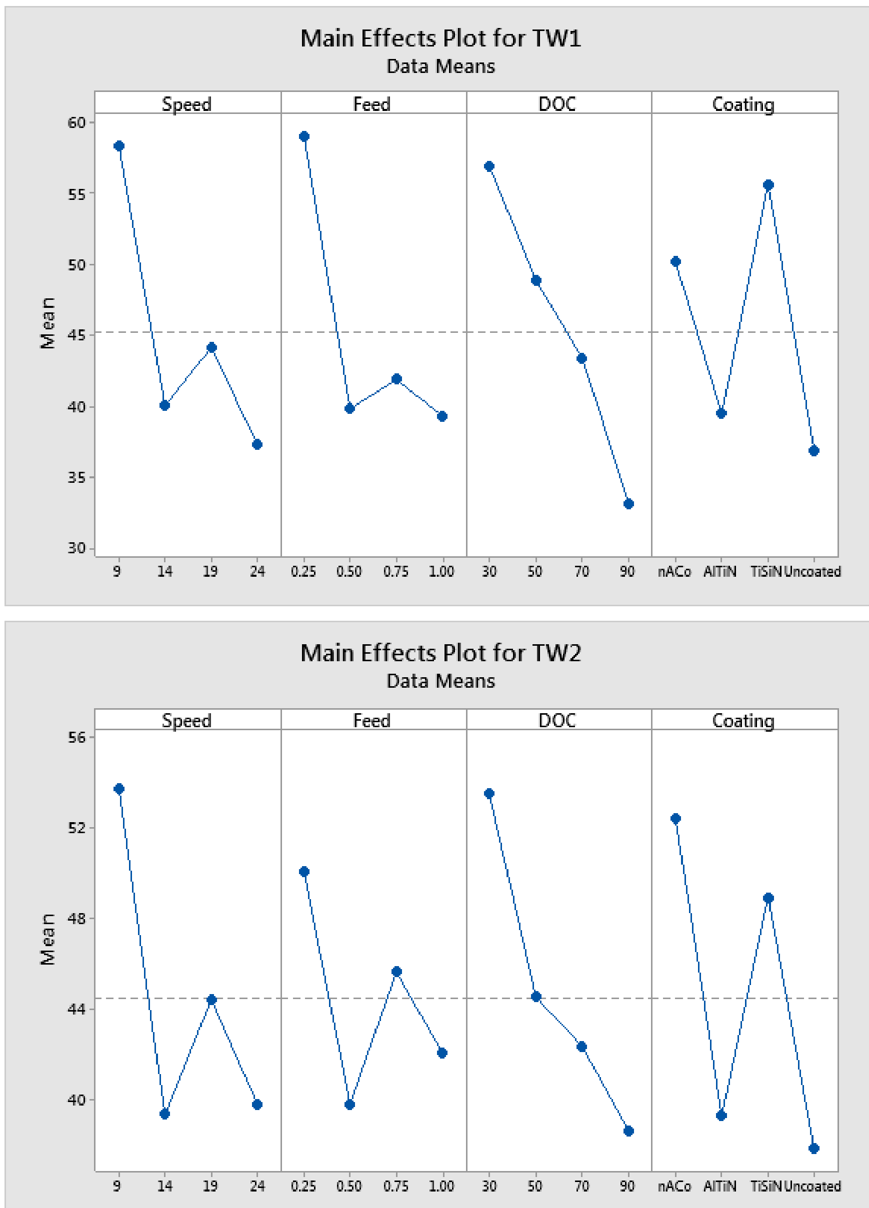


Figure 4.4; The main effect plot for tool wear

CHAPTER 5: CONCLUSION

In the present experiment, Inconel 718 is micromachined to investigate the effect of varied cutting parameters and tool coatings on burr formation and surface roughness. For micro-milling research, low speeds below the cutting-edge radius and feed rates (m/tooth) that were less frequently covered in earlier literature were used. The results of the studies and the ANOVA-based statistical analysis allow us to draw the following conclusions:

- ANOVA analysis found that the most important factors to reduce surface roughness were cutting speed and tool coating.
- Cutting speed was shown to be the most important component in reducing surface roughness; feed rate and tool coating were found to be among the most common methods of reducing burr development in down milling, which accounts for nearly half of the total variability.
- It was established that feed rate (m/tooth) and tool coatings were important factors in reducing burr width.
- Cutting speed, DOC, and tool coating type were the most important parameters for tool wear.
- Furthermore, it has been found that low-speed machining yields surface finishes and burr width results that are comparable to those obtained from higher-speed machining.
- The remarkable finding of these experiments is that the coefficient of friction of the tool coating affects surface roughness and burr growth while milling Inconel 718 at low speed. A high coefficient of friction is thought to raise the machining temperature and promote material deformation, but it will also promote burr production.

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