Investigation of Chips Morphology with Tool Wear in High Speed Turning of Nickel based Super Alloy

Pankaj Shende and Dr. Hardik Bhupendrabhai Ramani
Department of Mechanical Engineering,
Dr. A.P.J. Abdul Kalam University, Indore (M.P.) - 452010
Corresponding Author Email: shendepankaj2004@gmail.com

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Abstract
Nickel-based super alloys have found extensive use in the fields of aerospace, petro chemistry, marine technology, and other industries due to their outstanding corrosion resistance, oxidation resistance, stability and reliability at various temperatures. Even though a nickel-based super alloy is a form of treated material, cutting causes a substantial amount of cutting heat to be produced due to the contact between the tool and the work piece. The work piece's poor thermal conductivity also causes a lot of cutting heat to build up at the point of contact, which increases tool wear, shortens tool life, necessitates more frequent tool replacements, and causes other problems that drive up the company's production costs.This study covers the current status of research on failure mechanisms, tool wear optimization, etc. and discusses the mechanisms of tool wear in the machining of nickel-based super alloys (abrasive wear, adhesive wear, plastic deformation, chemical wear, etc.). According to a review of the literature, the goal of incorporating tool coatings, optimising tool materials and cutting parameters, or enhancing the cutting environment is to control the heat during the processing of nickel-based super alloys in order to improve the tool environment and lengthen tool life. The prospects for avoiding tool wear while machining nickel-based alloys are also highlighted.

Keywords: Nickel based super alloys; Tool wear; Optimization in cutting tool; Extension in tool life;

1. Introduction

Cutting occurs frequently in everyday life, research, and technology. In comparison to traditional grinding, finishing and machining of hardened steels has many technical and financial advantages, including quicker setup and tool changes and less detrimental environmental effects. As a result, it has gained more attention in numerous industrial applications[1]. As the need to increase production efficiency has grown, machining technology has advanced rapidly. This technology has several benefits, including high rates of material removal and low cutting forces that result in outstanding dimensional accuracy and surface quality.Higher cutting speeds, however, frequently result in the development of serrated chip flow, which shortens the life of the tool, deteriorates the surface polish, and reduces the accuracy of the machined item. In general, it is believed that saw-toothed or segmented chips, which are of considerable research interest, a highly nonlinear and dynamic plastic deformation process causes them to form. It has been demonstrated that this process has a negative impact on cutting forces, machine vibration and deflection, tool wear, and surface finish. It is quite interesting to investigate how cutting conditions affect chip shape even if the majority of researchers have concentrated on tool wear evaluations and chip formation mechanisms[2]. It has been noted that when cutting conditions and tool wear change, the chip dimension changes. On the basis of their geometric shapes, chips produced during the machining of metals and alloys can generally be divided into four groups: flow, saw-toothed/ segmented, wavy, serrated, and discontinuous. It has been observed that several methods have also been devised to characterize chips when other non-metallic engineering materials are being machined[3]. Advanced materials like ceramic and hybrid composite chips might have very different physical properties from those seen in metal milling.One study examined the classification of seven different types of chips produced when non-metallic elastomers were machined in various cutting environments. Investigated how cutting pressures significantly decreased with higher cutting speed and feed[4].However, it is still unknown how to systematically examine and characterize chip morphology in hard machining. This study's primary goal is to further describe and characterize various chip diameters as functions of cutting conditions in hard machining. The report first provides the study's tools and work samples. Following that, the experimental setup and design as well as the experimental findings on chip morphology are discussed. Additionally, information on chip thickness, micro hardness, roughness, and SEM images of the chips is provided. The presentation of conclusions and suggestions for additional research follows. Knowledge of chip morphology will facilitate a better understanding of Nickel based super Alloy[5].

Super alloys made of nickel are a family of materials that are widely employed in situations with complicated loads, high temperatures, and extremely corrosive airflow. Excellent mechanical qualities, strong thermal stability, and resistance to fatigue and creep are all present in these materials. They are extensively utilised in nuclear power plants, gas turbines, and aircraft engines[6]. However, because of their high material toughness and propensity to work harden, nickel-based super alloys are difficult to make.The improper cutting conditions can lead to poor surface quality when processing nickel-based super alloys, which can have a major impact on the fatigue strength, corrosion resistance, and tribological properties of components[7]. For example, high surface roughness values reduce the component fatigue life, and surface imperfections are often the cause of fatigue cracks. Investigated the effects of surface abrasion and residual tension on the Inconel-718 fatigue life following shot-peening[8]. Lower surface roughness will result in components with longer fatigue lifetimes. It has been found that1the fatigue life of 30Ni-CrMo-V12 steel in the low1cycle fatigue regime is predominantly influenced by the crack propagation life, which consists of multiple surface cracks with interactions and coalescences[9].Using flaws data for metallic materials, a probabilistic1model was developed to evaluate the fatigue life of Nickel alloys. The findings demonstrated that the probabilistic model could account for the size effect and that there was good agreement between model predictions and experimental findings[10]. Therefore, it is crucial to investigate how the machining process influences the condition of the machined surface in order to enhance the surface quality and functional performance of machined parts and components[11].

2. Literature review

About 45% of wrought nickel-based products and 25% of cast nickel-based products are composed of nickel alloys, specifically Inconel 718[12]. This alloy is widely utilised in crucial components including liners, vanes, and discs. Since the 1960s, Inconel 718 has become a popular nickel alloy due to its superb high-temperature strength, excellent mechanical properties, and outstanding corrosion resistance produced at comparably low costs. As a result, some articles on the machining capabilities of Inconel 718 during the past few decades were published[13]. However, Inconel 718 is regarded as one of the hardest alloys to cut.

The following are the primary poor machinability qualities:
(1) Strong propensity for building edge (BUE);
(2) Behaviors that increase cutting force through hard work;
(3) Due to the rough, abrasive carbide particles, tools wear out quickly;
(4) High temperatures without compromising strength;
(5) High cutting temperature resulting from poor thermal conductivity;
(6) Extreme hardness;

Super alloys based on nickel are extremely difficult to produce and meet quality standards due to all of these characteristics[14]. The machining of Inconel 718 presents a number of technical and financial challenges purely because of these intrinsic qualities. The result was that the alloy's milling, drilling, and turning operations were carried out at comparatively modest cutting speeds and feeds in comparison to the machining of other alloys like steel and aluminum. As a result, practical Inconel 718 machining typically requires more time and money[15].Planning the machining process, enhancing surface integrity, and ultimately improving product performance all benefit from a better understanding of chip formation mechanism. Research into the mechanism of chip generation under various cutting settings is essential to gaining a thorough understanding of the entire cutting process because of its importance[16]. Therefore, it is imperative to make an effort to have a complete understanding of the chip generation mechanism in the machining of Inconel 718. This paper reviews that mechanism[17].

Nomenclature
v cutting speed (m/min)
d depth of cut (mm)
AISI American iron and steel institute
CBN Cubic boron nitride
SEM Scanning electron microscope
f feed (mm/rev)
Ra Average surface roughness
HV Vickers hardness
HRC Rockwell hardness
CNC Computerized numerical control

3. A Chip Formation Analysis

3.1 Chip burrs

Due to the milling process, The chips exhibit a plastic deformation in three dimensions. For the oblique cutting model, the milling procedure is streamlined in order to examine chip formation. A schematic of the production of chip burrs is shown in Figure 1, where I represents the cutting edge's inclination angle and n represents the cutting tool's rake angle[18].

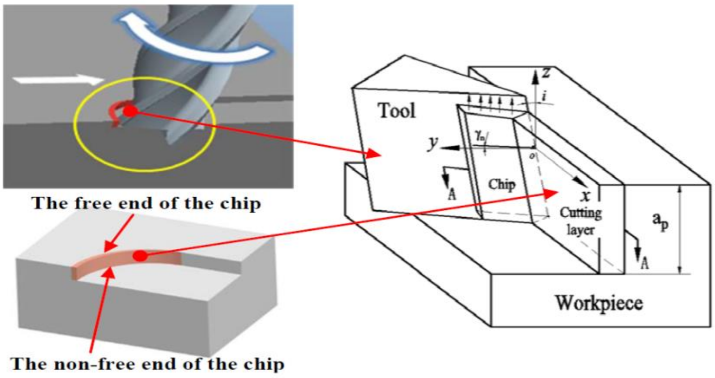


Figure 1: The burrs on the chip surfaces (see online version for colours)

The primary cutting edge is no longer parallel to the direction of cutting speed during the oblique cutting operation. Due to the inclination angle, the chip will not flow normally in the direction of the primary cutting edge[7]. Because chip flow is slower than cutting speed, the non-free end of the chip still runs into resistance from the substrate surface during the immediate cutting process. Superalloys based on nickel undergo substantial deformation during milling[19]. A high-speed rotating tool shears and extrudes the cutting layer violently and quickly. The following chip segment on the shear plane is pressing against the chip at the moment. The chip moves quickly along the rake face of the tool and begins to separate from the work piece[20].The plastic is unable to flow freely over the rake face because the chip encounters a large frictional barrier from the rake face during its immediate passage. The chip starts to flow in the direction of the free end and hardens as a result at a very high strain rate[21]. Chip burrs gradually develop their distinctive morphology at the chip's free end. While the non-free end of the chip will remain relatively smooth due to the resistance of the surface there, chip burrs won't form there. Short tool life and poor machined surface quality may result from a little change in the chip formation process as the cutting layer material gradually separates from the work piece[22]. Increased cutting speed will also change the material's plastic flow, which will change the characteristics of chip burr morphology[23].

3.2 Serrated chip morphology

The production of serrated chips during high-speed milling of the nickel-based superalloy Inconel 718 has been attributed to the shear localization [24]. Insufficient plastic deformation results in the chips separating and creating a serious imbalance. Thermoplastic shear instability, also known as adiabatic shear, is a deformation phenomena that is specific to high-speed cutting of nickel-base super alloys. The nickel-base super alloy's shear localisation is determined by the material's deformation characteristics. The heat generated during cutting is held in the shear zone because Inconel 718 has a low thermal diffusivity, and because it does not have enough time to dissipate, an adiabatic shearing state results.When the impact of thermal softening caused by partial high temperature is greater than the impact of strain rate, more severe shear localization will occur. The serrated chip shape is produced as a result of intensifying the thermal softening effect, which makes the shear zone the area of chip deformation that is least significantly affected[25].

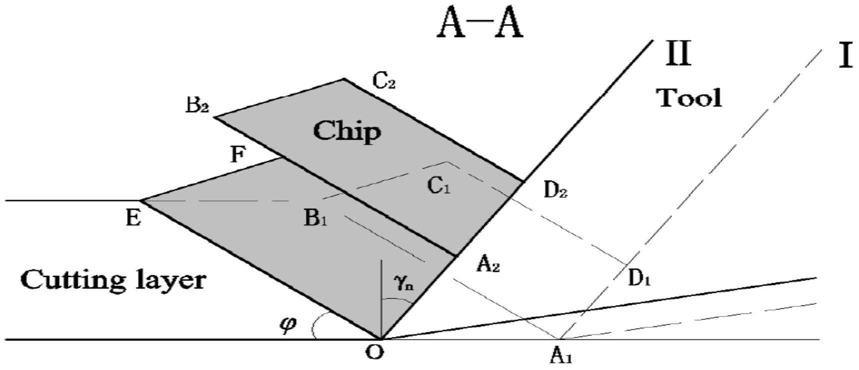


Figure 2: Model for serrated chip formation

The creation of serrated chips during high-speed milling of Inconel 718 is simplified in Figure 2. The chip segment changes from A1B1C1D1 to A2B2C2D2 after the shear localization, effectively obtaining its ultimate shape, when the tool moves from position I to position II. It then gradually climbs the rake face until it is pulled apart from the tool by the succeeding chip segment. Furthermore, during tool movement, the chip is susceptible to stress and shear force in the shear zone, tension and friction from the rake face, as well as stress and friction, all of which cause a certain plastic deformation.The geometry of the section changes from a parallelogram to a trapezoid during the transition from OA1B1E to OA2FE. Initial plastic deformation along the shear angle is shown in the chip section. When a material's yield limit is surpassed, shear instability occurs, and the segment slides in the direction of the shear plane and rake face. The second chip section is created once shear localisation is complete[26].

Figure 3: The chip imaging system's microscopic vision system (see online version for colours)

4. Experimental Methodology

The interactions between the tool and the work piece that are mechanical (thermodynamic wear, predominantly abrasion) and chemical are the most common sources of tool wear (thermochemical wear and diffusion). When it comes to the machining of nickel-based super alloys, in-depth reports on a variety of tool wear mechanisms, including adhesive wear, abrasive wear, diffusion wear, oxidation wear, and debonding failure, have been documented in the literature. The sources, mechanisms, classifications, and effects of the wear are summarised in Figure 4. One of the recognized mechanisms for tool wear is the adhesion process, which is significant in tool failure.High temperatures and stresses that cause the work piece to stick to the tool surfaces cause adhesive wear in the tool, which results in the formation of the built-up edge (BUE), which leads to tool failure through attrition at medium cutting speeds and plastic deformation and/or tool failure through chipping and flaking of the tool material at high cutting speeds[27].

In order to enhance study into the intricacies of machining tool wear mechanisms, we first identify a number of typical tool wear forms. Abrasion and adhesion are the two types of tool wear that occur most frequently while dealing with super alloys based on nickel. They are often caused by excessive cutting forces produced by the tool when it comes into contact with the work piece, different lubricating applications made during the cutting process, etc. They can occur at both high and low cutting temperatures. We provide an overview of the usual wear mechanisms of nickel-based superalloys. At high temperatures and pressures, a coating applied to the tool's surface may aid to slightly increase its longevity.The components of the coating react with the tool, creating new compounds on its surface and causing scratches that degrade the surface of the part. This paper discusses the improvement of tool wear in nickel-based super alloy machining, as well as the shortcomings of the existing body of knowledge and potential lines of future investigation. Both high and low cutting temperatures can cause them. Here is a summary of the usual wear mechanisms of superalloys based on nickel[2]. They are frequently brought on by the tool's high cutting forces when it makes contact with the work piece, various lubrication techniques employed throughout the cutting operation, etc.

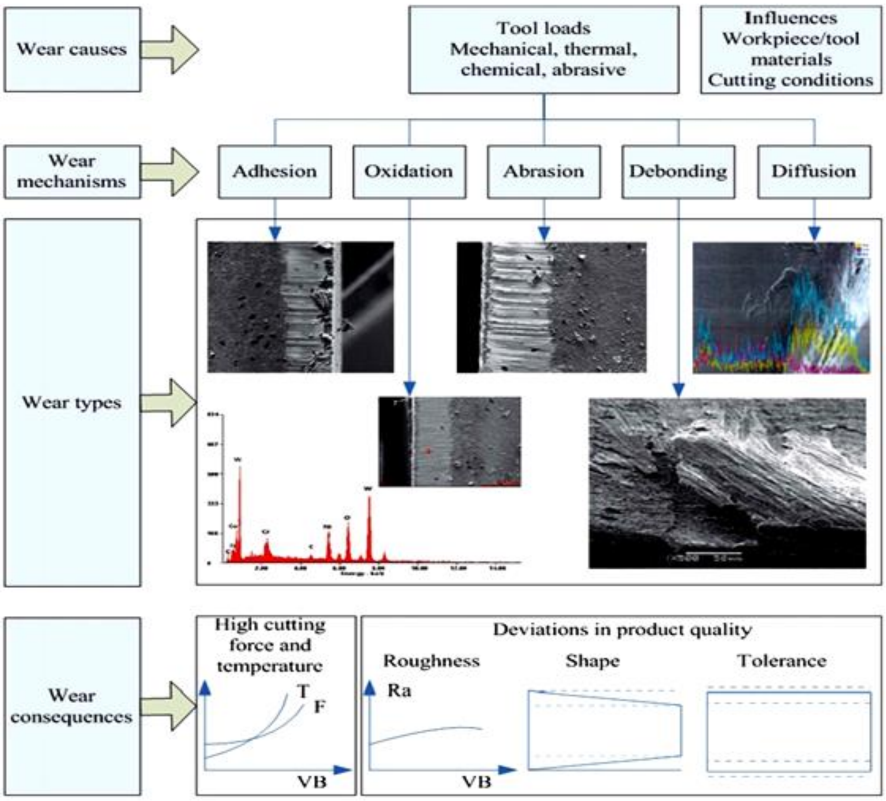


Figure 4: The reasons for wear, its mechanisms, types, and effects while cutting nickel-based super alloys

5. Result and Discussion

In order to comprehend surface roughness, chip geometry, and cutting force magnitude, experimental findings were studied. Eight experiments total were conducted using combinations of the different parameters shown in Table 1. The key control parameters were cutting speed, radial feed, and axial feed. However, as indicated in Table 1, As a result, two more parameters for axial feed and cutting speed were derived. A stylus type perthometer was utilised to gauge the work piece's surface roughness with a cutoff length of 0.8 mm (Ra in m).

Table 1. Circumstances for processing experimental runs

Exp. No.	**Cutting speed**		**Radial feed**	**Axial Feed**	
	(rpm)	(m/min)	(mm)	(μm/tooth)	(mm/min)
1.	5000	314	1.7	2	20
2.	3000	188.4	1.7	2	12
3.	3000	188.4	1.7	1	6
4.	5000	314	1.7	1	10
5.	5000	314	3	2	20
6.	3000	188.4	3	1	6
7.	3000	188.4	3	2	12
8.	3000	314	3	1	6

Surface roughness measurements reveal distinct bands on the machined surfaces. Figure 4 shows an example of a specimen with various bands and the surface roughness values that go with it. The surface roughness measurement on the machined surfaces identifies a few discrete regions of varied roughness. In the band 1 region at the tool tip, as shown in Fig. 4, an average maximum surface roughness of 2.48 m Ra can be observed. It is shown that the surface roughness ratings are significantly higher at the tool tip.Since the chip was left on the machined surface close to the tool tip area, it is assumed that this is what caused the surface flaws. Due to the extremely low cutting speed in this region, there is significant material deformation, which leads to a subpar surface finish [10]. Surface roughness values change dramatically in band 2. Surface roughness of 0.27 m in this area may be the result of straightforward chip removal.

Table 2. Surface roughness analysis of variance (ANOVA) findings

Source	**Degrees of freedom**	**Sequential sums of squares**	**Adjusted sum of squares**	**Adjusted mean of squares**	**Test statistic**	**Probability**	**Percentage contribution (%)**
Feed rate	1	0.29203	0.29203	0.29203	44.18	0.000	19%
Insert nose radius	2	1.19165	1.19165	0.59583	90.15	0.000	77%
Insert coating	1	0.05964	0.05964	0.05964	9.02	0.020	4%
Error	7	0.04627	0.04627	0.00661			
Total	11	1.58960					

The claim that surface roughness is mostly determined by feed rate draws attention to the importance of feed rate in machining processes. Key effects graphs are displayed in Fig. 5 in the current study to illustrate how each input parameter affects the surface roughness. It is clear that feed rate has a detrimental effect on the quality of the work piece's surface; therefore, as feed rate is increased during an operation, surface roughness also increases. The feed rate is intended to be increased because most research on material machining focuses on maximum material removal.Since the amount of material that may be removed at once is constrained by the work piece's surface roughness, an optimization is required to acquire the best outcomes from machining operations. Poor surface finish is a result of increased cutting forces brought on by an increase in feed rate.

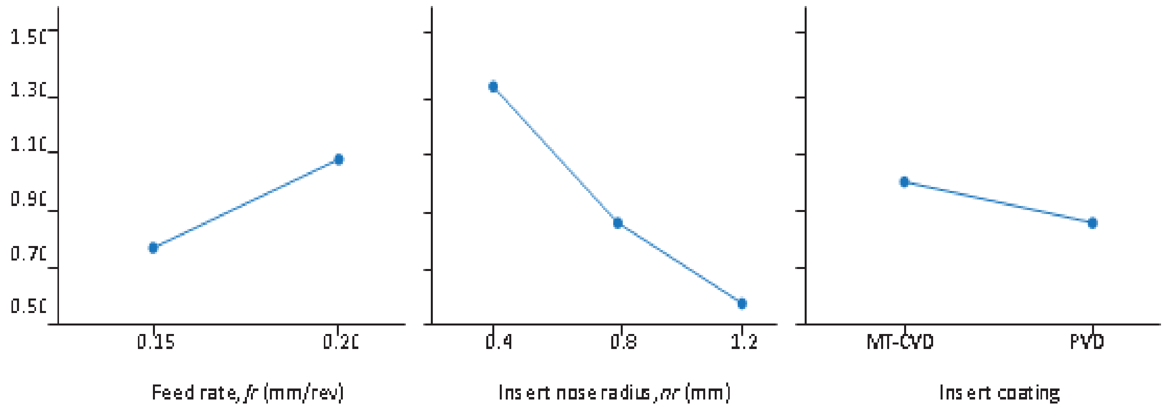


Figure 5: Plot of the main effects for surface roughness (Ra). PVD stands for physical vapour deposition. MT-CVD stands for medium temperature chemical vapour deposition.

Repeated measurements on each specimen showed near values based on the roughness results, indicating that the repeatability of the measurements is pretty excellent given that the SD is within 5% of the mean surface roughness. According to the ANOVA results, the insert nose radius, feed rate and coating each contributed 77%, 19%, and 4% of the total variance. In this context, the work piece's surface roughness is most strongly influenced by the insert nose radius. While the weight of the insert coating has a very small impact on the work piece's surface quality, the feed rate has a significant impact.

6. Conclusion

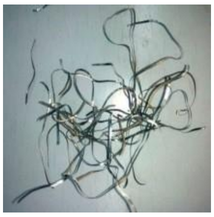
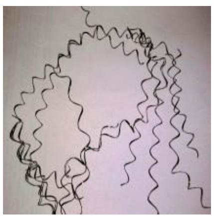
This study demonstrates that there is a large chip length compression, which is offset by a commensurate increase in chip width and thickness. The proposed models and the associated experimental results, which vary from 3 to 13 percent, are in good agreement, according to the experimental validation of the chip dimensions. Surface roughness generally reduces from the cutter tip area towards the cutter's periphery as a function of depth of cut/chip cross section area.

Inconel-718 has been successfully hard turned utilizing CBN tool inserts in a dry environment. After that, a chip morphology examination was performed. The experimental research led to the following conclusions:

(1) Continuous chips were produced from all cutting settings, and the cutting speed and various feed rates both contributed to the development of saw-tooth shapes in the chips.

(2) According to Fig. 5, Surface roughness is significantly influenced by cutting speed. Because faster cutting speeds produce higher surface finishes.
(3) The saw tooth-like chips that are formed as a result of cyclic crack propagation are explained by the SEM pictures of the chips, which also show shear patterns in the majority of the chips. Additionally, research shows that reducing the feed tends to increase chip thickness.
(4) The decrease of surface quality is caused by the higher feed rate (0.11-0.14mm/rev), which encourages the creation of saw teeth on the chip edges.
(5) The experiment also shows that the cutting speed tends to decrease as chip thickness increases. In general, this study indicated that the chip thickness is influenced by both the cutting speed and the feed rate.
(6) The explanation of chip morphology and its link to cutting conditions provided by this experimental study will be helpful to researchers and manufacturers in choosing cutting settings.
(7) As it transitions from serration to ribbon, chip shape gradually gets more pronounced. The thickness of the chip with the serrated chip shape is also getting thinner.
(8) Understanding chip formation is essential when milling Inconel 718 at high speeds. The findings of this work provide theoretical and experimental support for the best cutting speed selection based on the characteristics of the chip generation process, which will be highly helpful for enhancing surface quality.

Table 3.Chip shapes obtained under Dry and Minimum Quantity Lubrication (MQL) circumstances.

Cutting Conditions	**Dry** (Long continuous chips of a blue color)	**MQL** (Small helical chips of a light golden color)
Vc= 200 m/min *f = 0.10 mm/rev*		
Vc= 250 m/min *f = 0.15 mm/rev*		
Vc= 300 m/min *f = 0.20 mm/rev*		

The use of dry machining produces some unbroken, extraordinarily long continuous chips with a bulk ratio of about 68, whereas the use of near-dry machining produces small, fragmented chips with a bulk average ratio of 8.1. A move toward more environmentally friendly manufacturing could be seen in the dry chips that the near dry machining technology produces.

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