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Auteur: Morvarid Memarianpour
Author:

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Directeurs de recherche: Luc Baron, Marek Balazinski, Sylvain Turenne, & Seyed Ali Niknam
Advisors:

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affiliée à l'Université de Montréal

**Innovative strategies to improve the tool life when machining Nickel-based
Inconel 718 superalloy**

MORVARID MEMARIANPOUR

Département de génie mécanique

Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctorat*

Génie mécanique

Septembre 2024

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POLYTECHNIQUE MONTRÉAL

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Cette thèse intitulée:

Innovative strategies to improve the tool life when machining Nickel-based Inconel 718 superalloy

Présentée par: **Morvarid MEMARIANPOUR**

en vue de l'obtention du diplôme de *Philosophiæ Doctorat*

a été dûment acceptée par le jury d'examen constitué de :

Aouni LAKIS, président

Luc BARON, membre et directeur de recherche

Marek BALAZINSKI, membre et codirecteur de recherche

Sylvain TURENNE, membre et codirecteur de recherche

Seyed Ali NIKNAM, membre et codirecteur de recherche

Sofiane ACHICHE, membre

Maryam ARAMESH, membre externe

DEDICATION

This Ph.D. dissertation is dedicated to my family, friends, and colleagues. I would like to express my deep gratitude to my dear parents, whose encouragement gives me the tenacity to work harder. I also dedicate this dissertation to my wonderful brothers, many friends, and colleagues; all they have done is appreciated.

ACKNOWLEDGEMENTS

I want to take this opportunity to express my sincere gratitude to my advisor, Professor Marek Balazinski, for his outstanding support, help, suggestions, great encouragement, and guidance. His wisdom, kindness, and trust in my life have always inspired me. I would also like to thank my co-supervisors, Prof. Sylvain Turenne and Dr. Seyed Ali Niknam, for their continuous guidance, help, and support. This work would not succeed without their precious advice.

RÉSUMÉ

Dans les différentes études sur l'usure et la durée de vie des outils, trois zones distinctives ont été classées en fonction de l'usure de l'outil par rapport au temps de coupe. Elles sont connues comme l'usure initiale, l'usure à l'état stationnaire et les périodes d'usure accélérée. Cependant, le phénomène initial d'usure de l'outil et son influence sur la vie de l'outil ne sont pas encore clairement compris. Ceci devient plus compliqué quand on traite avec des superalliages à base de nickel qui sont difficiles à usiner. Parmi ceux-ci, l'Inconel 718 est généralement un des matériaux les plus difficiles à usiner en raison de sa dureté élevée et de sa haute résistance aux températures élevées. Il existe quelques études limitées sur l'usinabilité de l'Inconel 718 lors de l'utilisation d'outils en carbure. En particulier, les effets des paramètres de coupe sur l'usure initiale de l'outil lors du tournage d'Inconel 718 n'ont pas encore été étudiés. Pour combler le manque de connaissances découlant de l'examen de la littérature, les effets des paramètres de coupe sur les mécanismes initiaux d'usure des outils (période de transition) sont étudiés dans ce travail. À cet effet, les mesures d'usure des outils ont été effectuées au microscope optique et l'évaluation microstructurale de l'usure initiale de l'outil par microscope électronique à balayage (SEM) et spectroscopie par dispersion d'énergie (EDS). Ensuite, on trace le diagramme de progression de l'usure de l'outil par rapport à chaque condition de coupe utilisée, ce qui a permis de déterminer une durée du stade initial de 4 secondes. Sur la base d'observations expérimentales, l'abrasion est le mode d'usure initial dominant de l'outil lors du tournage de l'Inconel 718. On a constaté qu'une vitesse de coupe accrue a conduit à une adhérence accrue sur la face du flanc de l'outil, malgré la vitesse d'alimentation utilisée. Après la période de transition de 4 secondes, l'usure et la durée de vie de l'outil ont été évaluées en variant les conditions initiales d'usinage. Autour de la période de transition, on observe à partir de la morphologie des surfaces d'usure que l'abrasion et l'adhésion sont les principaux mécanismes d'usure en cause. Après la période de transition, on note que de faibles vitesses de coupe et d'avance conduisent à une augmentation de la durée de vie de l'outil comparée à celle reliée aux conditions de référence. Il est donc possible d'améliorer la durée de vie des outils en choisissant des conditions d'usinage optimales durant la période de transition. L'intégration de la caractérisation expérimentale et de l'optimisation de la durée de vie de l'outil dans les superalliages à base de nickel est le principal aspect d'originalité de ce projet.

Mots clés: Tournage, Usure initiale des outils, Inconel 718, Superalliages

ABSTRACT

In various studies performed on tool wear characterization and tool life improvement, three distinctive regions of tool wear have been classified according to increased tool wear versus cutting time. They are known as initial, steady-state, and accelerated wear. However, broad scopes have not clearly understood the initial tool wear phenomenon, its formation factors, and its influence on tool life. This becomes more complicated when dealing with nickel-based superalloys, which are classified as difficult-to-cut materials. Inconel 718 is generally classified as one of the most difficult-to-cut superalloys due to its high hardness and strength at elevated temperatures. However, limited studies have been conducted on the machinability evaluation of Inconel 718 when using carbide tools. In particular, the effects of cutting parameters on the initial tool wear when turning Inconel 718 have not yet been studied. According to a lack of knowledge determined from a literature review, within this study, the effects of cutting parameters on the initial tool wear mechanisms were investigated, followed by characterizing the wear modes at the initial periods of cut (transition period) under various cutting conditions. The tool wear morphology at the transition period, and the optimum tool life was determined, and it was found that the initial period lasts 4 seconds from the beginning of the cut. Based on experimental observations, abrasion was the primary initial tool wear mode when turning Inconel 718. Furthermore, it was found that increased cutting speed led to increased adhesion on the tool flank face despite the feed rate used. At the next stage, the tool wear growth and tool life were investigated based on varying the initial conditions at the transition period, set at 4 seconds. The tool wear morphology was studied during transition under several cutting conditions. It was noted that abrasive and adhesion are the main wear morphology in the transition period. After the transition point, similar cutting conditions as the reference condition were used. The tool wear morphology and size were recorded and analyzed in each condition. It was revealed that lower cutting speed and feed rate during the transition period improved tool life compared to the reference condition. In other words, using optimum cutting parameters in the transition period of the cutting process may enhance tool life at a higher cutting time. Conducting the integration of experimental characterization and optimizing the tool life in the nickel-based superalloys is the principal aspect of originality in this project.

Keywords: Turning, Initial tool wear, Inconel 718, Superalloys.

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LIST OF SYMBOLS AND ABBREVIATIONS

NBSA	Nickel-based superalloys
FCC	Face Centered Cubic
HSTR	High-strength, thermal-resistant
FD	Fractal Dimension
CBN	Cubic Boron Nitride
EDS	Energy Dispersive Spectroscopy
PCBN	Poly-crystalline Cubic Boron Nitride
PCD	Polycrystalline Diamond
PVD	Physical Vapor Deposition
SEM	Scanning Electron Microscope
EPMA	Electron probe micro-analyzer
WC	Tungsten Carbide
MQCL	Minimum Quantity Cooling Lubrication
V_c	Cutting speed (m/min)
V_{Bmax}	Flank Wear
a_p	Axial depth of cut
f_r	Feedrate
f	Feed (mm/rev)
FES	Field Emission Source
T	Tool life
t	Time

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CHAPTER 1 INTRODUCTION

This chapter presents general information on the subject, followed by a statement about the research questions and motivation for the research project. The research approach, research objectives, and hypothesis statements are then discussed to identify the problem statements.

1.1 Problematic of research

Inconel 718, a nickel-based superalloy (NBSA), is widely used in the aerospace and nuclear industries due to its high thermal resistance and ability to retain mechanical properties at temperatures exceeding 700°C. High hardness, work hardening tendency, abrasive carbide particles in the microstructure, a strong tendency to weld and form built-up edges (BUE), and low thermal conductivity introduce nickel-based superalloys as difficult-to-cut materials. They tend to retain their strength at high temperatures generated by machining. The associated problems with tool life and surface quality when machining nickel-based superalloys must be investigated broadly. Induced residual stresses from machining operations negatively impact the mechanical strain and corrosion properties. Cutting speed affects tool wear and tool life when cutting nickel-based alloys. The primary sources of attention in machining superalloys is short tool life, deteriorated surface quality, and tensile residual stress, which may affect the mechanical strain and corrosion properties [2]. Notch wear formed due to high thermal combination, work hardness, workpiece strength, and abrasive particles is typical tool wear morphologies observed during the machining of the Inconel 718 [3-5].

The initial tool wear morphology and size are known to have a direct relationship with ultimate tool life. As per the author's knowledge, surprisingly, except for a few works [6-9], limited information is available on factors governing initial tool wear and ultimate tool life when machining hard-to-cut materials (e.g. TiMMC). No similar studies were found on machining Inconel 718. Therefore, proposing innovative strategies to improve the tool life in machining superalloys based

on information gathered from initial tool wear is the subject of further investigation. All of the facts mentioned above raise fundamental questions that need to be investigated further:

1. The first question concerns the initial tool wear behaviour, specifically the initial tool wear phenomenon during Inconel 718 machining. What is the wear mechanism at the first moment of the cutting operation? When it occurs, how long does it take, and why does its wear rate increase so quickly during the first wear period and then abruptly decrease to the steady-state period?
2. The second question is the relationship between the initial conditions or initial tool wear behavior and tool life. Is there any possibility of improving the ultimate tool life based on optimized cutting parameters?

Thus, this work assessed the effects of initial cutting conditions and wear mode on the tool life under various cutting conditions when machining NBSAs.

1.2 Structure of thesis

This thesis consists of eight chapters. It starts with an introduction and a literature review in Chapter 2. Chapters 3 and 4 are devoted to research objectives and research methodology. The experimental conditions and parameters used in this research work are presented in Chapter 4. The published research articles associated with the projected goals are presented in Chapters 5 and 6. Chapter 5 presents an investigation on the initial tool wear behaviour during high-speed turning of Inconel 718. Concerning the first phase of the experimental work, the speed was maintained at 150 m/min, and three feed rates were used (0.15, 0.25, and 0.35 mm/rev). The edges of each insert were used only once during the same machining test, with a specific cutting time ranging from 1-4 seconds within one-second intervals. As well as various high speeds (100, 125, 175, 200 m/s) and 0.25 mm/rev feed rate were investigated at a transition time in the second phase. The cutting time of 4s was considered as the transition time. The Chapter 6 examines the impact of the cutting condition and transition period on tool life when machining Inconel 718. The tests were conducted in two stages. The first stage investigated tool life when machining Inconel 718. The 45 m/min cutting speed and 0.25 mm/rev feed rate were kept constant. Afterwards, initial cutting speeds of 25-65

m/min and initial feed rates of 0.15-0.35 mm/rev were used. Notably, the cut depth was kept constant throughout the experiments. The discussion of the work presented in Chapter 7 is linking each chapter outcomes to proposed research objectives. In addition, it helps clarify certain aspects and shortcomings. The discussion also shows the achievements of this research work on improving certain aspects of science related to tool life improvement when machining Inconel 718. Finally, some conclusions, recommendations, and plans will be presented in Chapter 8.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview of nickel-based superalloys

Nickel is element No. 28 in the periodic table with a melting point of 1455°C. The density of nickel is about 8900 kg/m³. The crystal structure of nickel is FCC (Face Centered Cubic), which can be plastically deformed at severe rates. Therefore, it is one of the most versatile and prominent metals with high strength at elevated temperatures, ductility, and excellent heat resistance.

Nickel-based superalloys (NBSAs) have high mechanical strength and surface structure variations at high temperatures. Amongst Ni superalloys, the Inconel 718 is generally known as one of the most difficult-to-cut materials due to its high hardness and high strength at elevated temperatures [10]. Therefore, superalloys usually are used at 700°C or higher temperatures at which high stresses occur. They play a vital role in developing and manufacturing aero jet engines. Table 2.1 presents the total amount of Ni contents in different alloys. The chemical composition of Inconel 718 is shown in Table 2.2.

Table 2.1 Total amount of Ni contents in different alloys

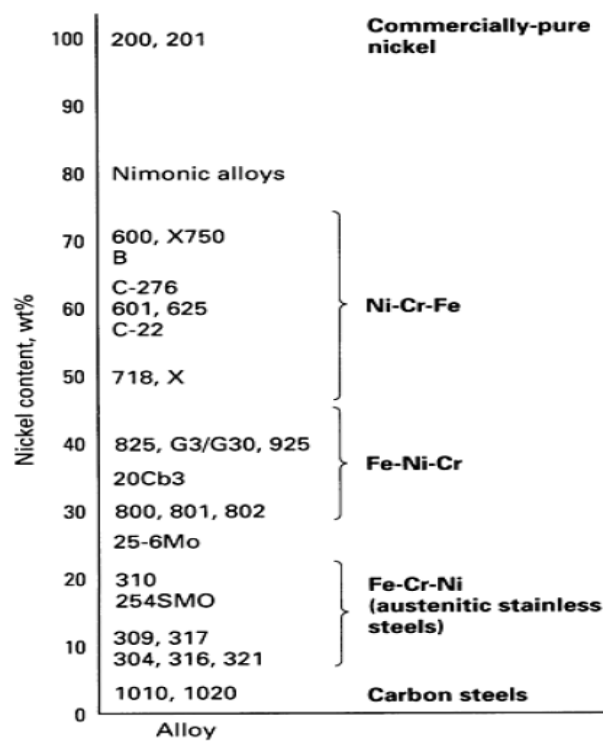


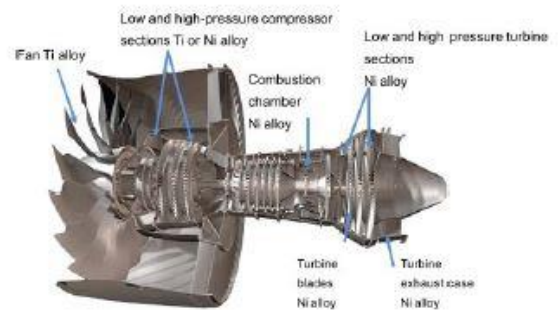
Table 2.2 Chemical composition of Inconel 718 alloy (wt%) [7]

Element	(%wt)	Element	(%wt)
Ni	53.0	Si	0.30
Cr	18.6	Mn	0.20
Cb	5.00	Ti	0.9
Mo	3.1	C	0.04
Al	0.40	Fe	18.5

The main applications of these alloys are within but not limited to (1) aircraft gas turbines (disks, combustion chambers, casings, shafts, exhaust systems, blades, vanes, burner cans, afterburners, thrust reversers), (2) biomedical applications, (3) reciprocating engines (turbochargers, exhaust valves, hot plugs, valve seat inserts), (4) steam turbine power plants (bolts, blades, stack gas re-heaters), (5) space vehicles (aerodynamically heated skins, rocket engine parts), (6) gas turbines and other structural elements that experience high temperature [2, 11] (Figure 2.1 and Table 2.3).



(a)



(b)

Figure 2.1 (a) Aircraft gas turbines, (b) jet engine [12]

Table 2.3 A brief overview of the application of superalloys in various industries [12]

Application Sector	Application Examples
Airplane Engines	Compressor Discs, Casings, Turbine Discs, Shafts, Rotors, Kings, Blades, Exhaust systems, Bearing housings, Fan discs
Biomedical Applications	Dentistry and Orthodonty devices, Prosthetic Cardiovascular devices
Reciprocating Engines	Turbochargers, Exhaust valves, Hot plugs
Metal Processing	Hot work tools and dies, Casting dies, Extrusion dies, Rails for walking beam furnaces, Heat treating trays, Transfer rolls
Turbine Power Plants	Bolts, Blades, Stack gas reheaters, Buckets, Boilers, Transition pieces
Chemical and Petrochemical Industries	Nuts and bolts, Cryogenic tankage, Pressure vessels
Aerospace Industry	Structural components, combustion chambers, nickel-hydrogen batteries, Hydraulic tubing, High-pressure fuel turbo-pump, Airfoils, Landing gears
Gas Turbines	Vanes, Blades, Coatings, Transition ducts, Heatshield, Nozzles, Thermal barrier coatings

2.2 Microstructure of Inconel 718

Adequate knowledge of the microstructure of the workpiece plays a vital role in machinability evaluation. The microstructure of Inconel 718 consists of gamma and gamma prime phases in the presence of carbides and metal precipitates. Figure 2.2 shows a sample microstructure of the nickel alloy with these phases. The gamma phase is the continuous matrix in the FCC structure. It consists of a high percentage of disordered solid-solution elements like Co, Cr, Mo, and W. This phase is soft and ductile at all temperatures and has a moderate strength decrease with an increase in temperature. Gamma prime is the main strengthening phase in superalloys like $\text{Ni}_3(\text{Al}, \text{Ti})$. It is a coherently precipitating phase with a stable crystal structure and long-time stability. It is brittle except at a very high temperature. It has an excellent strength, which increases with temperature up to 827°C.

Along with these phases, there are various inter-metallic phases of metals like iron, cobalt, molybdenum, chromium, and carbides. The microstructure of the nickel alloy is strengthened by these phases [13]. During machining, plastic deformation, and material volume changes occur with the temperature rise [14].

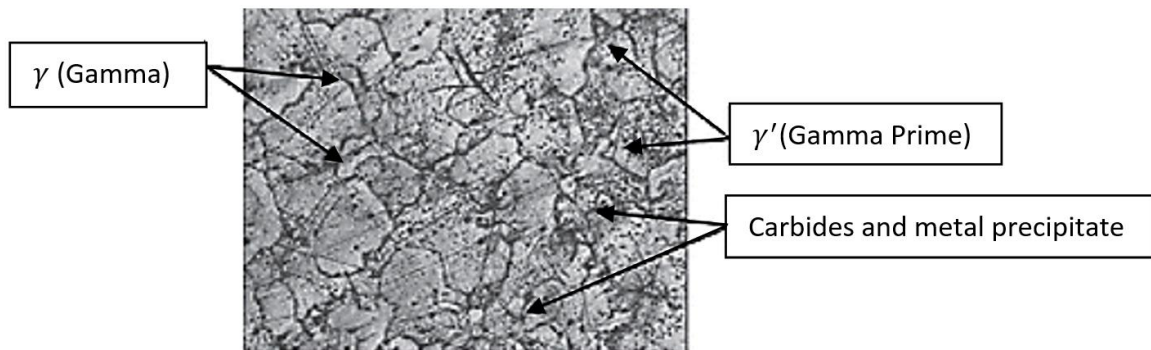


Figure 2.2 Microstructure of the nickel alloy [15]

2.3 Tool wear

The severity of tool wear depends on parameters such as the tool material and geometry, workpiece material, cutting parameters, cutting fluids, and machine-tool characteristics. Those zones near the cutting edge where wear typically appears are called the wear land (Figure 2.3) [16]. According to ISO 3685:1993, tool life is often quantified according to the crater or flank wear. Tool wear characteristics are usually represented as a plot of material wear versus sliding distance or time of cut for a particular combination of tool-work parts. Many factors, such as cutting conditions, cutting tool, workpiece material, machine tool, and coolants, play their roles in the variation of tool wear. Different locations of tool wear are shown in Figure 2.3.

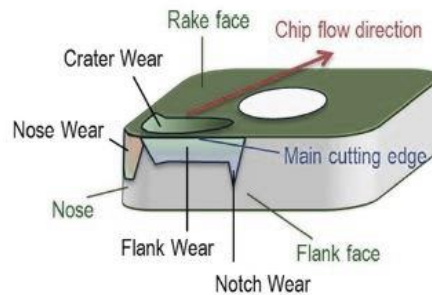


Figure 2.3 Location of tool wear [17]

Tool wear may lead to catastrophic negative impacts such as increased cutting forces and temperature and poor surface finish and tolerance. Consequently, tool breakage is expected. Lubricants and coolants reduce friction and temperature, resulting in lower tool wear. Some of the most frequent wear occurring during machining superalloys are notch and flank wear.

Notch wear

Notch wear (Figure 2.4) occurs at the tool nose and depth of cutting regions, especially during the turning and ramping of nickel-based alloys. Notch wear caused by high temperature, high workpiece strength, work hardening, and abrasive chips increases with speed and is related to hardness.



Figure 2.4 Notch wear

Flank Wear

The wear formed on the cutting tool relief surface is known as flank wear (Figure 2.5), similar to a flat-worn surface. Three stages of flank wear (Figure 2.6) are [18]: (1) break-in period (rapid initial wear), (2) steady-state region (temperature-insensitive region), (3) failure region (temperature-sensitive region).

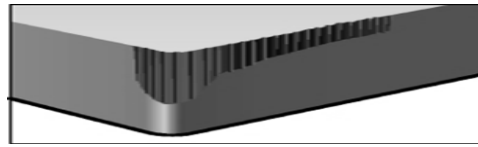


Figure 2.5 Flank wear

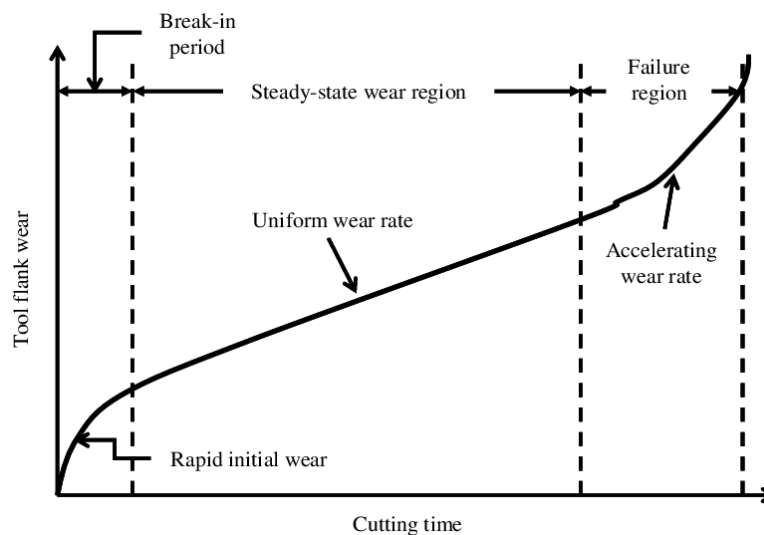


Figure 2.6 Three-stage flank wear curve [19]

The generation of high cutting temperature at the workpiece and tool interface is considered one of the main problems in machining Inconel 718. When cutting speed (V_c) exceeds 100 m/min, high cutting forces and temperature at the machining zone may appear, resulting in the rapid growth of tool wear due to thermal softening or thermal cracking behavior [20]. The leading causes of tool wear are coating delamination (coated tool), adhesion, attrition, diffusion, and plastic deformation [18, 21]. Hence, the phenomenon affects productivity, tool life, and surface integrity.

2.4 Machining and machinability of nickel-based alloys

When heat treatment is applied to Ni-based superalloys, their hardness increases. Second-phase particles make both the alloys stronger and abrasive, hence challenging machining. It can be stated

that machining a softer material is less complicated when using typical heat treatment methods. One solution to improve the machinability of superalloys is to use high-pressure coolant supply techniques, including cryogenic and Minimum Quantity Cooling Lubrication (MQCL) machining. Various factors, such as machining costs, operator safety and health, environmental impact, waste management, and energy consumption, can all be considered when determining the sustainability of a machining process. Many studies used the life cycle assessments (LCA) of Inconel 718 for various machining techniques to better understand the material long-term sustainability in terms of environmental and cost-related factors [22]. Cutting fluids are critical in machining difficult-to-cut materials such as Inconel 718. Industrialists have turned to alternative lubrication techniques in response to the negative environmental impact and high production costs of cutting fluids. Table 2.4 summarises the machinability, costs, and ecological impacts of various lubricating technologies for different machining operations and their machinability, costs, and environmental concerns [23].

Table 2.4 Summary of machining Inconel 718 with different lubrication-cooling technologies [23]

Lubrication-cooling technologies	Machinability performance	Environmental impact	Cost analysis
Flood cooling/wet machining	Good lubrication and cooling, low contact friction, poor machinability at hi-speed conditions	Hazardous to the Environment and biological problems to the operator	High coolant, acquisition, handling, and disposal costs
Dry machining	High temperatures, more friction and adhesion between the cutting tool and work material	No pollution and eco-friendly technique	Reduced disposal and cleaning costs
Machining with coated tools	Self-lubrication, low contact friction, high wear, and resistance in low and medium speed conditions	Sustainable machining, eco-friendly	High machining costs
Cryogenic cooling	High cooling, high productivity, good tool life, better wear resistance, good surface quality	Eco-friendly, inert nature, non-toxic	High tooling and handling costs (uneconomical)
Solid lubricant-assisted machining	Self-lubrication, low contact friction, improved surface finish, low cutting forces & tool wear	Operator-friendly, no hazardous fumes	Low equipment costs
High-pressure cooling	Improved chip control, low energy, reduced cutting forces, good surface finish, high productivity, low temperatures	Eco-friendly, low energy consumption	High initial costs
Hybrid machining	Good surface finish and low-cutting forces	Environmentally benign process	High processing costs
MQL machining	Thermal stability, low flank wear in turning, good hole quality in drilling, and better surface finish in grinding	Ecofriendly technique, lower power consumption	Economical solution, low cooling costs, minimal machining costs

The tribological mechanisms of the Inconel 718 alloy were investigated under various cooling and lubrication conditions. The research outputs explored how cooling and lubrication affect tool wear, surface roughness, and cutting forces when machining Inconel 718. It was observed that flood

cooling significantly reduced cutting forces and tool wear in the machining Inconel 718. Flood cooling raises surface roughness due to built-up cutting tool edges. MQL, on the other hand, reduces cutting forces and tool wear [24].

Graphing multivariate data in the form of a two-dimensional chart of three or more quantitative variables represented on axes that all begin at the same point is represented by a radar chart, $(K\rho C)^{1/2}$ is the factor of thermal inertia, K is the heat conductivity, C is the heat capacity, and ρ is the density of the material (Figure 2.7). The relative position and angle of the axes are typically uninformative in this context. Although many parameters can be used in the analysis, radar charts are most effective when only a few parameters are used (no more than 8) [25]. Figure 2.8 shows the section area representing difficulty in machining; the more significant the section area, the more complex the machining.

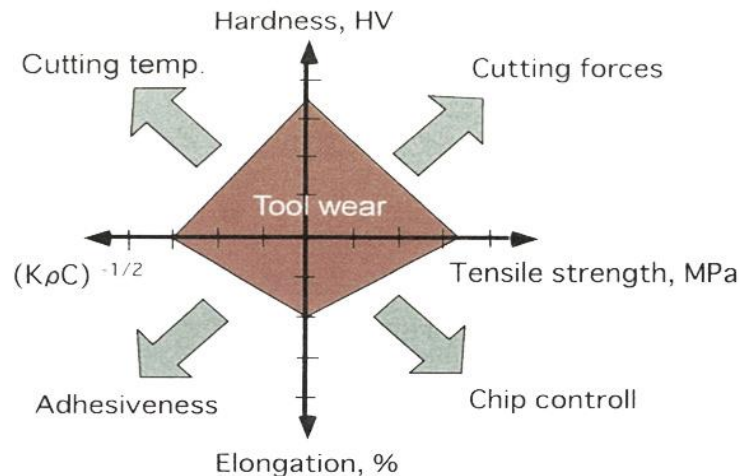


Figure 2.5 Schematic illustration of the radar chart [26]

Nickel-based superalloys are unique alloys with high-temperature strength, toughness, and resistance to degradation in aggressive corrosive or oxidizing environments. In addition, they have twice the tensile strength, hardness, and inverse thermal diffusivity of AISI 1045 (Figure 2.8). Consequently, it is anticipated that high cutting forces, high cutting temperatures, abrasive wear,

and adhesive may occur. As noted in the reported studies, [26, 27] adhesion and abrasion are the most critical wear mechanisms when machining Inconel 718.

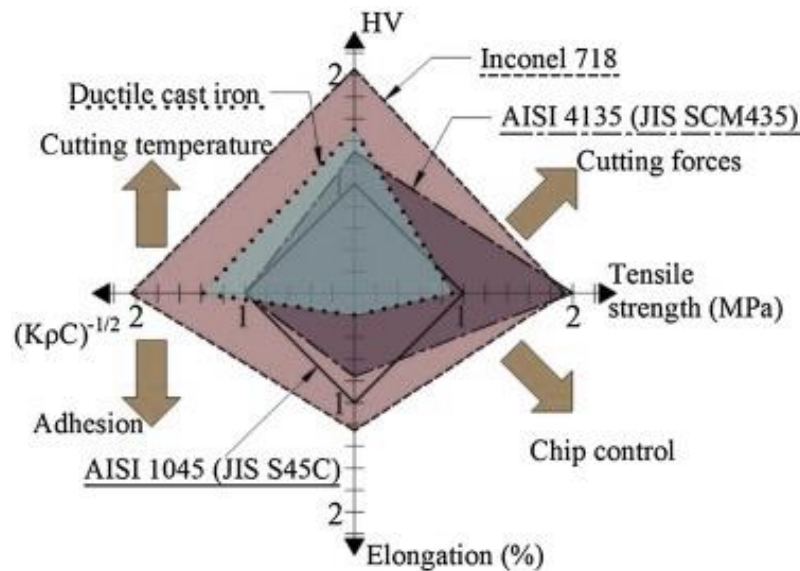


Figure 2.6 Comparison of machinability of different alloys [26]

However, while the tool life-based method is relatively simple, it has several limitations, particularly when assessing difficult-to-cut materials. A single machinability index does not provide enough information before, during, and after machining (Figure 2.9). In addition, it is unreasonable to cut all materials with the same tool, particularly different materials. Therefore, various operations such as turning, milling, and drilling have evolved [28].

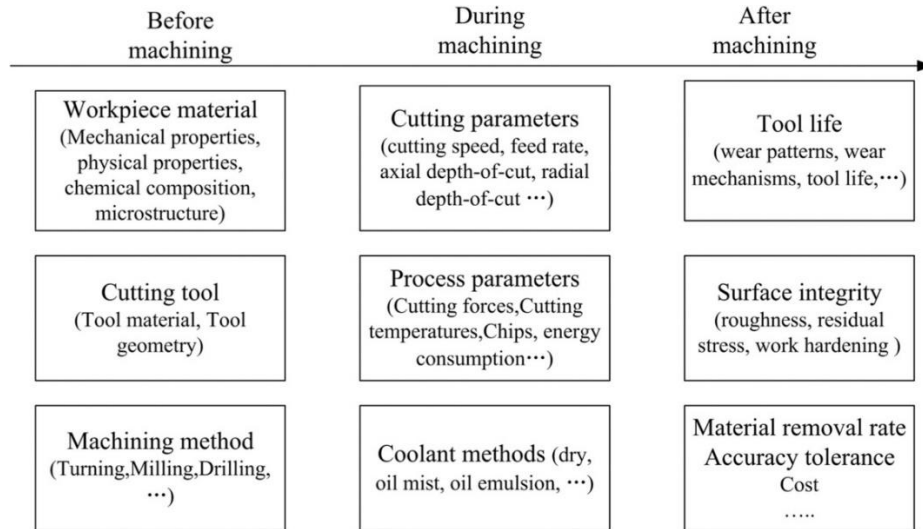


Figure 2.7 Factor in machinability assessment [28]

Due to the extremely high toughness of Inconel 718, its poor machinability resolves itself into two fundamental problems:

- The inability of the tool material to provide extended tool life due to the work hardening and attrition properties of the alloy, as well as the metallurgical damages to the workpiece due to very high cutting forces, may also increase the work hardening, surface tearing, and distortion of the machined components due to induced stresses [29].
- During the machining of these alloys, temperature and stresses close to the tool cutting edge are considerably high, leading to severe tool damages such as flank wear, notching wear, and edge chipping, resulting in short tool life and degradation of the integrity of the finished surface [30]. In addition, welding and adhesion of worked material on the cutting tool frequently happen during machining, causing severe notching and alteration of the tool rake face due to the consequent pull-out of coating and tool substrate [31].

2.5 Machining and machinability of Inconel 718

The machining of nickel-based alloys is expensive because of their desirable high-temperature properties, high creep and corrosion resistance, and the ability to retain a high strength-to-weight ratio [32]. Several studies reported using ceramic tools to manufacture nickel-based alloys [33]. When turning Inconel 718, crater and micro-edge chippings were observed in the whisker-reinforced ceramic tools. Adhesion, abrasion, and diffusion were observed when cutting Inconel 718 with whisker-reinforced ceramic tools under various lubrication conditions. Cutting-edge chipping was also noted [34]. However, carbide tools are still the prime choice when machining superalloys at low cutting speed. Amongst the superalloys, specific attention has been paid to machining Inconel 718 using carbide tools. Liao and Shiue [35] studied the wear mechanism of cemented carbide tools in turning Inconel 718 and analyzed the worn surfaces of the cutting tools. SEM and EPMA examinations indicated that diffusion of the components Ni or Fe of the workpiece into the tool matrix (Co) by a grain boundary diffusion mechanism is considered the primary tool wear mechanism during high-speed turning conditions (35 m/min). Kamata and Obikawa [36] determined the finish-turning of Inconel 718 by applying the quantity of lubrication (MQL) with three different types of coated carbide tools. Three selected coatings were TiCN/Al₂O₃/TiN (CVD), TiN/AlN superlattice (PVD), and TiAlN (PVD). Cutting speeds were set at relatively higher values: 1 and 1.5 m/s. At a cutting speed of 1 m/s, TiCN/Al₂O₃/TiN coating in MQL cutting exhibited the best performance, while TiN/AlN superlattice coating in MQL cutting exhibited the second-best performance. TiCN/Al₂O₃/TiN coating attained the longest tool life in wet cutting, but the surface finish was not good. The tool lives were drastically shortened. In addition, the surface finish in MQL cutting increased because the worn tool flank surface became rough [37].

Abhay Bhatt et al. [21] investigated the wear mechanisms of uncoated tungsten carbide (WC) and coated tools (single-layer (TiAlN) PVD and triple-layer (TiCN/Al₂O₃/TiN) CVD) in oblique finish turning of Inconel 718. Tool wear rate and wear mechanisms were evaluated for cutting speeds $50 < V < 100$ m/min, and feed rates of $0.075 < f < 0.125$ mm/rev, at a constant depth of cut of 0.25 mm. It was concluded that abrasive and adhesive wear were the most dominant wear mechanisms, controlling the deterioration and final failure of the WC tools. Li et al. [38] examined

the machinability of several inserts, including PVD- and CVD-coated carbide grades and Sialon ceramics of various geometrical shapes in high-speed machining of Inconel 718. Taylor's model was used within certain cutting speeds. The tool life examination was conducted to establish tool life models through a rapid face-turning test. The major wear mechanisms of nickel-based alloys are abrasive wear, adhesion wear, micro-breakout, and chipping.

According to Zhou et al. [16, 33, 39], surface damage is produced by whisker-reinforced ceramic cutting tools in the finish turning of Inconel 718. The effects of the cutting parameters and coolant conditions on the tool wear and machined surface were investigated. The types of damage, breakage, plastic flow, cavities, side flow, and built-up edges were observed and discussed. Coated tools were evaluated in turning Inconel 718, medium carbon SAE 1045 steel, and ductile iron at low and high cutting speeds. TiAlN-coated tools showed the best metal cutting performance, followed by the TiCN and TiN-coated tools. The superior performance of the TiAlN-coated tools, which was even more significant at higher speeds, is related to the higher resistance of the coating to abrasive and crater wear. These characteristics can be attributed to higher hot hardness and oxidation resistance of TiAlN at the temperatures usually encountered at the tooltip during machining operations [40, 41].

Focke et al. [40] concluded that abrasion wear plays the most crucial role in the wear of the cutting tools when turning Inconel 718. Zhou. et al. [42] revealed that the new coated carbide tools could be used at the cutting speed of up to 100 m/min; nevertheless, the time required to machine this alloy is still considerably high. High-speed machining using advanced tool material, such as CBN, is considered an alternative for improving the productivity of this material due to its higher hot hardness compared to the carbide tool. Special attention was paid to studying the surface roughness, metallographic analysis of the surface layer, and surface damages in turning age-hardened Inconel 718 [31, 43-45]. Considering the chip flow pattern, Wright and Chow [43] resolved that the failure of the cutting edge in the machining of nickel-based alloys is mainly due to the increased normal stress acting on the cutting edge. All the studies above certainly contributed to understanding the failure of carbide tools in machining nickel-based alloys. However, the investigations have not yet been completed. The groove wear on the minor flank of the cemented carbide tool in the turning of

pure nickel had been studied by Tan [41]. He found that temperature is the main driving element of tool wear. His proposal for the tool wear mechanism is not different from carbide tool wear in the machining of mild steel. Kramer and Suh [46] proposed the solution wear theory, which attributed the wear of the carbide tool to the solubility of tool particles in the material [41]. A triple PVD coated ($\text{TiCN}/\text{Al}_2\text{O}_3/\text{TiN}$) carbide tool was used in machining Inconel 718 at speeds up to 50 m/min using conventional and various high coolant pressures, up to 203 bar [37].

Recent research studies exhibited that using textures on the tool surface may increase wear resistance. Thomas and Kalaichelvan [47] developed single-design surface texture tools and studied the machinability of mild steel (EN3B) and aluminum (AA 6351) during dry turning with texture tools and untextured tools. Arslan et al. [48] concluded that textured surface tools could improve material removal rate and process. The lubrication strategy and texture geometry significantly affect machinability, mainly tool life and surface quality. Metal-cutting industries could use this technology to manufacture cutting tools for hard-to-cut materials [49]. According to [52-54], it can be inferred that no similar work was conducted using surface textured tools when machining IN 718. According to the literature review, the carbide tool is generally used at low-speed machining of Inconel 718. Especially the uncoated carbide tools. Furthermore, a lack of knowledge was observed on carbide tools in high-speed machining, and carbide tool's initial wear mechanism is yet to be investigated. The lack of knowledge and expertise is intended to be remedied in this work. Various dominant process parameters on tool wear modes and machinability attributes must be recognized for a more accurate tool life improvement. This can be done by numerical and experimental studies, followed by statistical verifications.

The essential information establishes that the modeling and optimization strategy might include cutting force attributes and initial tool wear results, which have received less attention in the open literature. It is believed that initial tool wear may provide good information on cutting physics, enabling us to monitor and predict the ultimate tool life. However, no studies were found on the initial tool wear when machining superalloys. Furthermore, the factors governing initial tool wear must be mainly understood. In addition, there is still a low volume of studies on the effects of various lubrication modes on the machinability of nickel-based superalloys, particularly the tool

life. Knowing that the machining superalloys are accompanied by high levels of cutting temperature in the cutting zone, optimizing the lubrication performance by improving the lubrication of the tool is of prime importance. It was mentioned that one of the current industrial considerations is to avoid lubrication usage during machining processes. Nonconventional cooling methods with improved-based lubricants are proposed regardless of significant environmental, occupational health, and safety effects.

It was also reported that choosing appropriate machining parameters is critical in achieving the desired surface finish and dimensional accuracy while minimizing tool wear during Inconel 718 machining. As noted in [50, 51], the use of advanced cutting tools and coatings, optimizing cutting parameters with advanced modeling and simulation techniques, besides adequate knowledge of the effects of different cooling and lubrication strategies on Inconel 718 machinability are needed.

Nickel-based superalloys with high strength, hardness, high-temperature resistance, and chemical reactivity require non-conventional machining methods when conventional methods fail. Non-conventional machining techniques such as EDM (Electrical Discharge Machining), ECM (Electrochemical Machining), LBM (Laser Beam Machining), and PAM (Plasma Arc Machining) and their application for nickel-based superalloys [52]. Finally, it can be concluded that in the area of machinability improvement in nickel-based superalloys, in particular, tool life improvement when machining Inconel 718 has now created a solid base for many industrial applications. There are, however, several directions for research that are promising to follow in the future.

The effects of machining parameters on the steady-state wear period have been thoroughly investigated in all three wear periods mentioned previously. However, according to the literature, adequate knowledge of wear modes and morphology and factors governing elevated initial tool wear morphology and size in the machining of Inconel 718 is still required in wider scopes. An understanding of the initial tool wear mechanism is needed when turning Inconel 718 at relatively high cutting speeds, feed rate. In addition, the interaction effects between the initial cutting condition and transition period and their direct effects on the initial cutting condition and transition period are subject to additional studies during this project.

Machining parameters such as depth of cut, cutting speed, and feed rate play a vital role in the machining performance of the workpiece and cutting tool material [53]. Although small, the cutting tool is one of the most critical parameters affecting machining operation. Those cutting tool materials used in machining nickel-based alloys need to have: (i) good wear resistance, (ii) high strength and toughness, (iii) high hot hardness, (iv) good thermal shock properties and (v) adequate chemical stability at elevated temperatures [54]. Improving efficiency means improving cutting conditions (cutting speed, feed) without losing machined surface quality. Figure 2.10 shows three groups of tool materials that are commonly used to process Ni-based alloys.

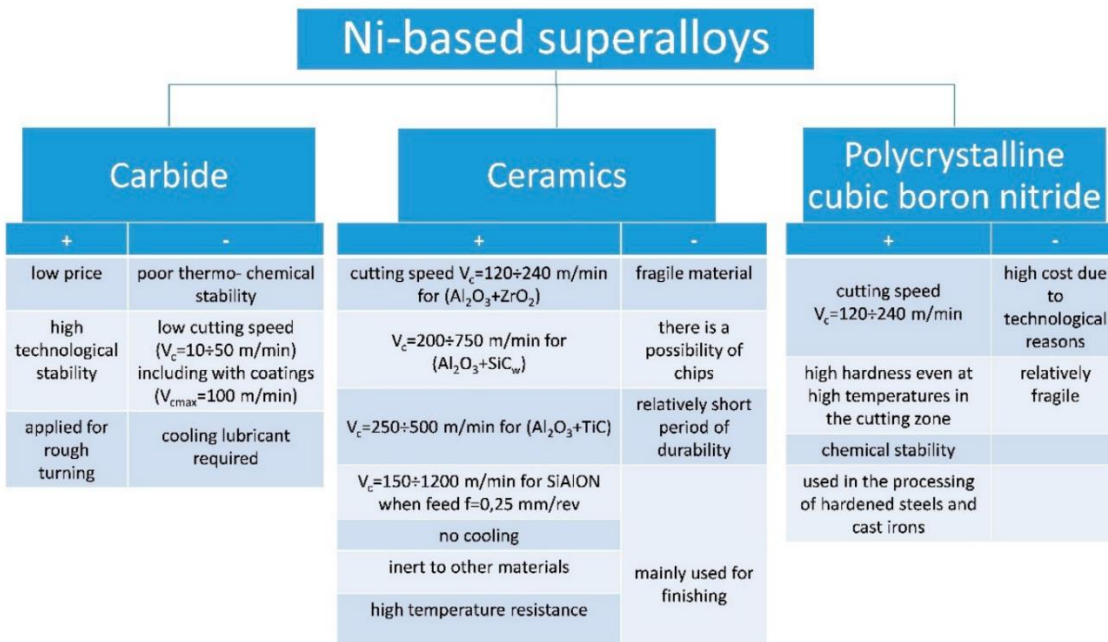


Figure 2.8 Material categories in the machining of Ni-based superalloys. [55]

In the industry, various types of cutting tools with varying characteristics are now used for hard machining. Due to their excellent cost-performance ratio, carbides are currently the most commonly used tool for machining Ni-based superalloys. However, when machining nickel-based alloys with these tools, the recommended cutting speeds range from 10 to 30 m/min [10]. Higher speeds are not recommended due to the loss of cutting tool characteristics, mainly related to the

ultra-high local temperature in the tool–part contact zone, resulting in reduced tool life. When machining nickel-based alloys, cubic boron nitride cutting tools outperform cemented carbides. Polycrystalline diamond tools have nearly 500 times the wear resistance of tungsten carbide tools and are extremely hard. PCD tools, on the other hand, are incredibly fragile and have a low toughness. Ceramic tools are used for various operations and materials, including the high-speed finishing of high-temperature alloys [55, 56].

These materials have been considered the prime choice in past decades for machining superalloys. High-speed steels are usually employed in intermittent cutting operations (milling, drilling, tapping, and broaching), while cemented carbides are mainly used in continuous cutting operations (turning, boring, and facing). Currently, several new ceramic tool materials (Al_2O_3 –TiC mixed ceramics, Si_3N_4 ceramics/Sialon, and the latest SiC whisker-reinforced Al_2O_3 ceramics containing ~25% SiC whiskers) have been used increasingly for machining nickel-based alloys [57].

Most cutting tool materials lose their hardness at elevated temperatures, increasing tool wear and failure. Ceramics, coated carbide tools, cubic boron nitride (CBN)/polycrystalline cubic boron nitride (PCBN), and polycrystalline diamond (PCD) are used for high-speed machining of Ni and Ti-based alloys. Ceramics and CBN/PCBN have not been preferred for machining Ti alloys due to their excessive wear and the high reactivity of Ti alloy with ceramics [58, 59]. However, the progress and advancement in cutting tool materials and machining techniques led to remarkable removal rates when machining difficult-to-cut superalloys [60]. Also, the triple-layer (TiCN/ Al_2O_3 /TiN) CVD coating exhibits the highest wear resistance at 100 m/min speeds and low feeds. In contrast, the uncoated WC tool performed best in the low range of cutting speeds (50 m/min) and intermediate feeds. The tool with single-layer (TiAlN) PVD coating outperformed the other tools at 75 m/min [61].

High-speed machining of Inconel 718 with CBN inserts led to the following observations: 1) At cutting speed over 100 m/min, diffusion due to the high cutting temperature is the dominant factor in promoting crater wear. As a result, the crater wear progressed proportionally to the cutting length. 2) In the high-speed machining of Inconel 718, the micro-surface topography of the CBN tool has a strong correlation with the crater wear resistance [62].

2.6 Conclusion of literature review and refining of problematic

It is essential to note that machining technology advancements are not limited to using carbide tools and optimizing process parameters. The emergence of new tool materials, such as ceramic and diamond coatings, and advanced manufacturing techniques, like additive manufacturing, provide potential avenues for further enhancing the machinability of Inconel 718 and other superalloys.

In conclusion, the literature review reveals that carbide tools, particularly uncoated ones, are commonly used in low-speed machining of Inconel 718. However, there is a lack of knowledge regarding their applications in high-speed machining and the mechanism of initial tool wear. Therefore, dominant process parameters affecting tool wear modes and machinability attributes must be addressed. Numerical and experimental studies, followed by statistical verification, are the proposed approaches for this concept. Surprisingly, limited research studies are available on factors governing initial tool wear and ultimate tool life. Exploring initial tool wear is believed to provide valuable insights into cutting physics and enable the monitoring and prediction of tool life. However, in this context, no studies were found on machining superalloys.

In terms of machinability improvement in NBSA, mainly tool life improvement when machining Inconel 718, a solid foundation has been established for many industrial applications. However, there are several promising research directions to pursue. Firstly, the existing knowledge has not been widely applied across various industries and workpiece classes, offering potential fields for applied research with immediate industry impact. Secondly, there is a growing focus on the broader issue of edge and part conditions and cleanliness. Mechatronics products, micro-products, and high-performance demands require technical cleanliness and the elimination of edge disturbances. The development and application of technologies for clean mechanical machining are still in their early stages.

Future industrial research should monitor and optimize various machining processes, utilizing numerical and statistical control theories and intelligent systems incorporating networked control systems, wavelets, artificial intelligence, expert systems, fuzzy control, neural networks, and other advanced approaches.

Overall, machining Inconel 718 presents challenges, but successful machining can be achieved with the appropriate tools, techniques, high-quality cutting tools, suitable cutting speeds and feeds, and using coolant to manage heat and reduce tool wear. In this regard, adequate knowledge of the effects of cutting parameters on the main machinability attributes, such as tool life, is essential, but it requires additional investigations.

CHAPTER 3 RESEARCH OBJECTIVES

A lack of information is still observed in the machinability evaluation of superalloys, particularly when longer tool life is demanded. Therefore, the primary goal of this work is to propose innovative strategies for increasing tool life when machining NBSAs. Accordingly, the following hypothesis is presented.

3.1 Hypothesis statement

The following hypothesis was considered to discover the effects of cutting parameters on machinability attributes when machining NBSA. A particular interest will be paid to surface integrity attributes, tool wear morphologies, and tool life.

- Tool life and tool wear are affected by the cutting conditions.
- Lubricated machining may affect the tool life while increasing contamination.
- All the inserts/cutting tools should be used from the same production batch with similar geometry and microstructure to respect repeatability.
- Average flank wear length (V_{BB}) is an accepted criterion to quantify tool wear (ISO 3685, 1993).
- The optimum tool life can be reached when V_{BB} is smaller than 0.3 mm.
- The tool rejection criteria for rough machining are used, and the tool life testing results are assessed according to ISO Standard 3685. In addition, maximum flank wear > 0.7 mm, maximum crater wear > 0.14 mm, and notch wear > 1.0 mm were quantified from [63].
- When the surface quality of the work material exceeds $6\text{ }\mu\text{m}$ on the centerline average, machining conditions are not acceptable, and inspections and reconsiderations of machining parameters are demanded.
- When flaking or fracture occurs in the cutting tool, the cutting tests must abound; otherwise, the machine tools, spindle, and work parts are affected.

3.2 Specific objectives

Although machining nickel-based superalloys has been studied broadly, the literature review denotes a lack of knowledge about tool life improvement when machining superalloys, particularly NBSA. Therefore, the following specific objectives are drawn to reach the main aim of this work.

O1. Study the initial tool wear when machining nickel-based superalloys

It is believed that the duration of initial tool wear and various wear morphologies in the initial moments when machining nickel-based superalloys have intense effects on the ultimate tool life. Therefore, those factors governing initial tool wear must be analyzed, followed by determining the transient time where the initial tool wear ends and the steady-state wear region starts. Next, the transition time needs to be evaluated, followed by microstructural evaluations of the cutting tools and the chips, which help better understand the tool wear modes at each time interval. Finally, the effects of cutting speed on the tool wear mode under a similar feed rate and cutting time must be discussed.

O2. Determine the effects of the initial cutting conditions on ultimate tool life

As noted earlier, it is expected that a good selection of the cutting parameters to improve the initial tool wear may tend to optimize the useful tool life. Therefore, theories and algorithms are needed to correlate the initial tool wear and the cutting forces to the ultimate tool life. However, according to the literature review, no work was found on predicting the ultimate tool life based on initial tool wear recorded within the primary moments of the cuts.

CHAPTER 4 RESEARCH METHODOLOGY

4.1 Methodology

Referring to the conclusion of the literature review and problematics, two main research objectives were defined in this project. The main scope of these objectives (Figure 4.1) is beyond the following domains: tool wear characterization and tool life optimization when machining NBSA.

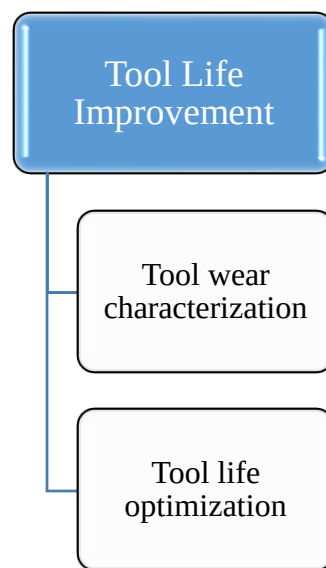


Figure 4.1 The main scope of research objectives

Machinability analysis and material improvement are complicated and linked with various material characteristics (chemical, mechanical) and experimental conditions (e.g., machine tool, cutting tool, etc.). These parameters can be classified into two different categories: mechanical parameters and material parameters [64]. The following assumptions were made to develop the experimental setup. Machining operations were assumed chatter-free. Vibrations, machine, and dynamic tool behavior were studied in preliminary tests, and the chatter-free condition was confirmed. The deflection of the tool and workpiece was assumed to be negligible; this condition was fulfilled using a rigid tool and workpiece. The experimental results were used as the basis of analysis. The goal is to improve the tool life through input optimization or adequate selection of cutting

parameters. To that end, the experimental characterization must be followed. They are related but limited to the following working projects.

Mechanical parameters are related to specific parameters such as tool geometry, different types of cutting tools and cutting conditions, including cutting speed, feed rate, and depth of cut.

Material parameters are classified according to the type of reinforcement, particle size, etc. These parameters mostly affect the hardness and deformation behavior of the material. The particle volume percentage affects machinability, machining forces, and surface integrity.

4.2 Experimental plan

The workpiece was a cylindrical Inconel 718 with the chemical compositions in Table 2.2. The cutting tools used in all experiments were SECO carbide/cermet inserts CNMG 432-MR4 TS2500 coated with $\text{TiCN}/\text{Al}_2\text{O}_3$ (CVD) (Figure 4.2 a). In addition, the CNC-MAZAK Nexus 200 was used in the turning tests (Figure 4.2 b). The experimental works were repeated twice, and the average readings of V_{Bmax} were used in subsequent studies. A new and sharp insert edge was used in each machining test. The following cutting angles were used in the experimental tests: rake angle $\gamma_0 = -6^\circ$, back rake angle $\gamma_p = -6^\circ$, nose radius $R_n = 0.031$ in, tool cutting angle $\kappa_r = 95^\circ$, and insert thickness $s = 0.187$ in. (Figure 4.3).

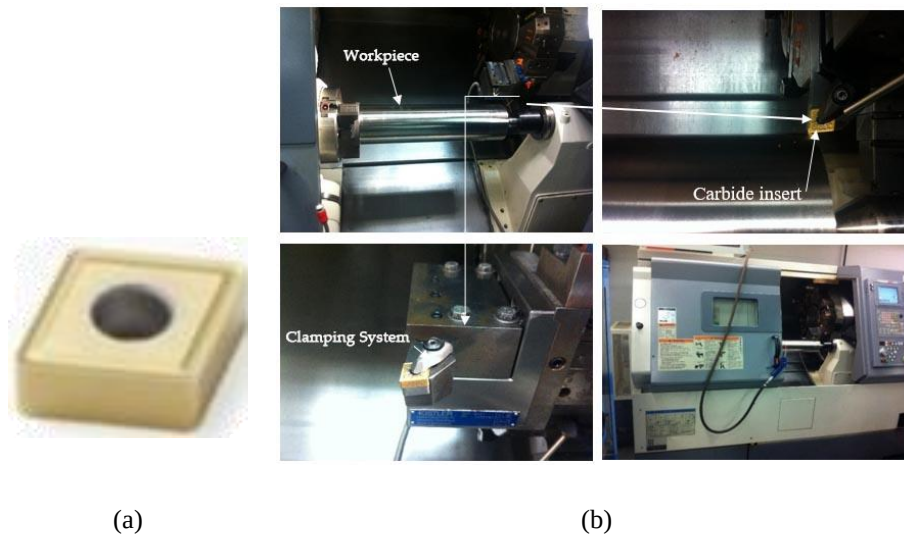
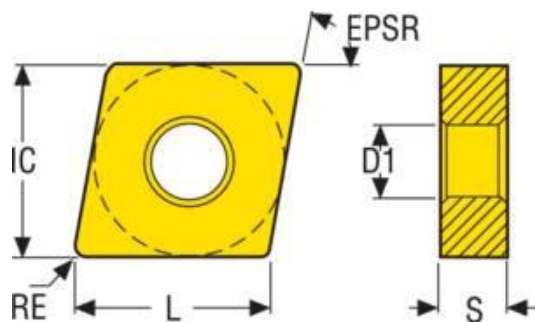


Figure 4.2 (a) The insert that was used; (b) Set-up machining



IC	Inscribed circle diameter	0.500 in
RE	Corner Radius	0.031 in
L	Theoretical cutting-edge length	0.508 in
EPSR	Insert included angle	80.000 deg
D1	Fixing hole diameter	0.203 in
S	Insert thickness	0.187 in

Figure 4.3 The tool specification

- **Cutting force acquisition and analysis**

The Kistler's dynamometer was used to monitor and record the cutting force signals in three directions related to the thrust force (F_R), feed force (F_F), and cutting force (F_C), as depicted in Figure 4.4. The sampling frequency of 1000 Hz was used to analyze the cutting force signals. The cutting forces were analyzed in both time and frequency domains to evaluate the machining tests vibrational modes (chatter and forced).

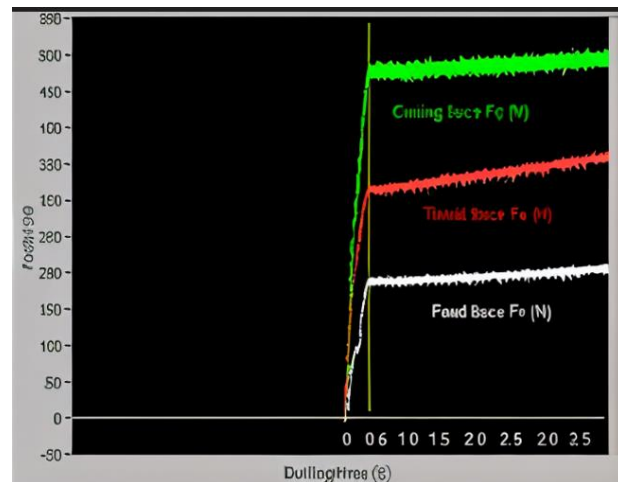
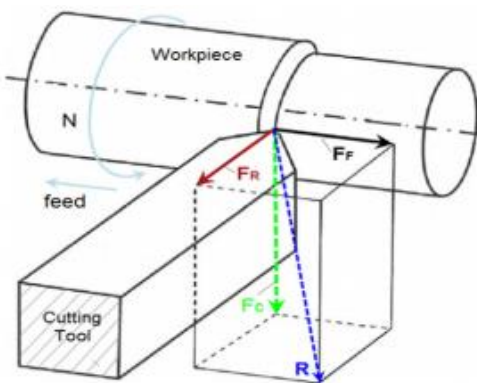
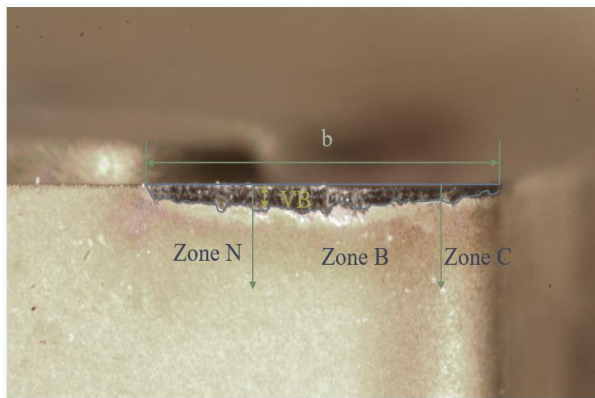


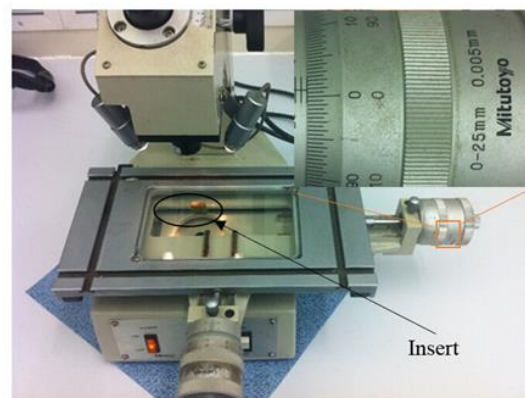
Figure 4.4 Schematic view of cutting forces in turning operation [65]

- **Tool wear measurement**

The flank wear V_{Bmax} and the notch wear were measured using a Mitutoyo optical microscope and by counting the pixels in the photos captured with the Canon EOS 300D digital camera. V_{Bmax} can also be measured using an optical microscope (Figure 4.5). However, it is impossible to adjust the focus by changing the distance between the lens and the insert. Otherwise, a ruler may be required to acquire a new conversion factor. Therefore, adding a ruler to the photo is the best solution to avoid mistakes.



(a) Typical flank tool wear with three zones



(b) Optical microscope

Figure 4.5 (a) Typical flank tool wear with three zones, (b) optical microscope [65]

- **Microstructural analysis and characterization**

Two SEM (Jeol, JSM 840A, and Jeol JSM 7800F FEG-SEM) equipped with an Oxford X-ray detection system (AZtec EDS) for elemental analysis and quantitative mapping were used to study insert wear mechanisms. Moreover, Joel JSM is equipped with field emission guns (FEG), which provides the extreme resolution of 0.8 nm at 15 kV and 1.2 nm at 1 kV. The micrographs of the microstructures were captured at low and high magnification. It is to be noted that all turning tests were repeated twice, and the average values of responses were considered in the result analysis.

To model (predict) the tool life, followed by optimization, specific stages were presented in Figure 4.6. Machining goals are to minimize machining costs while increasing quality and

productivity. This is achievable if the machining is done at maximum cutting conditions while also improving the tool life. After verification tests, the machining results can be used as input for modeling and optimization tools.

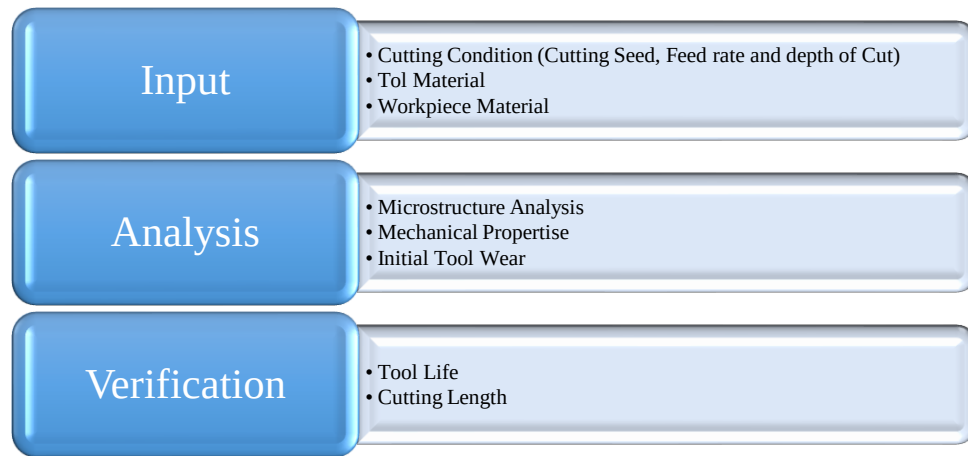


Figure 4.6 The main steps required for statistical modeling of the tool life.

CHAPTER 5 ARTICLE 1: Initial tool wear behavior in high-speed turning of Inconel 718¹

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Morvarid Memarianpour¹; Seyed Ali Niknam²; Sylvain Turenne¹; Marek Balazinski¹

Abstract: Three distinctive regions of tool wear, known as initial wear, steady-state wear, and accelerated wear are understood adequately. However, the effects of cutting parameters on the initial tool wear mechanism, morphology, and size have received less attention as compared to the other two regions. By knowing that adequate control of initial tool wear may lead to extended tool life, in particular in hard-to-cut metals such as superalloys, this subject becomes a source of attention. Amongst superalloys, Inconel 718 is considered one of the most difficult to cut materials, which has a wide range of industrial applications. This study intends to evaluate the effects of cutting parameters on initial tool wear as well as tool wear progression when turning Inconel 718. Therefore, microstructural evaluation of the initial tool wear mode under various cutting conditions, as well as tool wear measurements were conducted. It was observed that certain elements of the workpieces were migrated to the insert's flank face. This is evidence of adhesion in the initial moments of the cutting process. Dislike many other easy-to-cut materials, the steady-state wear period when turning Inconel 718 is significantly short under a higher level of cutting speed and feed rate.

Keywords: Tool wear, Inconel 718, Turning, Superalloys, High-speed machining.

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1. Mechanical Engineering Department, Polytechnique Montreal, Canada.
m.memarianpour@polymtl.ca; sylvain.turenne@polymtl.ca; marek.balazinski@polymtl.ca
 2. Sustainable Manufacturing Systems Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.
saniknam@iust.ac.ir; seyed-ali.niknam@polymtl.ca

5.1 Introduction

The machining of superalloys is associated with high mechanical stresses and wide surface structure variations at high temperatures. Amongst superalloys, Inconel 718 is known as one of the most difficult to cut materials due to its high hardness and prominent strength at elevated temperatures [2, 10]. However, Inconel 718 is still known as one of the most highly used materials in aerospace and automotive industries and products, including industrial gas turbines, space vehicles, rocket engines, nuclear reactors, submarines, stream production places, petrochemical devices, and glass industries [10, 66, 67]. Despite broad applications of Inconel alloys as aforementioned, machinability evaluation of Inconel 718 at high-speed machining conditions as well as an adequate selection of cutting parameters and suitable cutting tools are considered as delicate subjects which has received limited attention in the open literature. One of the main machining attributes is tool wear. Generally, the tool life is directly related to the wear value that can be perceived from the tool wear curve. The wear value is generally referred to the flank wear (V_{Bmax}) that can be measured against the recorded cutting time in the tool wear curve [68]. Three typical sections exist in the tool wear curve (Fig 5.1). According to [69], the main wear modes are initial or running-in period (I), steady wear within the steady-state (II) and accelerated wear (III) [70, 71]. Among the wear periods mentioned, the effects of machining parameters on steady-state wear period have been very well understood [72, 73], but the initial wear has not been fully determined yet. Unfortunately, no adequate source of information is available about the V_{Bmax} when machining Inconel 718 with different cutting tools. In fact, accurate understanding of the initial tool wear mechanism and governing factors on initial tool wear rate may lead to better control and optimization of the machining process which eventually may lead to extended tool life [66, 74-76] when machining hard to cut materials such as Inconel 718. Therefore, it is highly recommended to study the initial tool wear mechanisms during the first seconds of machining operation. Recently, Duong et al. [71] reported those cutting conditions that affect the initial tool wear and tool life within turning Ti-MMCs. It was stated that the Chaos theory could be used to explain the relationship between initial tool wear and ultimate tool life. In fact, the use of adequate levels of

cutting parameters such as cutting speed (V_c), depth of cut (a_p) and feed rate (f_r) within the first few seconds of machining may tend to improve the tool life.

It is to note that the mechanism of initial wear is totally different as compared to those surfaces generated in continuous contact, as in the case of a car engine. Because, both surfaces of the cutting tool, in particular rake and clearance faces, are in direct contact with the newly generated surfaces, chip face and part face. Furthermore, during a machining operation, the chip flows on the rake face and the machined surface rubs the flank face, and essentially affects the running-in process [77]. Therefore, the initial tool wear morphology and mechanism within running in period of cutting process has a critical role in the tool wear evolution and entire tool life.

According to the review of the literature, no work was found on the effects of cutting parameters on the initial tool wear morphology and mechanism on Inconel 718 work in various types of machining operations. This subject will be studied in this work by investigating the initial tool wear mechanism when turning Inconel 718 at a relatively high level of cutting speeds and various levels of feed rate and cutting time. As well as an accurate selection of cutting parameters, by knowing that Inconel 718 is classified as a hard to cut material, it can be stated that adequate selection of cutting tools play a significant role in machining performance and tool life. Several studies reported the machining of superalloys using ceramic tools [16]. However, at relatively low cutting speed, PVD carbide tools are still considered as the prime choice when machining superalloys, including Inconel 718 [16, 31, 33, 37-40, 78]. However, the initial tool wear mechanism of carbide tools in high-speed machining is yet to be investigated when various levels of feed rate and cutting time are used. The lacks of knowledge aforementioned are intended to be remedied in this work. Furthermore, the tool wear progress when using carbide tools in turning Inconel 718 is also studied. Commercial cutting tools such as PCD, CBN and PVD carbide are recommended for machining hard to cut materials including titanium alloys Ti-6Al-4V and metal matrix composites (MMC). The PCD and CBN tools have a lower wear rate while the coated carbide tools are in general cheaper [71].

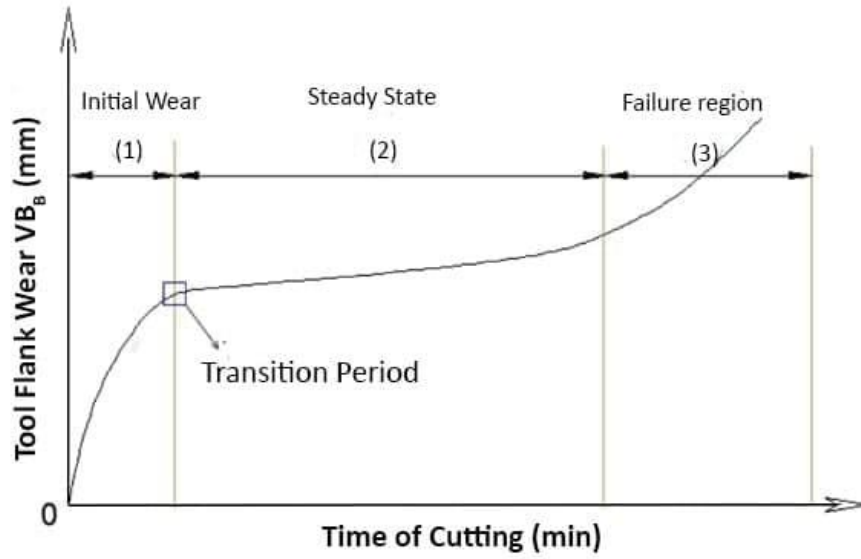


Figure 5.1 Tool wear curves evolution versus cutting time [71]

5.2 Experimental

Experimental plan

The workpiece was a 140-mm diameter cylindrical Inconel 718 comprised. All cutting tests were conducted on the PVD carbide inserts CNMG 432-MF4 TM2000 coated with TiCN/Al₂O₃ (CVD) manufactured with Seco (Figure 5.2a). Within the first phase of experimental works, the cutting conditions listed in Table 5.1 were used. This is to note that each insert edge was used only in one machining test with a specific cutting time, which varies from 1-4 seconds within the intervals of 1 second. The following cutting angles were used in experimental tests: rake angle $\gamma_0 = -6^\circ$, back rake angle $\gamma_p = -6^\circ$, nose radius $R_n = 0.031$ in, tool cutting angle $\kappa_r = 95^\circ$, and insert thickness $s = 0.187$ in. As shown in Table 5.1 the variation of V_{Bmax} at various levels of cutting speeds and constant levels of feed rate, cutting time and a_p are observed. In fact the cutting time 4 s was considered as the transition time when turning Inconel 718 using the abovementioned insert. It is to note that to avoid the coolant effects, experimental tests were conducted under dry condition. The experimental works were repeated twice, and the average of readings of V_{Bmax} was used in

subsequent studies. The CNC-MAZAK Nexus 200 was used in the turning tests (Figure 5.2b). The Kistler dynamometer was used to monitor and record the cutting force signals in three directions related to the thrust force (f_r), feed force (f_f) and cutting force (f_c).

Tool wear measurement

The flank wear V_{Bmax} was measured using a Mitutoyo optical microscope and by counting the pixels of captured photos with Canon EOS 300D digital camera. The V_{Bmax} can also be directly measured using an optical microscope or taking the photo and converting the pixels into standard scale units (e.g., mm). However, it is not possible to adjust the focus by changing the distance between the lens and the insert. Otherwise, it may require a ruler to acquire new conversion factor. The best solution to avoid any mistake is to add a ruler in the photo. To study insert wear mechanisms, two SEM (Jeol, JSM -840A and Jeol JSM 7800F FEG-SEM) equipped with an Oxford X-ray detection system (AZtec EDS) for elemental analysis and quantitative mapping were used. Moreover, Jeol JSM is a field emission SEM equipped with field emission guns (FEG) which provides the extreme resolution of 0.8 nm at 15 kV and 1.2 nm at 1 kV. The micrographs of the microstructures were captured at low and high magnification. It is to note that all turning tests were repeated twice and the average values of responses were considered in the result analysis.

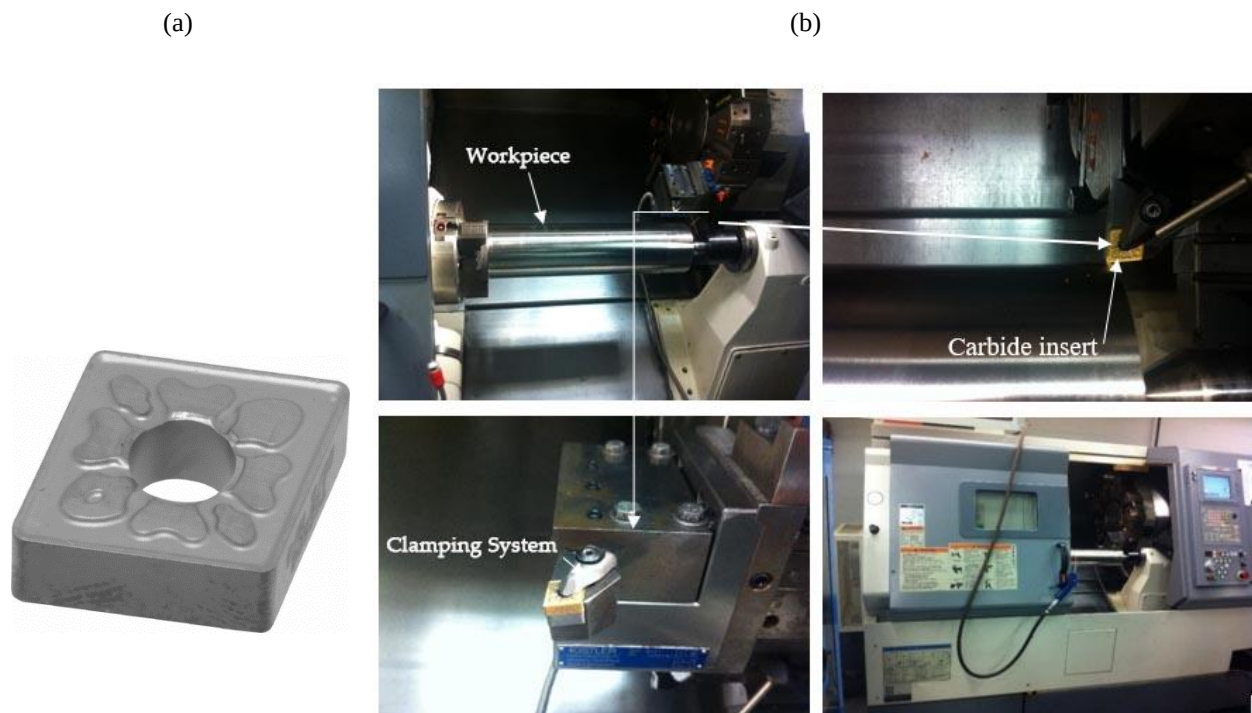


Figure 5.2 (a) The carbide insert used; (b) the machining set up used

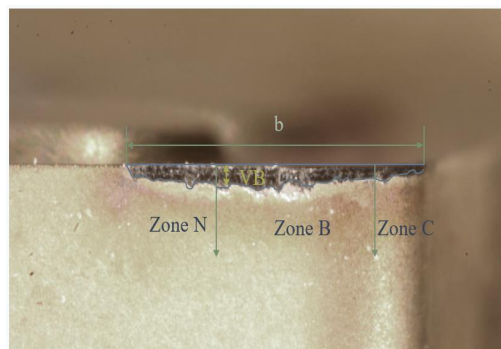


Figure 5.3 Typical flank tool wear with three zones [69]

Table 5.1 Cutting parameters used

Experimental phase	Experimental factors and levels			
	V_c (m/min)	f_r (mm/ rev)	a_p (mm)	Cutting time (s)
Phase 1	150	0.15, 0.25, 0.35	1	1, 2, 3, 4
Phase 2	100, 125, 175, 200	0.25	1	4

Table 5.2 Chemical composition of Inconel 718

Element	(%wt)	Element	(%wt)
Ni	53.4	Si	0.30
Cr	18.6	Mn	0.20
Nb	5.00	Ti	0.9
Mo	3.1	C	0.04
Al	0.40	Fe	18.5

5.3 Results and discussions

As noted earlier, the V_{Bmax} was used as the measure of wear which can also be considered as a performance indicator of the tool under the proposed cutting conditions. Similarly as presented in [71], the variation of tool wear rate corresponding to the cutting tw used are presented by polynomial regression of order three. As shown in Figure 5.4, the steady-state region of tool wear is not very uniform and the third region of the tool wear, different from what is shown in Figure 5.1, will be started approximately after one minute of cutting. The SEM/EDS measurements of V_{Bmax} were conducted at the intervals of 1 second under constant feed rate 0.15 mm/rev (Figure 5.4). According to experimental observations, it can be inferred that increased cutting time led to increased V_{Bmax} . Furthermore, various elements such as W, Al and Ti, which are the typical elements of tool material are observed on the worn surface of the insert. Furthermore, Ni, Fe, Cr and Mo exist on the workpiece.

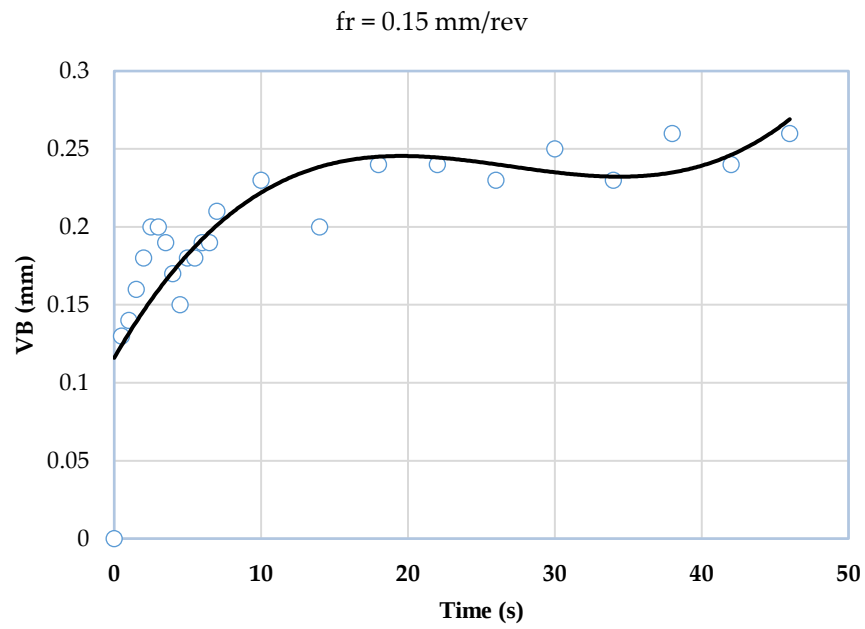
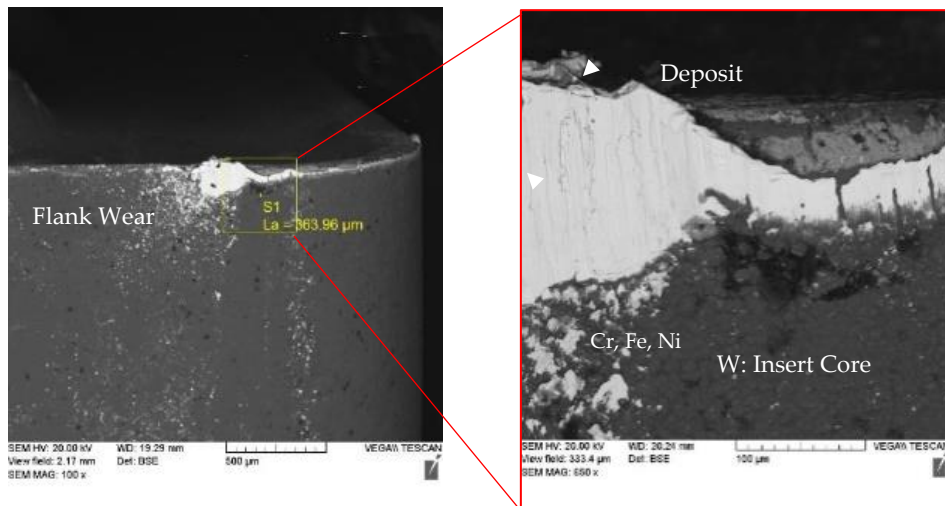


Figure 5.4 The progress of V_{Bmax} Phase 1 when $V_c = 150 \text{ m/min}$ & $f_r = 0.15 \text{ mm/rev}$

**Cutting
Time**

1s

Flank Face



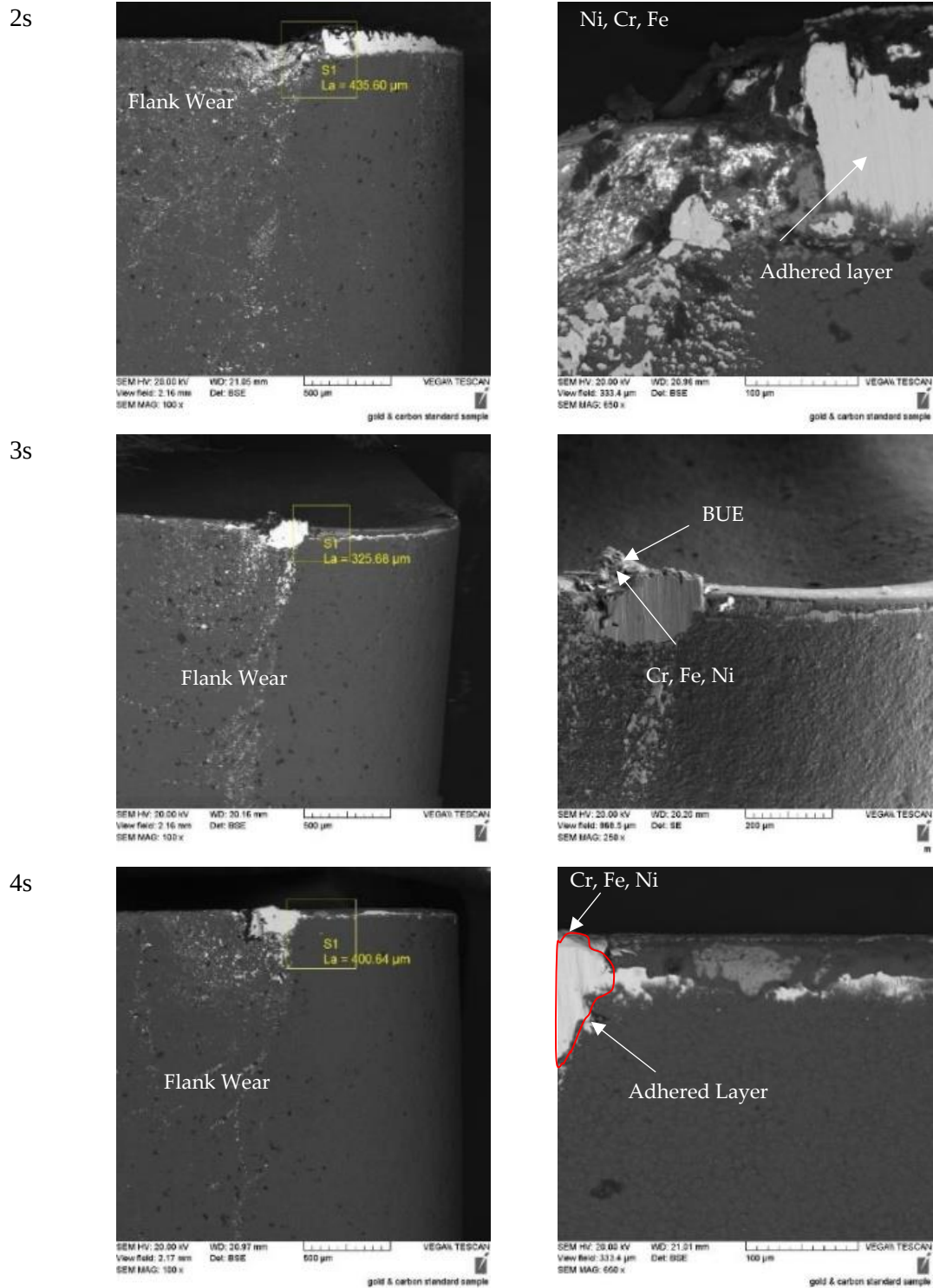


Figure 5.5 SEM micrographs of tool wear modes and region on the insert flank face

$$V_c = 150 \text{ m/min}, f_r = 0.15 \text{ mm/rev}, a_p = 1 \text{ mm}$$

Based on experimental observations, the elemental composition of the worn surface varies with cutting time (Figure 5.6). The detected amounts of Al, which are the highest portion within elements seem to have the most distinct difference over time. The rapid increase of elemental composition after three seconds of machining may resemble the workpiece deposition. The existence of Ti and Ni in the elements deposited on the worn area (Figure 5.6, Table 5.3) is the evidence of the components migrated from the workpiece (Inconel 718). The amounts of Ti on the worn surfaces seem to slightly increase with cutting time until the first second of machining. It then tends to decrease after 4 seconds of machining. The similar pattern was found for detected amounts of Cr, Fe and Ni. It is worth noting that according to EDS results of different specimens, variations in the composition may be found due to limited area analyzed. Additional investigations in this context are the subject of future works.

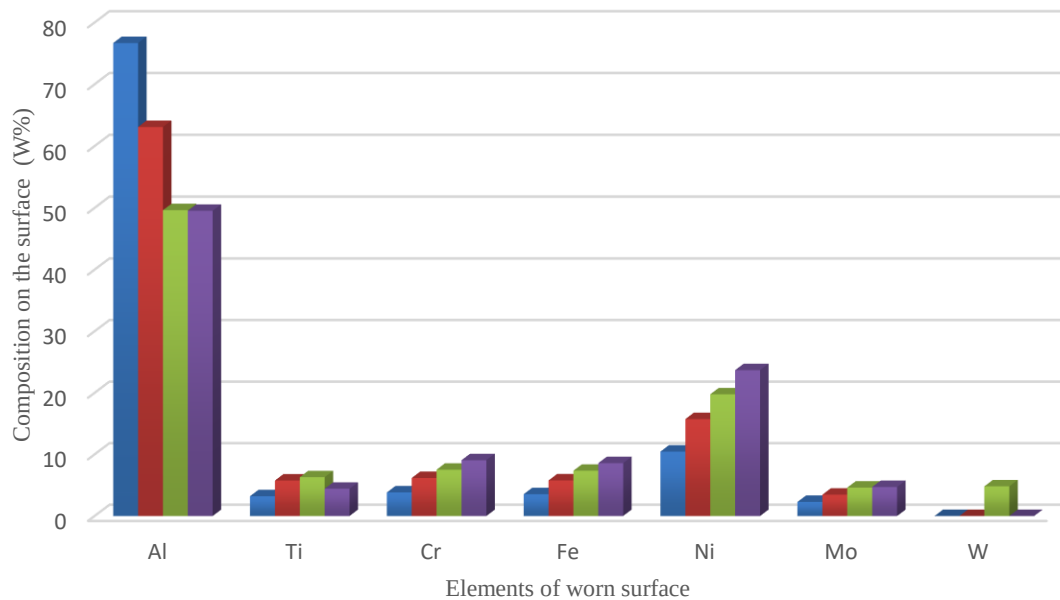


Figure 5.6 Elemental composition on the worn surface of the insert flank face under various cutting time in phase 1 when $V_c = 150$ m/min & $f_r = 0.15$ mm/rev

Table 5.3 Elemental composition on the worn surface of the insert flank face $V_c = 150$ m/min & $f_r = 0.15$ mm/rev

%wt	$f_r = 0.15$ mm/rev			
	1 s	2 s	3 s	4 s
Al	76.68	63.08	49.59	49.53
Ti	3.23	5.76	6.28	4.44
Cr	3.79	6.23	7.53	9.15
Fe	3.54	5.79	7.39	8.64
Ni	10.42	15.67	19.81	23.74
Mo	2.34	3.47	4.58	4.74
W	0.00	0.00	4.82	0.00
Total	100	100	100	100

According to SEM/EDS measurements of V_{Bmax} conducted on those cutting tests with $f_r=0.25$ mm/rev at the interval of 1s (Figure 5.7), it can be inferred that increased cutting time led to increased V_{Bmax} (Figure 5.7). In contrast to Figure 5.1 and Figure 5.4, the steady-state region Figure 5.7 is quite short and non-uniform. Furthermore, the third region was started approximately 30 seconds after the cutting process. In other words, changing the feed rates to higher level ($f_r= 0.25$ mm/rev) led to an increased rate of 100% on the V_{Bmax} . The elemental compositions of the wear lands in the flank face within the cutting times 1-4 seconds are presented in Table 5.4. The results show that the wear land (horizontal axis) consists of mainly Al, Ti, Cr, Fe, Ni, Mo and W (Figure 5.8) which are considered as the elemental compositions. The existence of Ti and Ni on the worn area (Figure 5.9a; Table 5.4a) is the evidence of the migration of elements from the workpiece.

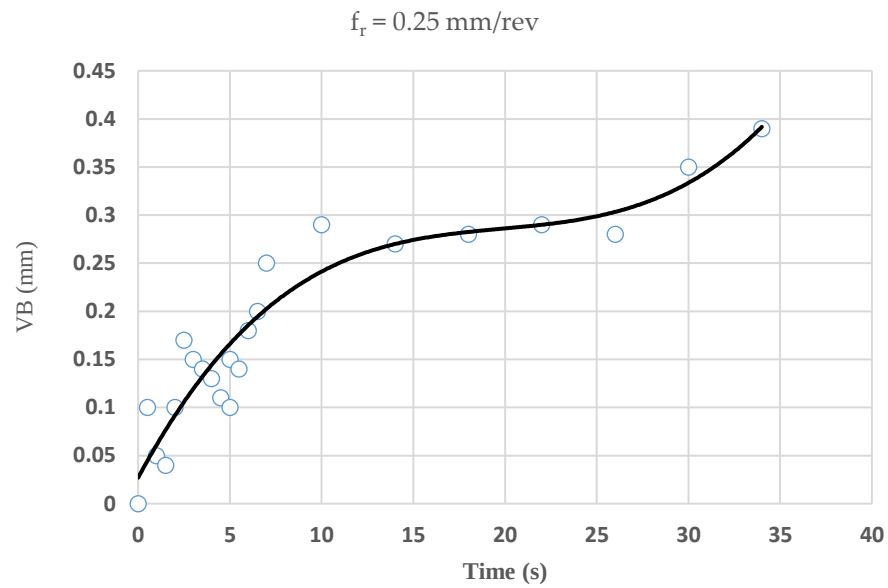


Figure 5.7 The progress of V_{Bmax} Phase 1 when $V_c = 150 \text{ m/min}$ & when $f_r = 0.25 \text{ mm/rev}$

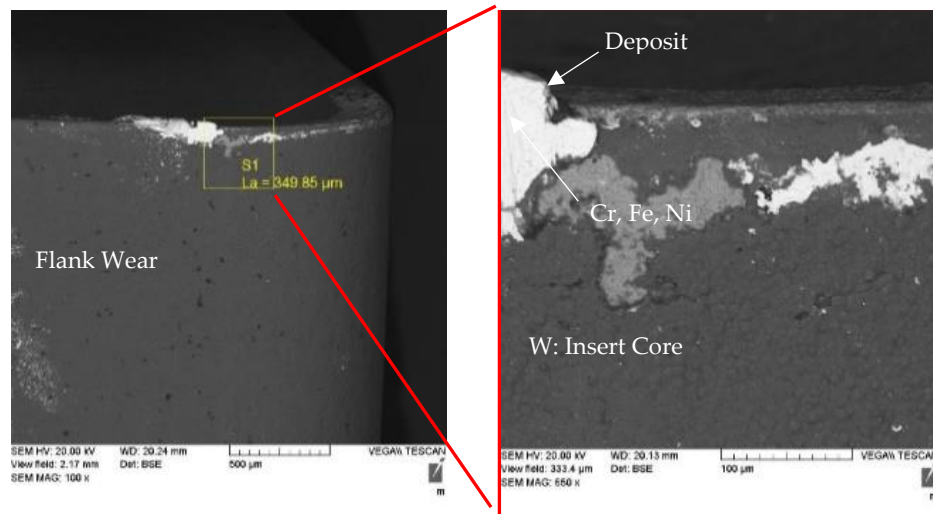
**Cutting
Time**

Flank Face

Original view

**Extended projection of the worn
area**

1s



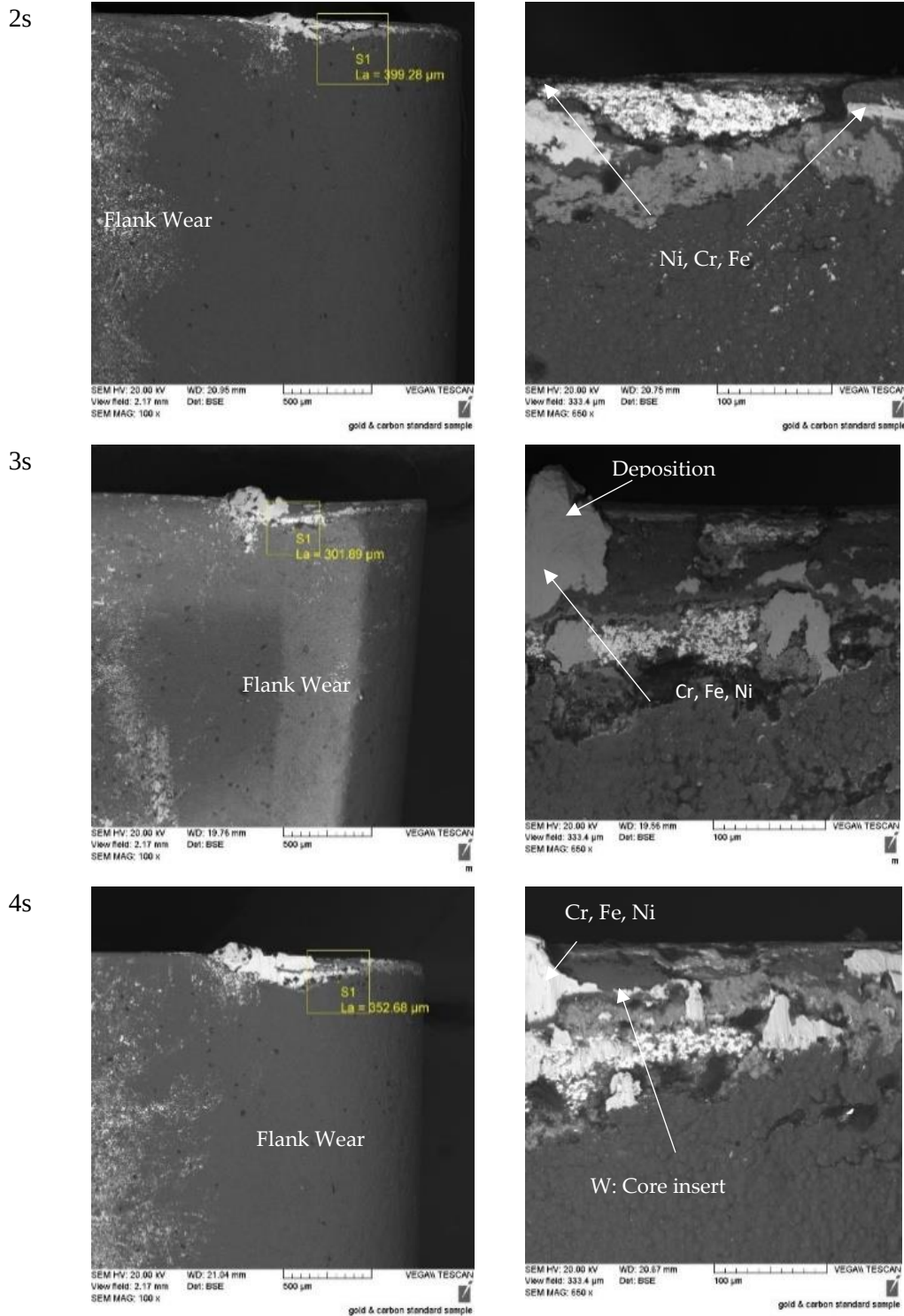


Figure 5.8 SEM micrographs of flank face and tool wear region

$$V_c=150 \text{ m/min}, f_r = 0.25 \text{ mm/rev}, a_p = 1 \text{ mm}$$

Based on experimental observations, elemental compositions of the deposit on the worn surface vary with cutting time (Figure 5.9(a)). The detected amount of Al, which has the highest weight percentage slightly decreases with cutting time. It also seems to increase slightly for the cutting time 3 s. The similar trend was observed in the detected amounts of Ni, Cr and Fe, except for the cutting time 2 s (Figure (5.9a)).

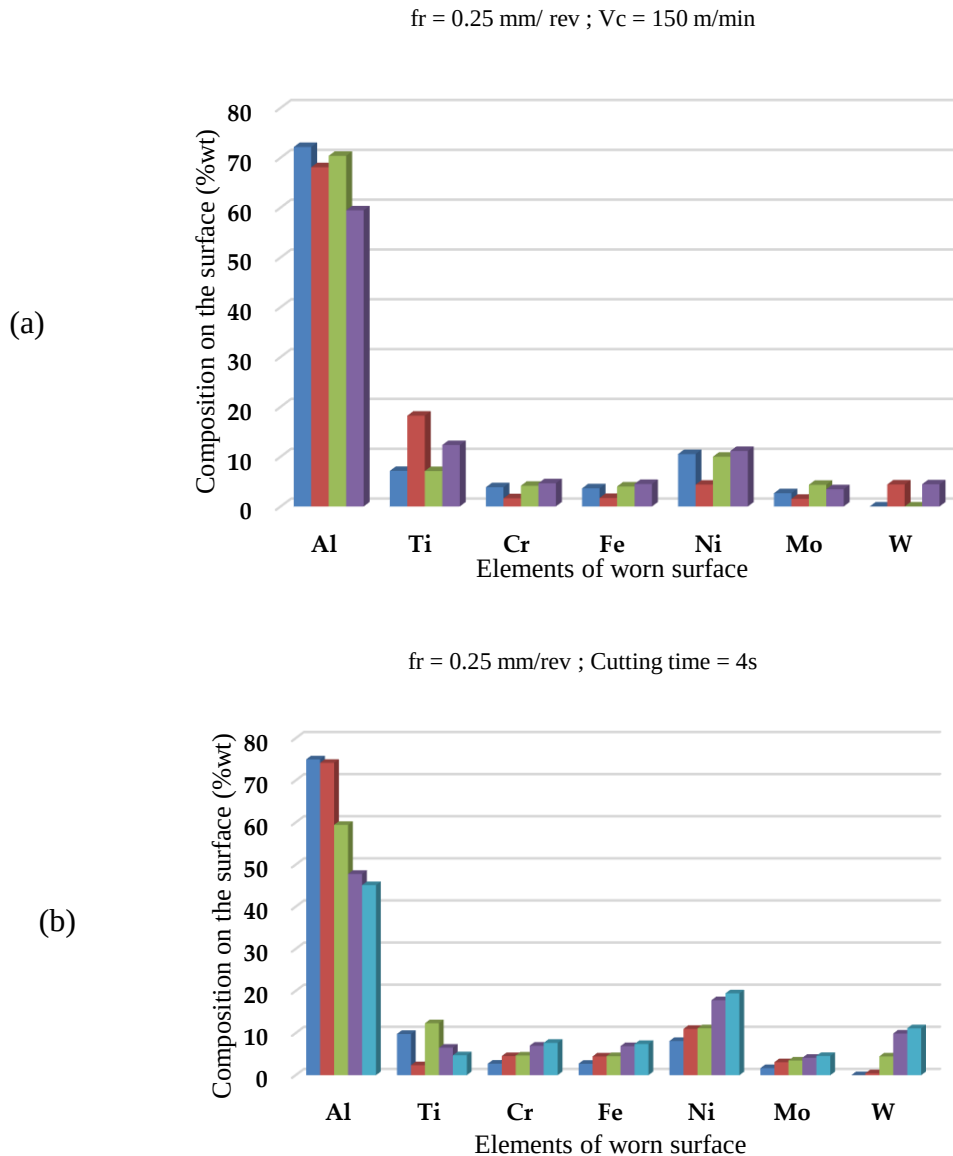


Figure 5.9 Variation of elemental composition on flank face wear land adhered material under (a) different cutting times (1s, 2s, 3s, 4s); (b) different cutting speeds (100, 125, 150, 175, 200 m/min)

To define the effects of different levels of cutting speeds on the flank wear, four levels of cutting speed (100, 125, 175 and 200 m/min) were used at cutting time 4 s under the constant depth of cut 1 mm and feed rate 0.25 mm/rev (Figure 5.9(b)). The detected amounts of Al, which has the highest weight percentage, seem to slightly decrease with increased cutting speed. However, it increases when using the cutting time 3 seconds. The detected amounts of Ni, Cr and Fe are increased at higher cutting speed (Figure 5.9(b)).

Table 5.4. Elemental composition on the worn surface of the insert flank face (wt%) at constant $a_p = 1\text{ mm}$ and $f_r = 0.25\text{ mm/rev}$ under (a) $V_c = 150\text{ m/min}$ at different cutting time (1, 2, 3, 4 s);
(b) different cutting speed (100, 125, 175, 200 m/min) at cutting time 4 s

(a)

%wt	Cutting time (s)			
	1 s	2 s	3 s	4 s
Al	72.22	68.13	70.41	59.38
Ti	7.12	18.21	7.09	12.3
Cr	3.87	1.68	4.22	4.71
Fe	3.59	1.73	4.01	4.48
Ni	10.46	4.38	9.87	11.11
Mo	2.74	1.51	4.4	3.52
W	0	4.36	0	4.5

(b)

%wt	V_c (m/min)			
	100	125	175	200
Al	74.89	74.24	47.78	45.13
Ti	9.84	2.41	6.51	4.72
Cr	2.73	4.52	6.88	7.67
Fe	2.71	4.46	6.92	7.42
Ni	8.12	10.88	17.84	19.37
Mo	1.71	3.09	4.13	4.62
W	0	0.4	9.94	11.07

According to Figure 5.11 and 5.12, several elements such as W, Al and Ti, are the major constituents of the tool material, as well as Ni, Fe, Cr and Mo, which mostly exist in the workpiece. The analysis of elemental compositions of flank face wear lands for different cutting times as

presented in Figure 5.10 and 5.11 reveals how compositions vary with cutting time. It can be underlined that the wear land (horizontal axis) consists of mainly Al, Ti, Cr, Fe, Ni, Mo and W. The detected amounts of Al, which are the highest in the insert composition weight percentage seem to decrease with cutting time slightly. However, an increasing trend was observed for the 3 s. The detected amounts of Ni, Cr and Fe have the same behavior and the amounts are increased.

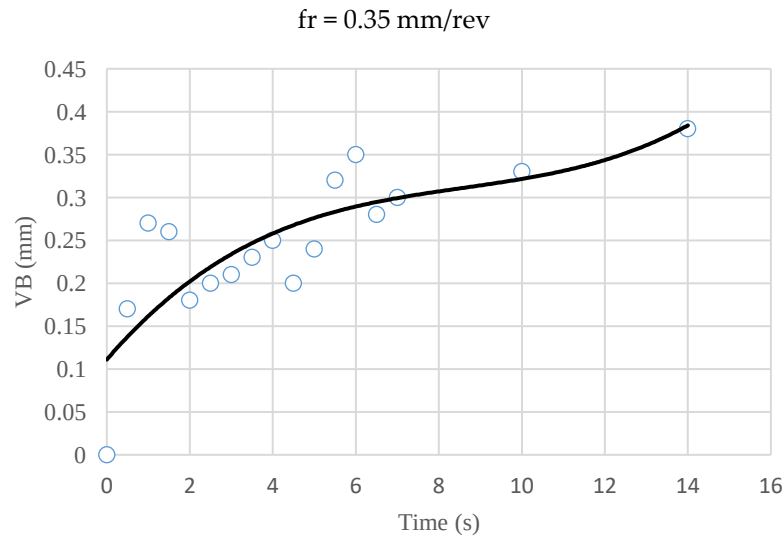
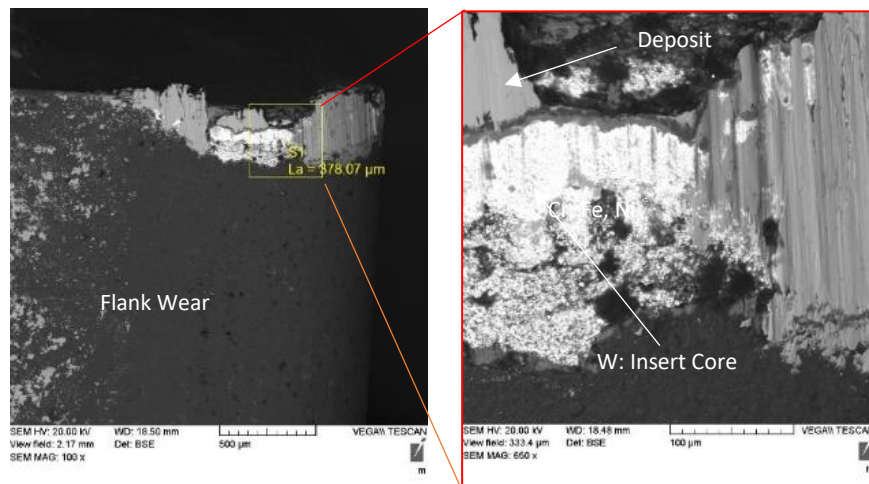


Figure 5.10 The progress of V_{Bmax} Phase 1 when $V_c = 150 \text{ m/min}$ & $f_r = 0.35 \text{ mm/rev}$

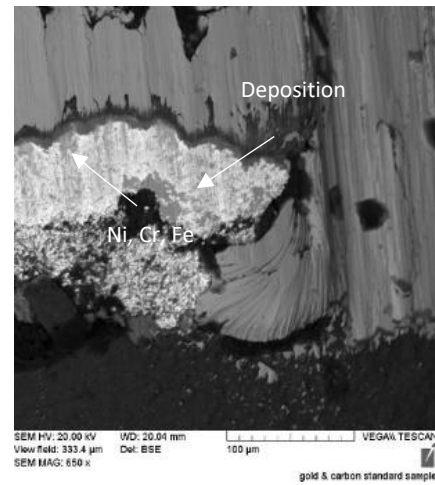
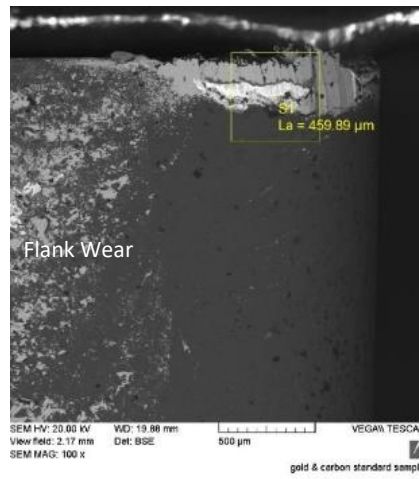
**Cutting
Time**

1s

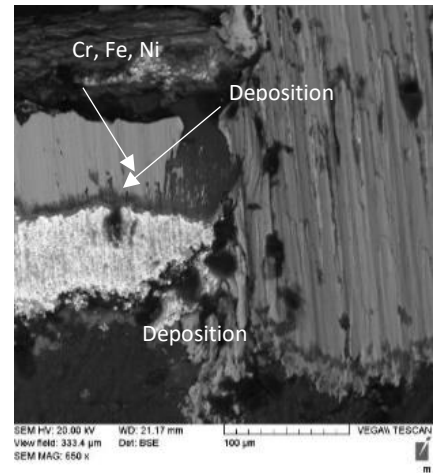
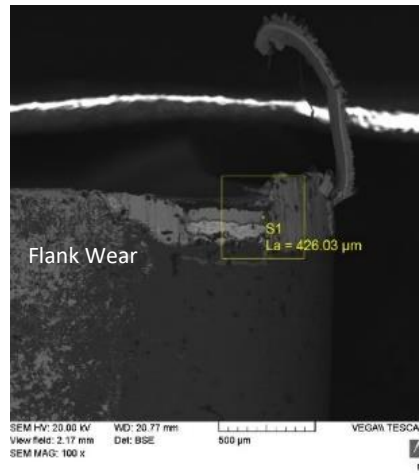
Flank Face



2s



3s



4s

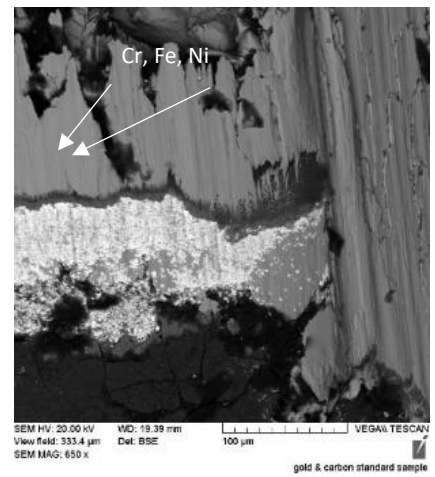
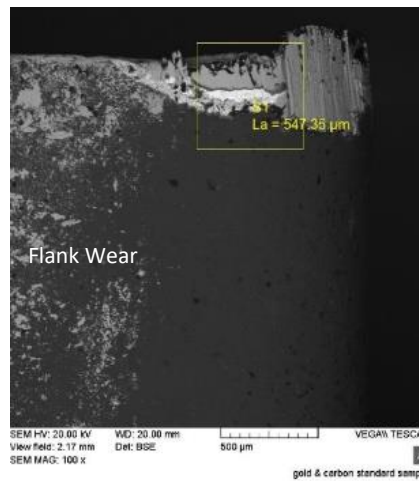


Figure 5.11 SEM micrographs of flank face and tool wear region

$$V_c = 150 \text{ m/min}, f_r = 0.35 \text{ mm/rev}, a_p = 1 \text{ mm}$$

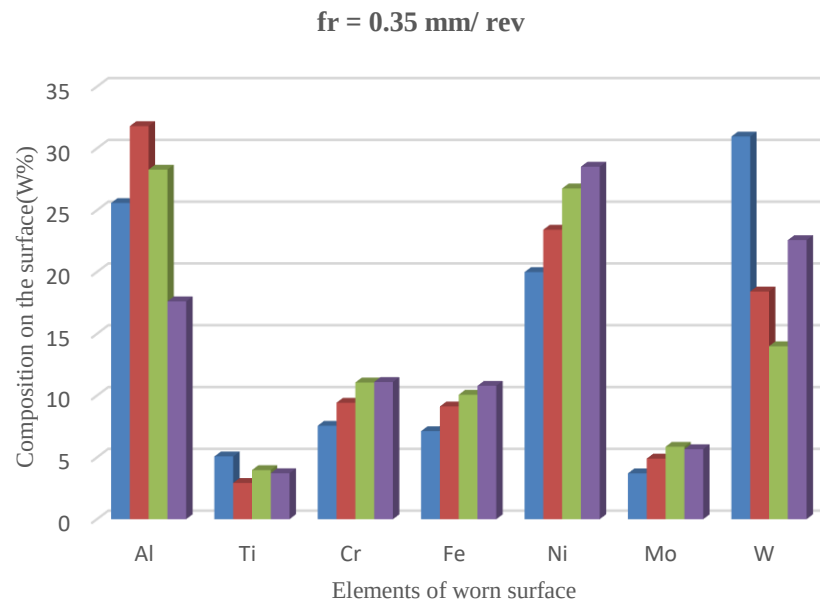


Figure 5.12 Variation of elemental composition on flank face wear land adhered material V_c
 $=150 \text{ m/min}$, $f_r = 0.35 \text{ mm/rev}$

Table 5.5 Variation of elemental composition on flank face wear (wt%) $V_c = 150 \text{ m/min}$, $f_r = 0.35$
 mm/rev

%wt	$f_r = 0.35 \text{ mm/rev}$			
	1 s	2 s	3 s	4 s
Al	25.56	31.81	28.34	17.58
Ti	5.11	2.93	3.83	3.73
Cr	7.64	9.44	11.12	11.11
Fe	7.13	9.12	10.07	10.81
Ni	19.94	23.38	26.76	28.48
Mo	3.72	4.91	5.87	5.67
W	30.9	18.39	14.01	22.62

5.4 Conclusions

It is known that the machinability of each individual material is directly affected by the microstructure of the tested workpiece. The microstructure of Inconel 718 which is a nickel-based alloy, consists of gamma and gamma prime phases in the presence of carbides and precipitates. Knowing that the tool wear is one the main performance indicator of machinability, special attention was paid to assess the effects of cutting parameters on the initial tool wear. No similar studied was found in this regard in the open literature. To gain a better evaluation of the cutting performance, the cutting parameters were selected according to recommendations by the cutting tool manufacturer SECO Inc and local manufacturing sectors. General conclusions drawn from experimental studies are as follows:

At relatively high cutting speeds, three different wear zones were identified on the carbide flank and rake surfaces. Deposit on the surface of the worn tool is composed of Ni, Cr, and Fe, which were adhered to the tool surface inside the contact region. Consequently, adhesion was found in most of the cutting tests performed.

Plastic deformation, chipping or carbon discolorations were not observed within the initial periods of cuts. The detected amounts of Al, which has the highest weight percentage, seem to slightly decrease when both cutting speed and cutting time increase. The detected amounts of Ni, Cr and Fe are increased at higher cutting speed and cutting time.

It can be stated that feed rate and cutting speed are considered as the major machining factors affecting the flank wear when carbide inserts are used. In fact, at higher levels of feed rate, non-uniform and rapid steady-state regions were observed. This observation reveals that as well as cutting speed, increased levels of feed rate not only accelerate the tool wear, but also changes the tool wear curve morphology.

The outlook of future works

Adequate estimation/knowledge of the ultimate tool life is an important step towards lean manufacturing. The experimental results in this study can be integrated with statistical approaches,

including Chaos theory and fractal analysis in order to establish a relationship between the optimum tool life, initial tool wear as well as cutting parameters.

Acknowledgments

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CHAPTER 6 ARTICLE 2: Study of the Effects of Initial Cutting Conditions and Transition Period on Ultimate Tool Life when Machining Inconel 718²

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Morvarid Memarianpour¹; Seyed Ali Niknam²; Sylvain Turenne;¹ Marek Balazinski¹

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Abstract- Rapid tool wear and limited tool life are major problems when machining Inconel 718, which still needs further attention. Amongst reported strategies, limited studies were reported on optimizing initial cutting conditions by means of tool life improvement. Therefore, in this work, the tool wear progress and tool life were investigated based on varying the initial conditions at the transition period, which was set at four seconds. The transition point was discovered from the previous works by the authors. After the transition point, similar cutting conditions as the reference condition were used. The tool wear morphology and size were recorded and analyzed in each condition. It was revealed applying lower cutting speed and feed rate at the transition period led to improved tool life as compared to the reference condition. In other words, the use of optimum levels of cutting parameters in the transition period of cutting process may enhance tool life at higher cutting time. For instance, initial feed rate (0.15 mm/rev) and cutting speed (25 m/min) led to the improvement in the ultimate tool life by about 67% and 50%, respectively. Besides, applying the lower initial cutting speed, i.e., 25 m/min, increased the tool life by about 50% when the insert reached the maximum flank wear (V_{Bmax}) of 300 μm in comparison with those at higher initial cutting speeds. This phenomenon may lead to have a better insight into the effect of the influence of the initial cutting conditions in the transition period on the tool life when machining hard to cut

¹ Mechanical Engineering Department, Polytechnique Montreal, Canada. m.memarianpour@polymtl.ca; sylvain.turenne@polymtl.ca; marek.balazinski@polymtl.ca

² Sustainable Manufacturing Systems Research Laboratory, School of Mechanical

Engineering, Iran University of Science and Technology, Tehran, Iran.
saniknam@iust.ac.ir; seyed-ali.niknam@polymtl.ca

materials. Moreover, the built-up edge (BUE) was exhibited as the primary wear mode in all cutting conditions.

Keywords: tool wear; Inconel 718; turning; built-up edge

6.1 Introduction

Among hard to cut superalloys, Inconel 718 has a vast variety of real-world applications in numerous industrial products and sectors [2, 27, 67]. As a high-temperature material, Inconel 718 is widely utilized in the aerospace applications. When needed for high-performance materials with promising mechanical as well as thermal properties (i.e., high strength and oxidation-resistant materials), Inconel 718 is considered as a specifically appropriate alternative for being used in the structures of aero engines and gas turbines where the temperature is high [79]. Despite wide applications and prominent features, the poor machinability of Inconel 718 at precision machining conditions is still considered a subject of interest, and additional investigations on optimizing cutting parameters and specifying appropriate cutting tools are still needed. Amongst machinability attributes, limited studies were reported in the literature about tool wear and tool life improvement when machining superalloys, including titanium metal matrix composites (Ti-MMC) and Inconel 718.

As it is well understood in the literature, the tool wear index is generally referred to as the maximum permitted flank wear (V_{Bmax}) that can be measured in the course of cutting process, and the corresponding results can be observed in the tool wear curve [68]. According to Figure 6.1, three typical sections exist in the tool wear curve. As noted in [69], the main wear modes are initial or running-in period (I), steady wear within the steady-state (II), and accelerated wear (III) [70, 71]. It has been known that both initial and steady wear periods occur very fast in the machining of superalloys, including Inconel 718. To prolong the tool life, one solution is to assess the wear modes and morphologies in both states and employ the adequate cutting parameters and lubrication strategies to reduce the presence of wear modes aforementioned. To that end, several studies were conducted to understand the wear modes in the steady-state wear period [72, 73]. The capability of three well-known cutting tool materials including PVD-TiAlN coated carbides, Al_2O_3 -TiC ceramic, and CBN in the turning of Inconel 718 was studied by Xaviour et al. [80] with various

cutting speeds (60, 80, and 120 m/min), feed rates (0.08, 0.10, and 0.12 mm/rev), and depth of cuts (0.2, 0.4, and 0.6 mm). It was revealed that the most suitable cutting speed for carbide inserts is 90 m/min at which the minimum value of the maximum V_{Bmax} was achieved. On the other hand, Xaviour et al. [80] investigated the V_{Bmax} in three different cutting tools including PVD TiAlN coated carbide, $Al_2O_3 - TiC$ ceramic, and CBN tools, and revealed that the optimal conditions for dry-cutting, MQL, and flood cooling are: cutting speed of 90 m/min, feed rate of 0.16 mm/rev, and depth of cut of 0.4 mm [81].

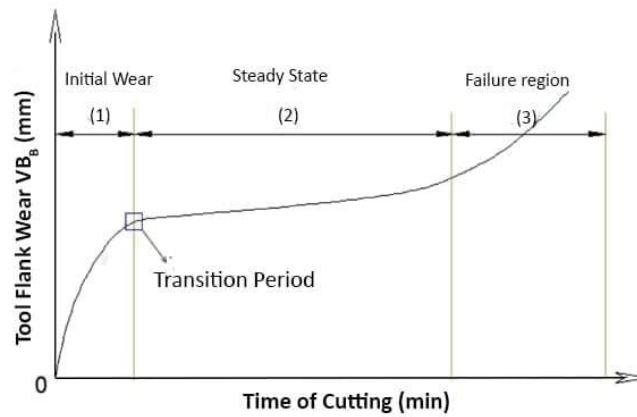


Figure 6.1. Evolution of Tool wear curves vs cutting time [71]

Among all three wear periods mentioned earlier, the effects of machining parameters on the steady-state wear period have been thoroughly investigated, but the adequate knowledge on the wear modes and morphology, as well as factors governing elevated initial tool wear morphology and size in machining hard to cut materials, are still demanded in wider scopes. In this regards, having a precise insight into the initial tool wear mechanism, morphology, and influencing parameters on initial tool wear size may result in better control and optimization of the machining process, and thus, extending tool life when machining hard-to-cut materials such as Ti-MMC [66, 75, 76, 82]. Therefore, within the first seconds of machining operation, it is strongly recommended to study the initial tool wear mechanisms. In this venue, Duong et al. [71] mentioned certain cutting conditions that influence the initial tool wear and tool life while turning Ti-MMCs. It was mentioned that the chaos theory could be employed to describe the relationship between initial tool wear and ultimate

tool life. Applying the optimal values of cutting parameters including cutting speed (V_c), depth of cut (a_p), and feed rate (f_r) within the very first seconds of machining may result in the improvement of the tool life. Memarianpour et al. [83] studied the effects of cutting conditions, with specific emphasis on cutting speed (V_c) and lubrication modes on tool wear progression when turning Inconel 718.

To identify and monitor the predominant tool wear mechanisms, several advanced characterization techniques, including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray photoelectron spectroscopy (XPS) were conducted on the cutting tools and inserts [84]. Abrasion, adhesion, and diffusion were considered as the most prevalent tool wear mechanisms occurring under different conditions while machining nickel-based alloys [21, 85]. One other key element in machining superalloys is the right selection of cutting tools. Commercial cutting tools such as polycrystalline diamond (PCD), cubic boron nitride (CBN), and physical vapor deposition (PVD) carbide, as well as ceramic, are among the best choices for machining hard to cut materials, including titanium alloys Ti-6Al-4V and MMC. Several studies reported the machining of superalloys using ceramic tools [16].

Furthermore, the progress of carbide tools wear in turning Inconel 718 was also investigated. In general, the PCD and CBN tools show a lower degree of wear rate while the coated carbide tools are more economic choices [71]. However, for machining superalloys such as Inconel 718 at relatively low cutting speeds, the PVD carbide tools are the primary choice [16, 31, 33, 37-40, 78]. However, the initial tool wear mechanism of carbide tools in high-speed machining needs to be further examined in wider scopes at different values of cutting conditions and cutting time. The lack of knowledge aforementioned was partially studied by Memarianpour et al. [83]. Unfortunately, no sufficient source of data has been provided about the variation of V_{Bmax} when machining Inconel 718 using different cutting tools.

In most of the works published in the literature, the tool wear was evaluated based on the measured values of flank wear (V_{Bmax}) in the course of cutting time [68], and no additional work was found on the effects of initial tool wear morphology and mechanism on ultimate tool life when machining

Inconel 718. Therefore, within this study, the effects of initial cutting conditions on the ultimate tool life were studied in turning Inconel 718 with carbide inserts.

Furthermore, this work intends to present the effects of initial cutting parameters on the ultimate tool life when machining Inconel 718. The proposed method can efficiently enhance the service life of the cutting tool. Moreover, to align with green manufacturing goals and objectives, dry machining was used in order to omit the use of lubricants. In general, the proposed method can be easily implemented in the industrial and manufacturing sectors.

6.2 Experimental work

6.2.1 Experimental plan

The workpiece used was a cylindrical Inconel 718 with the nominal bulk hardness and tensile strength of about $37.0 \pm 0.63 R_C$ and 1100 MPa, respectively. This was delivered in the shape of a cylindrical bar with a diameter of 114 mm and the chemical compositions based on the weight percent of elements (wt%) listed in Table 6.1. The cutting tool used in all experiments was carbide/cermet inserts CNMG 432-MR4 TS2500 coated with TiCN/Al₂O₃ (CVD), which was fabricated by Seco Inc. (Figure 6.2a). The CNC-MAZAK Nexus 200 was applied in the turning tests (Figure 6.2b). It ought to be noted that to prevent the coolant effects, experimental tests were undertaken under dry conditions. The experimental works were performed twice, and the average values of the obtained V_{Bmax} were utilized in successive studies. A new and sharp insert edge was used in each machining test. The following cutting angles were used in the experimental tests: rake angle $\gamma_0 = -6^\circ$, back rake angle $\gamma_p = -6^\circ$, nose radius $R_n = 0.031$ in, tool cutting angle $\kappa_r = 95^\circ$, and insert thickness $s = 0.187$ in.

Table 6.1 Chemical composition of Inconel 718 alloy (wt%)

Element	(wt%)	Element	(wt%)
Ni	53.4	Si	0.12
Cr	18.8	Mn	0.07
Cb	5.27	Cu	0.07

Mo	2.99	C	0.03
Ti	1.02	P	0.01
Al	0.50	Fe	balance
Co	0.17		

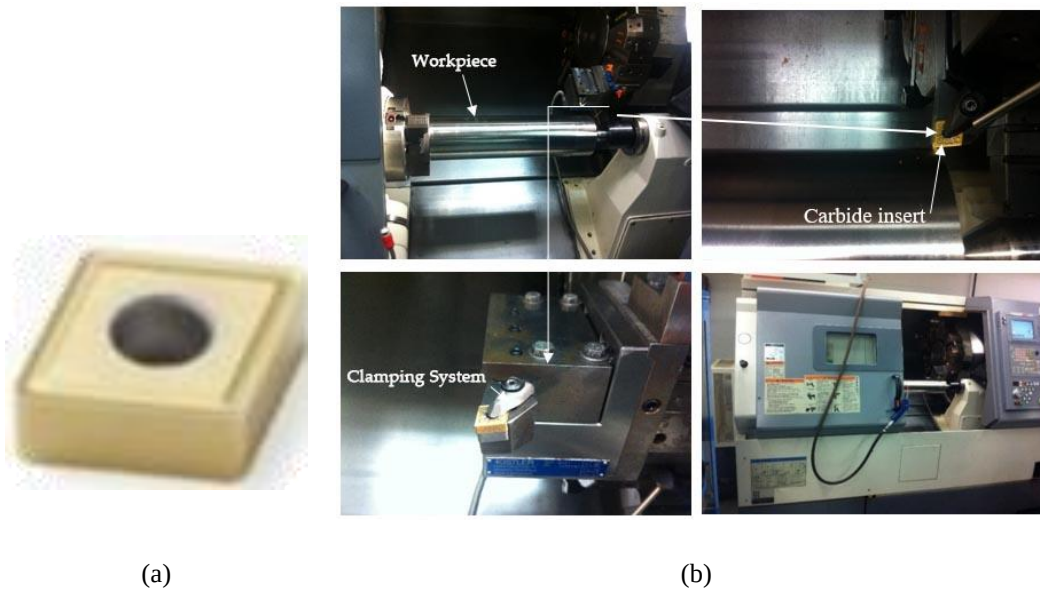


Figure 6.2. (a) The insert that was used; (b) Set-up machining

As noted earlier, according to the research outcomes reported in previous works by authors [83, 86], the cutting time 4 s was considered as the transition point, and the first four seconds of cutting operations was considered as the transition period, and the five different cutting conditions, as listed in Table 6.2 were used in the transition period. The first cutting condition was considered as the reference condition, and it was employed after the transition point in all the experiments. In this venue, the cutting conditions used after the transition point were similar to the reference condition. All the experiments have been repeated twice to respect repeatability concerns.

Table 6.2. Experimental conditions used

Cutting conditions	Transition period (0-4 s)		Cutting conditions after 4 s	
	V_c (m/min)	f_r (mm/rev)	V_c (m/min)	f_r (mm/rev)
1	45	0.25	45	0.25
2	25	0.25		
3	65	0.25		
4	45	0.15		
5	45	0.35		

6.2.2 Tool wear measurement

The experiments were carried out in two steps. The first stage was devoted to investigating the tool life during the machining of Inconel 718. In this regard, cutting speed and feed rate at 45 m/min and 0.25 mm/rev were kept constant, respectively. At the following stage, initial cutting speeds, as well as different initial feed rates ranging from 25-65 m/min and 0.15-0.35 mm/rev were used, respectively. It ought to be noted that the depth of cut was kept constant at 1 mm in all the experiments.

To study insert wear mechanisms, size, and morphology, as well as elemental analysis and quantitative mapping, two SEM (Jeol, JSM -840A, and Jeol JSM 7800F FEG-SEM) equipped with an Oxford X-ray detection system (AZtec EDS) were used. Moreover, Jeol JSM 7800F is equipped with field emission guns (FEG), which provides an extreme resolution of 0.8 nm at 15 kV and 1.2 nm at 1 kV. The micrographs of the microstructures were obtained at both low and high magnifications. The maximum values of recorded flank wear measurements were considered for additional studies.

6.3 Results and discussion

6.3.1 Effect of cutting parameters on tool life

Generally, cutting tool material undertakes severe mechanical and thermal stress when machining superalloys. These phenomena could appear as a result of high cutting stress and temperature near the cutting edge, which affects the cutting tool wear rate and short tool life [1, 3, 87]. As noted earlier, the cutting speed is considered as one of the most crucial parameters which directly affect the tool life. Moreover, tool life analysis in turning with variable feed rates when machining Inconel 718 was not reported in the literature. Therefore, in order to remedy the lack of knowledge observed, it was intended to investigate the effects of cutting parameters and initial wear modes on the initial and ultimate wear modes and tool life machining of Inconel 718. Therefore, according to Table 6.2, besides the reference cutting condition, four different strategies with a combination of various levels of feed rate and cutting speed were used. In this venue, the flank wear values in the transition period ($0 < t < 4$ s) as well uniform conditions ($t > 4$ s) were presented as a function of cutting time (Figure 6.3). The individual recorded values of V_{Bmax} were also shown in Table 6.3. As it can be inferred from Figure 6.3 and Table 6.3, the use of higher levels of cutting speed ($V_c = 65$ m/min; condition 3) in the transition period led to higher flank wear (V_{Bmax}). Thus lower tool life was recorded as compared to reference condition at higher cutting time. Contrary, based on Table 6.3 and Figure 6.2, using the lower cutting speed ($V_c = 25$ m/min; condition 2) led to lower V_{Bmax} at 4 s. Thus better tool life was also recorded at higher cutting time. Feed rate is another key factor affecting the wear morphologies and V_{Bmax} . Therefore, two different feed rate strategies, as noted as condition 4 and condition 5 (Tables 6.2 and 6.3), were used at constant cutting speed (45 m/min) and depth of cut (1 mm).

Table 6.3. The recorded value of V_{Bmax} at each cutting condition

Cutting time (s)	V_{Bmax} (mm)				
	Cutting condition 1	Cutting condition 2	Cutting condition 3	Cutting condition 4	Cutting condition 5
4	0.0994	0.0817	0.1583	0.1110	0.1260

8	0.2045	0.0905	0.2092	0.1190	0.1846
16	0.2756	0.1964	0.2741	0.1850	0.3127
26	0.3644	0.2745	0.4970	0.2700	0.5100
46	0.4412	0.3393	0.6373	0.3200	0.5627

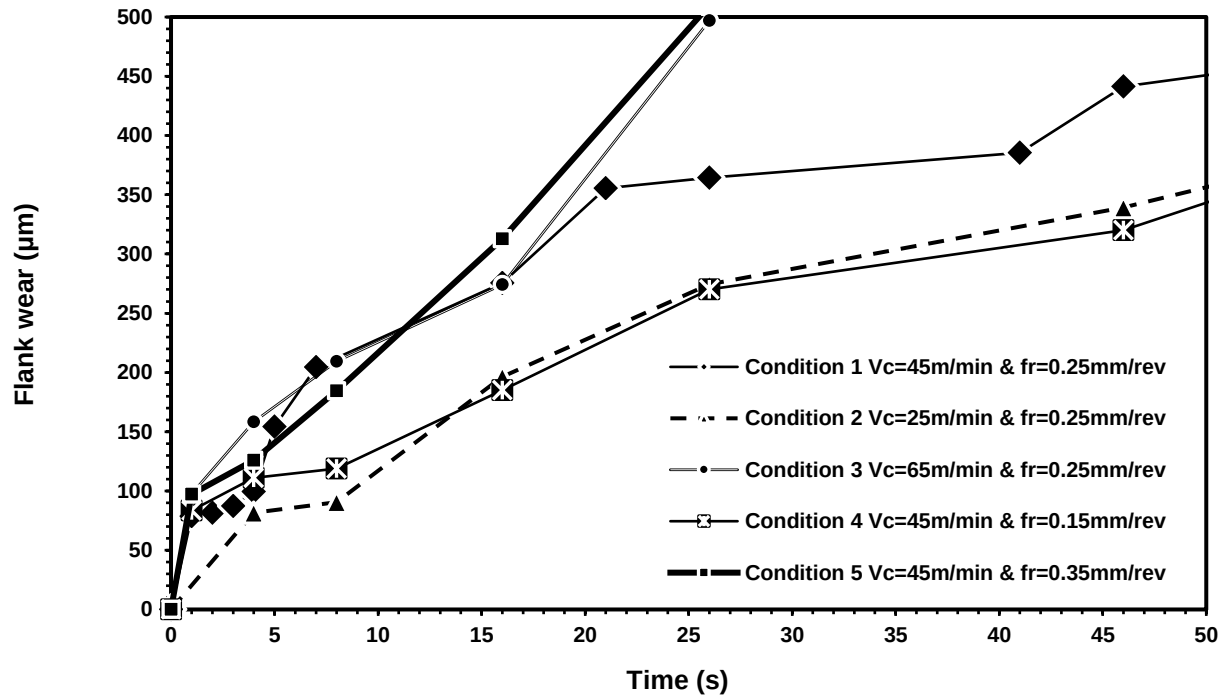


Figure 6.3. The V_{Bmax} vs. time under different cutting strategies in the transition period ($0 < t < 4$ s) as well uniform condition $V_c=45\text{m/min}$ & $f_r=0.25\text{ mm/rev}$ ($t > 4$ s)

As can be seen in Table 6.3 and Figure 6.3, the use of a lower feed rate (condition 4) at the transition period led to better tool life as compared to the reference condition (condition 1), while less tool life was recorded when the higher feed rate was used in the transition period (condition 5). In other words, increasing the feed rate from 0.15 to 0.35 mm/rev in the transition period led to increased flank wear (V_{Bmax}) from 111.0 to 126.0 μm at the end of the transition period ($t = 4$ s), respectively. Similarly, a higher cutting time, more rapid tool wear was shown. Knowing that a V_{Bmax} of 300 μm

is considered as the maximum permitted tool wear size in most of the reported works, ultimately, the permitted cutting time at the V_{Bmax} of 300 μm was dramatically decreased from 38.5 to 15.1 s when the initial feed rate was changed from 0.15 to 0.35 mm/rev, respectively. Similarly, compared with reference mode (condition 1), the permitted cutting time at the V_{Bmax} 300 μm was dramatically decreased from 33.9 to 17.4 s when the cutting speed was changed from 25 m/min to 65 m/min.

In principle, according to reported works in the literature [83, 88], it can be exhibited that the combination of lower levels of feed rate and cutting speed may improve the tool life. The main reason could be attributed to less presence and effects of friction, heat generation, and micro-structural deflections in the first few seconds of machining at lower levels of cutting parameters. However, these phenomena could be reconfirmed upon the adequate experimental characterization of the tool wear morphologies, vibration monitoring, and heat generation monitoring within the transition period.

The experimental results in Figure 6.3 and Table 6.3 also confirm that incorporating small adjustments in cutting conditions at the initial periods of cut may tend to a massive difference in the tool life at higher cutting time. According to experimental results, a direct relationship can be formulated between the initial tool wear and ultimate tool life. This relationship is widely affected by the cutting parameters such as V_c , a_p , and f_r . This phenomenon agrees with the principles of chaos theory, which stated a negligible difference at the beginning of the process may tend to large differences at a higher time. At relatively low cutting speeds, only the mechanically activated wear mechanisms occur (e.g., BUE formation, adhesion, abrasion, etc.). However, increasing cutting speeds and thus cutting temperatures may lead to thermal wear mechanisms (diffusion, oxidation, etc.). In other words, heating the cutting tool results in losing its strength, activating the diffusion and chemical wear mechanisms [85].

6.3.2 Experimental characterization of wear morphology

Figures 6.4 and 6.5 depict the SEM and EDX images for the wear mechanisms observed at different conditions. The wear mechanisms observed were mainly adhesive, abrasive, and BUE on the tool

flank face. The abrasive wear is a result of the presence of hard particles and impurities within the workpiece material [10], such as carbon, nitride, and oxide compounds, as well as built-up fragments. The adhering material became a stable BUE protecting the face. The adhesive wear is due to the high temperature and pressure during cutting, which causes micro welds between the clean and fresh surfaces of the chip and the rake face [27].

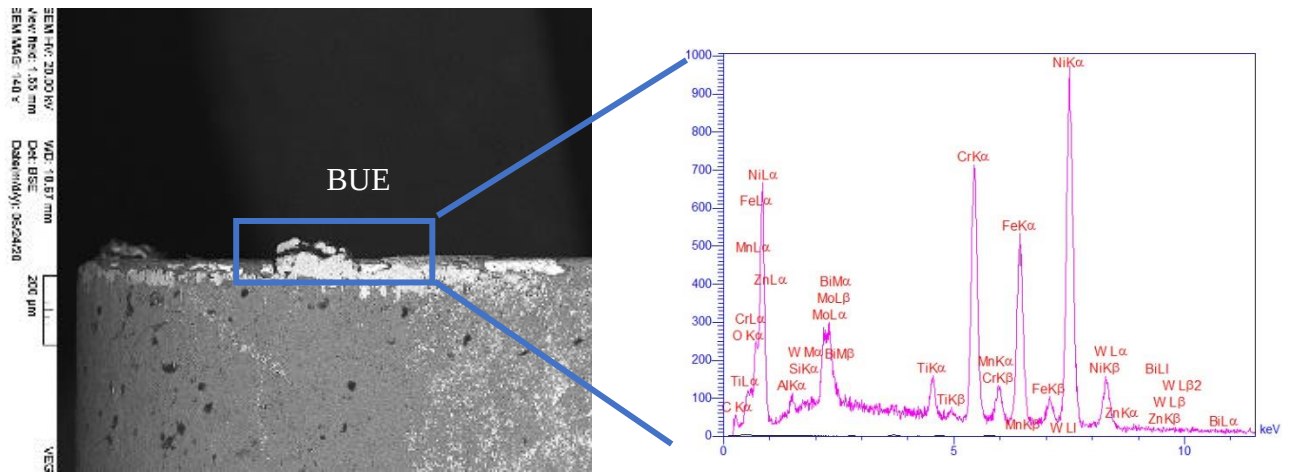
The analysis and assessment of wear morphologies and mechanisms were conducted from SEM and EDX techniques. As shown in Figure 6.4, slight BUE formations were observed on the SEM images of the cutting tools within the transition period. It can be noted that the BUE formation was exclusively observed in the cutting processes with the initial cutting speed of 45 m/min (Figure 6.4, conditions 1), while almost no BUE was detected when the initial cutting speeds of 25 and 65 m/min were employed (Figure 6.4, conditions 2 and 3). On the other hand, the adhesion mechanism was observed in all inserts (Figure 6.4, conditions 1-3). Besides, as shown in Figure 6.4, the flank wear observed in all three workpieces increased by higher initial cutting speed. These results further confirmed that the use of an initial cutting speed 25 m/min resulted in lower flank wear (Figure 6.4, condition 2). Furthermore, upon applying the lower initial cutting speed (i.e., $V_c = 25$ m/min), almost double cutting time was resulted at V_{Bmax} of 300 μm as compared to other tested conditions. In other words, lower cutting speed led to 50% improvement in the tool life as compared to conditions 1 and 3 with higher cutting speed (Figure 6.3). Also, the SEM analysis of cutting tools in steady-state at $t = 26$ s (Figure 6.5) revealed that all the cutting tools experienced severe BUE formation and adhesion. However, BUE formation was much severe under conditions 1 and 3 in comparison with findings related to condition 2. Abrasion was also noticed in the tests. However, due to lack of space, only EDX analysis of BUE formations were presented in this work.

On the other hand, at $t = 4$ s, the use of a lower initial feed rate (0.15 mm/rev, condition 4) and constant cutting speed ($V_c = 45$ m/min) led to less V_{Bmax} (Figure 6.4, condition 4) as compared with those strategies with higher initial feed rates (Figure 6.4, conditions 1 and 5). Moreover, as expected, slight BUE formation was also observed when a higher initial feed rate was used (Figure 6.4, conditions 1 and 5). Besides, at constant cutting speed (45 m/min) and higher initial feed rate, decreased tool life by about 67% was resulted (Figure 6.3). In other words, the lower the

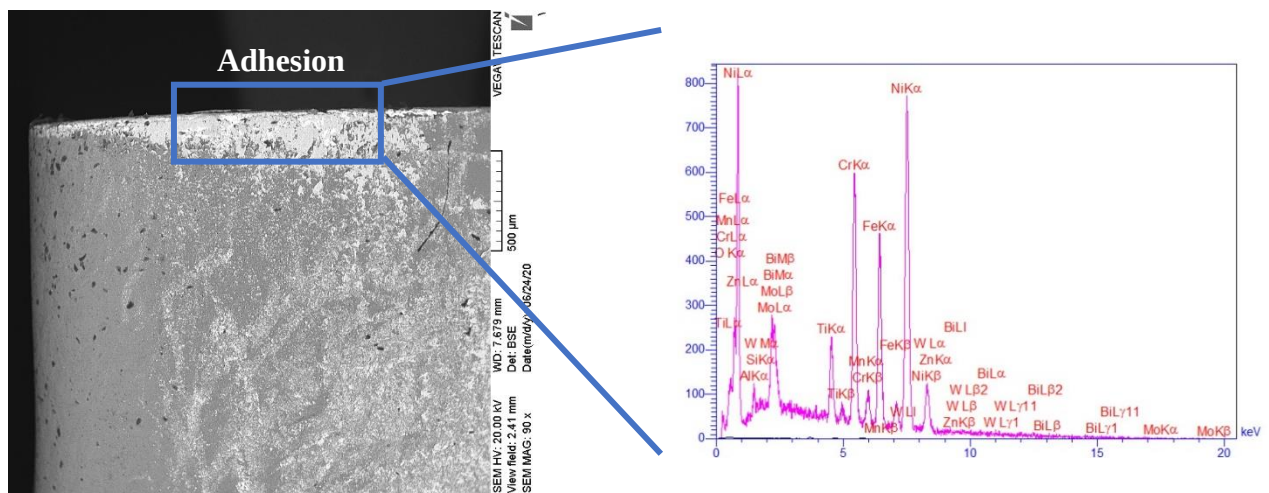
initial feed rate applied, the higher the tool life achieved. Also, a great extent of BUE formation, adhesion, and abrasion can be observed in the steady-state mode ($t = 26$ s), which can be observed in Figure 6.5 under conditions 1, 4, and 5. However, the degree of BUE formation was noticeably higher under the conditions 1 and 5 in comparison with that of occurred under condition 4.

To achieve a better insight into the wear mechanisms on the cutting tools, EDX analysis was conducted, and the associated results were presented in Figures 6.4 and 6.5. The obtained data from EDX analysis of the cutting tool in the transition time ($t = 4$ s) at the constant feeding rate of 0.25 mm/rev and the initial cutting speed of 25 m/min revealed that the coating layer of the cutting tool was almost preserved (Figure 6.4, condition 2). In other words, the degree of adhesion and diffusion were negligible when lower initial cutting speed was used. Besides, the peaks corresponded to various phases of Ni, Cr, and the other major elements existing in the structure of workpieces were observed in EDX results, indicating that adhesion occurred in the transition period when the initial cutting speed was adjusted to 25 m/min (Figure 6.4, condition 2). Similar observations were made when the initial feed rate of 0.15 mm/rev at the constant cutting speed of 45 m/min was applied (Figure 6.4, condition 4). Also, through the obtained EDX results, one might conclude that the coating layers (mainly consisting of Ti, Al, etc.) of cutting tools were slightly damaged and/or completely removed under all conditions. In other words, the peaks related to Ti and Al elements were omitted at the end of the transition period under all conditions, while the peaks attributed to Ni, Cr, Fe, etc., were appeared.

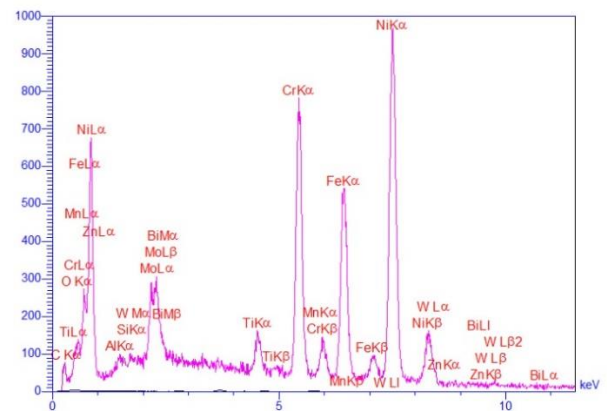
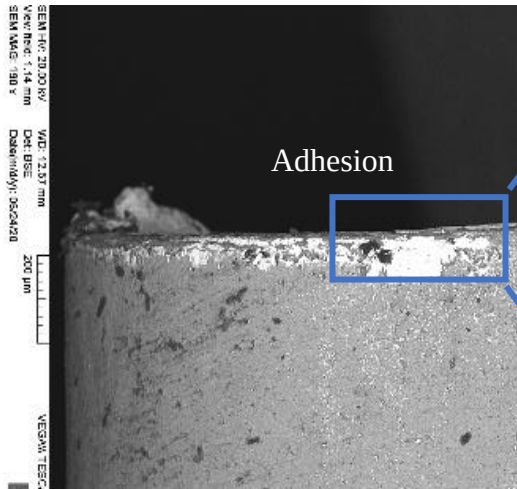
The EDX results obtained at steady state ($t = 26$ s) reveal that the cutting tools used in the cutting process under conditions 1, 3, and 5 lost their external coating layers. The presence of peaks corresponding to different phases of Ni, Cr, Fe implied the effectiveness of the adhesion mechanism, as mentioned earlier. The BUE formation, adhesion, and abrasion occurred with a lower degree when the cutting process was carried out under conditions 2 and 4. Ultimately, in the case of performing the cutting process under condition 5, the abrasion mechanisms were also observed due to the presence of the peak corresponding to W (Figure 6.5, condition 5).



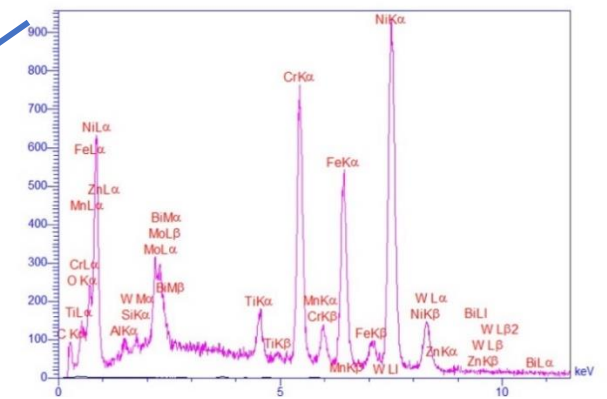
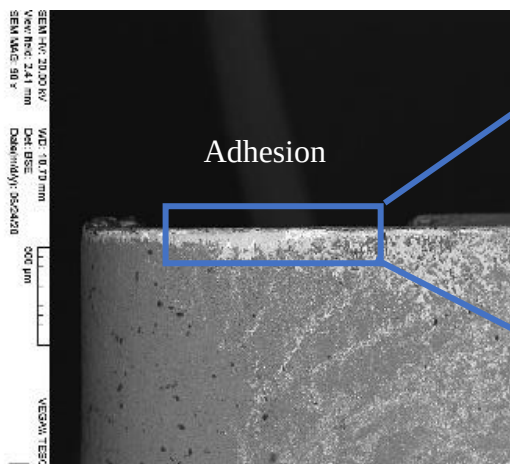
Condition 1: $V_c = 45$ m/min ; $f_r = 0.25$ mm/rev



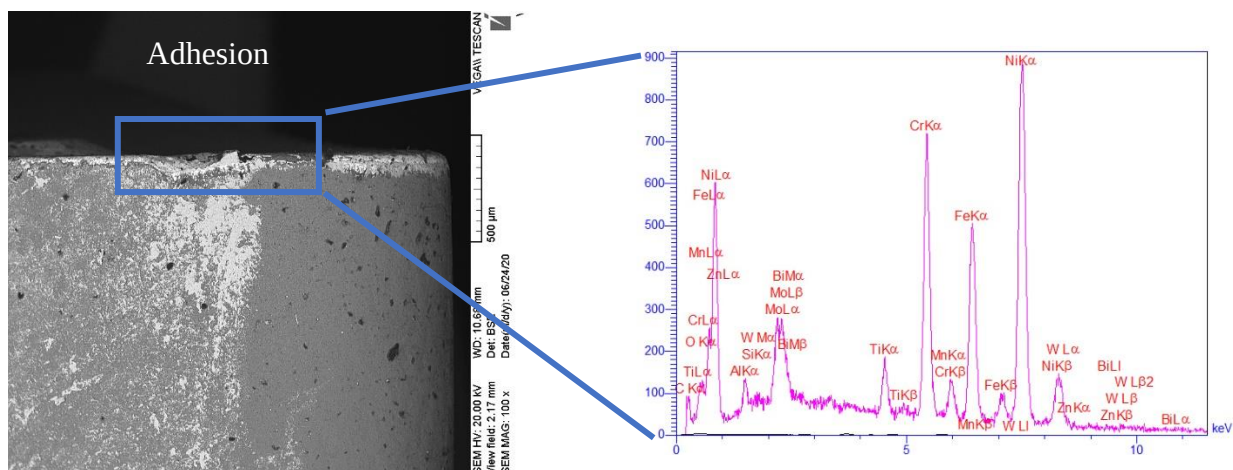
Condition 2: $V_c = 25$ m/min ; $f_r = 0.25$ mm/rev



Condition 3: $V_c = 65$ m/min ; $f_r = 0.25$ mm/rev

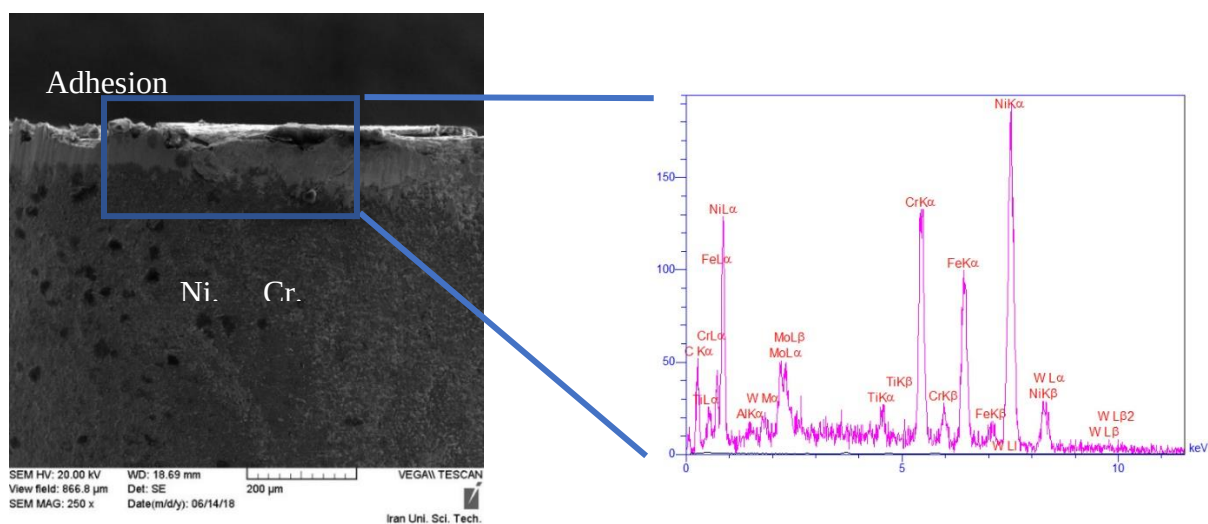


Condition 4: $V_c = 45$ m/min ; $f_r = 0.15$ mm/rev

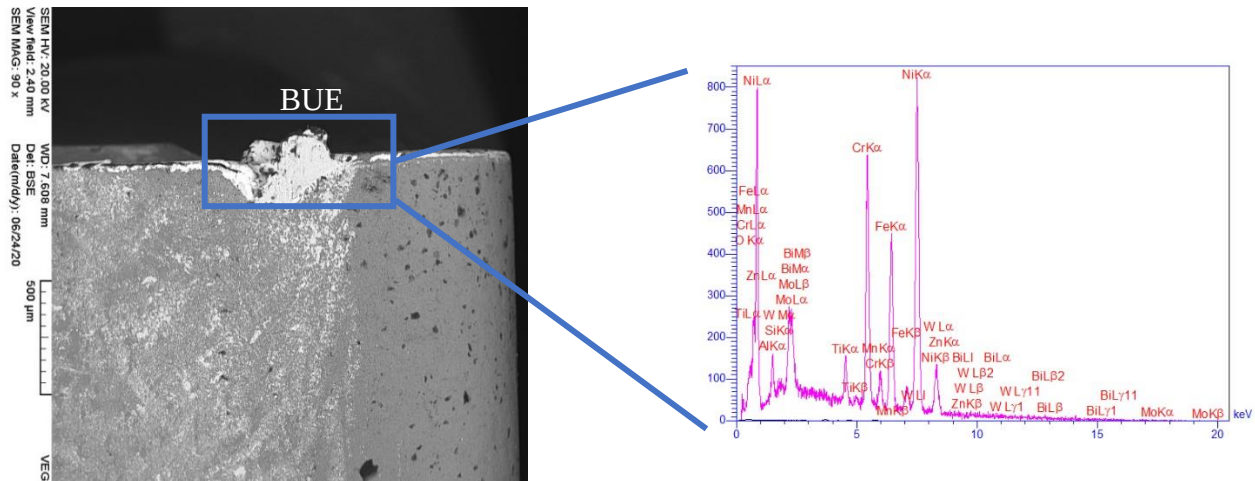


Condition 5: $V_c = 45$ m/min ; $f_r = 0.35$ mm/rev

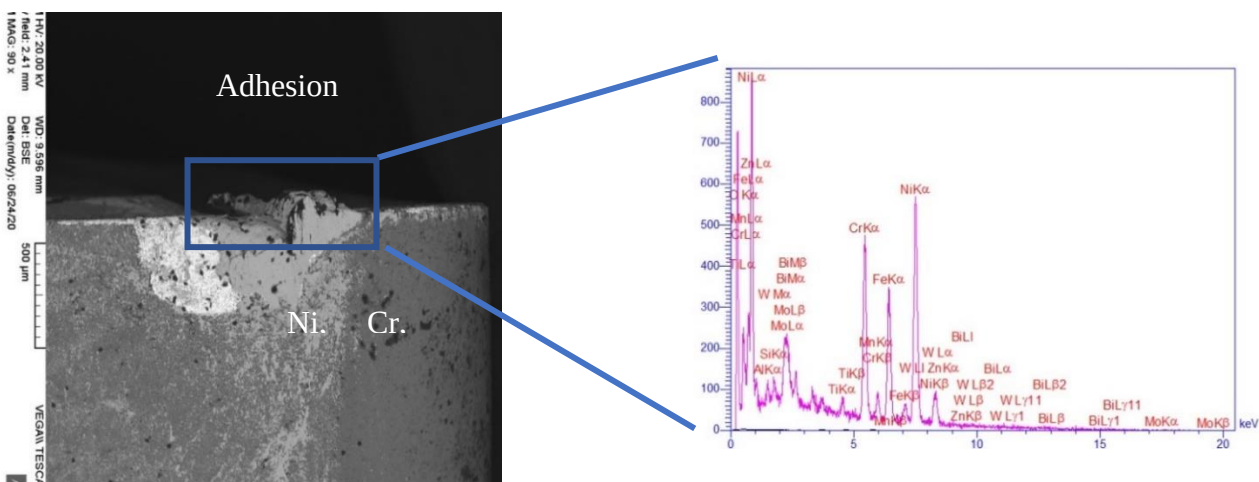
Figure 6.4. Initial tool wear mechanism on the flank face at $t = 4$ s under various cutting conditions



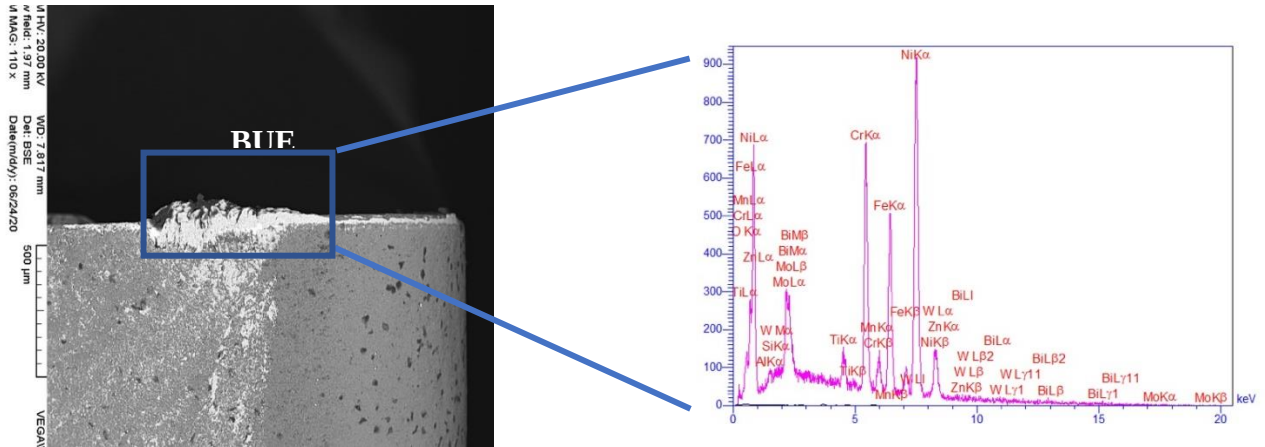
Condition 1: $V_c = 45$ m/min ; $f_r = 0.25$ mm/rev



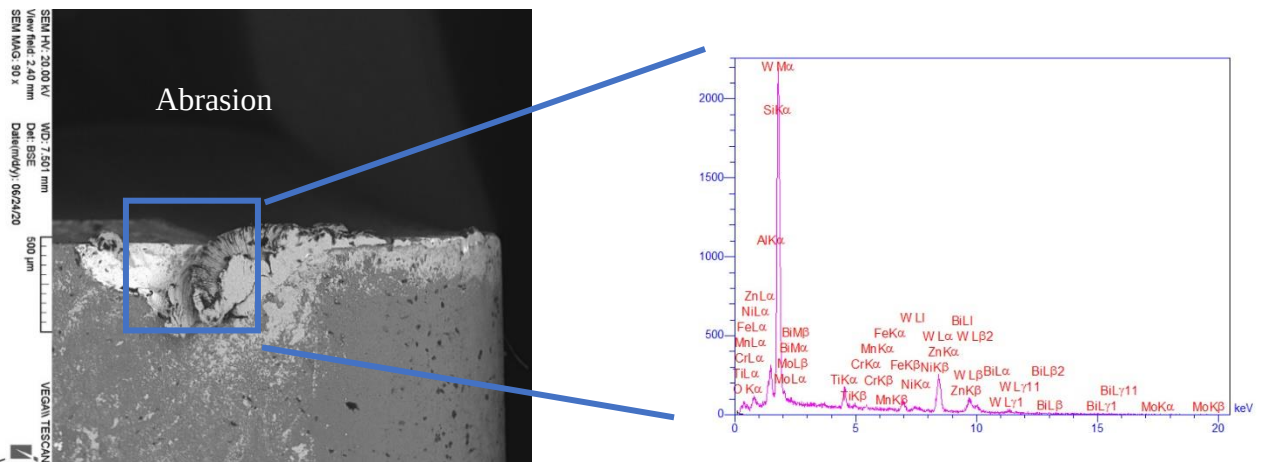
Condition 2: $V_c = 25$ m/min ; $f_r = 0.25$ mm/rev



Condition 3: $V_c = 65$ m/min ; $f_r = 0.25$ mm/rev



Condition 4: $V_c = 45$ m/min ; $f_r = 0.15$ mm/rev



Condition 5: $V_c = 45$ m/min ; $f_r = 0.35$ mm/rev

Figure 6.5. Initial tool wear mechanism on the flank face at $t = 26$ s under various cutting conditions

6.4 Conclusion

The literature review emphasizes that inadequate studies are available about factors governing initial tool wear morphology and size (V_{Bmax}) when machining Inconel 718. No work was found on investigating the correlation between the appeared initial tool wear within the transition period and

ultimate tool life when machining hard to cut materials, in particular Inconel 718. Therefore, in this work, the tool wear progress and tool life were investigated based on varying the initial conditions at the transition period, set at four seconds. As noted earlier, the transition point was discovered from the previous works by the authors. After the transition point, similar cutting conditions as the reference condition were used.

The obtained experimental results revealed that the cutting speed was the most effective cutting parameter to the flank wear size, followed by feed rate.

Both adhesion and abrasion wear was observed during the cutting process via the various mechanisms attributed to the thermo-mechanical effects. This observation can be stated in terms of an increment in the cutting force and temperature, resulting in micro-scale welds formation at the tool-workpiece interfaces. However, such phenomena could be improved by applying lower initial cutting speed and lower initial feed rate.

The transition period was defined in this work, and the turning tests with various cutting conditions were conducted. Cutting parameters were carefully chosen in compliance with the instructions made by the manufacturer of cutting tool, Seco Inc.

Five different cutting conditions were used in the initial period of cut, the so-called transition period. After the transition point 4 s, similar cutting conditions as the reference condition was undertaken within the specific time intervals up to 56 seconds. The tool wear morphology and size were recorded and analyzed in each case.

The following conclusions may be taken from the findings of this study:

1. Less initial tool wear was observed under lower cutting speed ($V_c = 25$ m/min) and feed rate ($f_r = 0.15$ mm/rev).
2. In most cases, BUE and adhesion were predominant wear mechanisms at the transition period ($t < 4$ s).
3. In all cases, the BUE was exhibited as the major wear mode in the cutting conditions at the steady state, while both adhesion and abrasion were observed. Such observations could be

attributed to the severe interactions between the hard particles of the Inconel 718 material and the cutting tool.

4. When the V_{Bmax} of 300 μm at constant cutting speed (45 m/min) was achieved, increasing the initial feed rate decreased the tool life by about 67%.
5. Applying the lower initial cutting speed, i.e., 25 m/min, increased the tool life by about 50% when the insert reached the V_{Bmax} of 300 μm in comparison with those at higher initial cutting speeds.
6. In general, it could be concluded that using optimum levels of cutting parameters in the transition period of the cutting process may lead to prolonging the tool life.

The findings in this work can shed light on the investigation of the effect of the initial condition and initial behavior on the tool life for further development and progress. Besides, the results obtained in this work can pave the way to new cutting strategies that emphasize tool life improvements in broader industrial sectors and processes.

CHAPTER 7 GENERAL DISCUSSION

The following section provides a general discussion of this thesis, highlighting the most critical findings from each research phase while allowing us to present the relationships between each projected objective. As noted earlier, the machinability of Inconel 718, a difficult-to-cut superalloy with extensive applications in numerous industrial sectors, is very important. Amongst machinability attributes, a thorough knowledge of factors governing tool life when machining Inconel 718 is critical. Hence, this study assessed the tool wear morphology and size and the effects of cutting parameters on the initial tool wear and ultimate tool life. The following lines present the relationship between findings and research objectives.

Inconel 718 has low thermal conductivity, high chemical reactivity, and high strength, indicating the most difficult challenges in machining. High levels of cutting forces, temperature, and rapid tool wear are typical observations in conventional machining (e.g., turning and milling) of hard-to-cut materials, such as Inconel. Suitable cutting parameters and advanced tools with high thermal stability and wear resistance are recommended to minimize these non-desirable phenomena. Therefore, the cutting speed and feed rate were improved during this work to reduce tool wear and improve the tool life.

The first part of this section is devoted to findings related to the effect of initial cutting conditions (i.e., the initial feed rate and initial cutting speed) on the tool wear behavior and ultimate tool life when machining Inconel 718 under dry conditions. The results revealed that the cutting speed was the most critical factor governing the flank wear size, followed by feed rate. Besides, adhesion and abrasion wear modes were observed during the cutting process, implying various spontaneous wear mechanisms resulting from the thermo-mechanical effects on the cutting tool. The present study fills a notable gap in the existing literature which mostly focus on different material, [71, 89] by investigating the nuanced aspects of tool wear morphology and its implications for tool life in Inconel 718 machining. Despite the widespread industrial importance of this material, previous research studies have overlooked the specific factors governing initial tool wear morphology and its relationship with ultimate tool life, particularly during the transition period between initial

cutting conditions and steady-state operation. To address this gap, our study innovatively explores the progression of tool wear and life through a systematic variation of initial cutting conditions. Focusing on the four-second transition period identified from previous studies which focus on different material or different transition time [71, 89], experiments were planned to explain the complex interaction between initial tool wear characteristics and subsequent tool life enhancement. The chosen transition period, $t=4$ s, was consistent across all cases investigated. After the transition period, similar cutting conditions were used as the reference condition. In experimental studies, varying cutting speed and feed rate while keeping other parameters constant may allow the researchers to isolate their individual effects on tool wear. The observation that cutting speed has a more significant impact on flank wear size than feed rate is consistent with the understanding that temperature-related wear mechanisms play a predominant role in tool degradation during machining, especially for materials with low thermal conductivity and high chemical reactivity, such as Inconel 718.

Furthermore, the specific conditions of the experimental setup, such as tool geometry, cutting fluid application, and workpiece material properties, can influence the relative importance of cutting speed and feed rate on tool wear. However, in machining Inconel 718 under dry conditions, the experimental findings suggest that optimizing cutting speed is paramount for minimizing flank wear and enhancing tool life. The destructive effects on the cutting tool can be reduced under lower initial cutting speed and feed rate levels. An investigation was conducted into the influence of initial cutting parameters on tool wear modes and ultimate tool life. By systematic variation of five different initial conditions, this work could determine the precise effects of these parameters on the observed wear mechanisms and overall tool life expansion. The results provide valuable insights into the practical implications of optimizing initial cutting conditions for mitigating tool wear and enhancing tool life in Inconel 718 machining processes.

7.1 The originality of the work and contribution to knowledge

Firstly, the existing knowledge has not yet been applied to many industries and workpiece classes. This forms a promising field for applied research with immediate effects on the industry. Secondly, the broader issue of edge and part conditions and cleanliness is becoming increasingly more

focused on mechatronics products, micro-products, and products with very high-performance demand; all need to be technically clean and without edge disturbances. Developing and applying the technologies necessary for clean machining of hard-to-cut materials, in principle, Inconel 718 still has considerable potential for applied research studies [90]. The future of industrial research studies on various aspects of machining processes monitoring and optimization are anticipated to be directed towards numerical and statistical control theories as well as intelligent systems, benefiting from networked control systems, expert systems, based artificial intelligence (AI) approaches, such as neural networks, ANFIS, and many other approaches.

Therefore, it is expected that this research will provide some new aspects and contribute to knowledge in the field:

1. For the first time, a detailed analysis was performed to investigate the tool wear mechanisms during the turning of NBSA.
2. The tool wear morphology was investigated in the initial moments when turning NBSA. This part can be expanded to drilling and milling under various cutting and lubrication conditions.
3. The effects of initial tool wear on ultimate tool life when machining NBSA were studied. This can be expanded in wider scopes under various materials and cutting conditions.
4. Tool life prediction and optimization based on statistical theories and algorithms have not been studied broadly, which remains for future work.

7.2 Novelty

Conducting the integration of experimental characterization tool wear morphology in the initial moment and cutting operation, parametric study for adequate selection of cutting parameters, and modeling the tool life during the machining of NBSA are the principal aspects of originality in this project. The literature analysis allows us to note that no survey considers the problem as a whole. The published articles illuminate a little about the factors governing initial tool wear and the

relationship between initial tool wear and the ultimate tool life when machining NBSAs. Therefore, the following lines can be used to present the novelty aspects of this research project:

- a) No work was found on factors governing initial tool wear when machining nickel-based superalloys.
- b) Tool wear modes in the initial moments were studied.
- c) The effects of initial tool wear on the ultimate tool life were studied.
- d) Tool life prediction followed by optimization based on statistical theories and algorithms has not been reported yet and was somehow studied in this work. Additional investigations can be conducted on a broader scope.

7.3 Future works

A recent literature review suggests the following future research recommendations [8, 91]:

- Developing advanced cutting tool materials and coatings capable of withstanding the high temperatures and stresses generated during Inconel 718 machining.
- Optimization of machining parameters using advanced modeling and simulation techniques like finite element analysis (FEA) and artificial neural networks (ANN) to achieve the desired surface finish and dimensional accuracy.
- Investigation of the effects of various cooling and lubrication strategies on cutting forces, tool wear, and surface quality during Inconel 718 machining.
- Research and development of hybrid machining processes such as laser-assisted, electrochemical, and ultrasonic to improve machining efficiency and tool wear.
- Research into the effects of various post-machining treatments, such as heat treatment, shot peening, and surface coating, on the surface integrity and fatigue life of machined Inconel 718 components.

CHAPTER 8 CONCLUSION

This chapter is dedicated to the significant observations made in this study. In this venue, the enhancement of knowledge and the development of technologies and their restrictions and limitations were studied.

It is worth mentioning that the effects of cutting parameters, including cutting speed and feed rate, on the initial tool wear mechanism, morphology, and size when machining Inconel 718 were studied in this dissertation. As a result, it was revealed that these parameters should be considered as the main machining factors governing the initial wear modes, flank wear modes in both initial moments of cut and exhausted tool, and finally, ultimate tool life. Consequently, the initial levels of cutting parameters seem to have undoubtful effects on the ultimate tool life. Hence, the effects of initial cutting conditions considering various initial cutting speeds ranging (100-200 or 25-65 m/min) and feed rates ranging (0.15-0.35 mm/rev) on the ultimate tool life during the machining of Inconel 718 were also investigated.

8.1 Initial tool wear behavior when machining Inconel 718

Knowing that tool wear is one of the main machinability attributes, special attention was paid to assessing the effects of cutting parameters on the initial tool wear. As a result, various cutting parameters were selected according to recommendations from the cutting tool manufacturer SECO Inc. and local manufacturing sectors to evaluate the cutting performance better. The general conclusions drawn from the experiment are as follows:

- At relatively high cutting speeds (e.g., 150 m/min), three different wear zones were identified on the flank and rake surfaces of the carbide inserts. The worn surfaces were covered with Ni, Cr, and Fe, which are the main elements of the tested material, and they adhered to the worn surface of the inserts. Consequently, adhesion was found in most of the cutting tests performed.

- The detected amounts of Al with the highest weight percentage seemed to decrease slightly at lower cutting speed and cutting time. This phenomenon may be attributed to higher cutting speeds and feed rates when the removal of the external coating layer of the cutting tool is demanded.
- The detected amounts of Ni, Cr, and Fe were increased at higher cutting speeds and cutting times. This phenomenon can be attributed to the generation of excessive temperature in the contact layer, which may expedite the migration of the work part elements to the cutting tool.
- It can be stated that cutting speed and feed rate are the main machining factors affecting flank wear when carbide inserts are used. In fact, at higher levels of feed rate (e.g. 0.35 mm/rev), non-uniform and rapid steady-state regions were observed. This observation reveals that as well as cutting speed, increased levels of feed rate accelerate not only the tool wear but also the tool wear morphology, and ultimately, the tool wear profile may change.

8.2 Effects of initial cutting conditions and transition point on ultimate tool life when machining Inconel 718

The literature search reveals preliminary studies on factors governing the initial tool wear morphology and size (V_{Bmax}) when machining Inconel 718. However, no work investigated the relationship between the initial tool wear within the transition period and the final tool life when machining difficult-to-machine materials, particularly Inconel 718. Therefore, in this work, the tool wear progress and life were investigated based on the variation of initial conditions in the transition period, set at four seconds according to preliminary studies performed in the first phase of this dissertation. In addition, cutting conditions similar to the reference condition were used to confirm the transition point. The recorded experimental results exhibited that cutting speed was the most influential parameter on the magnitude of flank wear, followed by feed rate.

Both adhesion and abrasion were observed during the cutting process through the various mechanisms attributed to the thermomechanical impacts. The presence of both wear morphologies could be enlarged at higher levels of cutting speed, which tends to increase the thermomechanical effects and intensify the formation of microscale welds at the tool-workpiece interfaces. Nevertheless, it was found that these phenomena could be improved at a smaller initial wear size. This needs a clear understanding of the transition point and cutting factors affecting the wear size and morphologies at the transition time. This work could successfully define the transition time, and turning tests were performed with different cutting conditions. The cutting parameters were set following the instructions of the cutting tool manufacturer, Seco Inc.

Five different cutting conditions were used in the initial period of the cut, called the transition period. After the transition point 4 s, cutting conditions similar to the reference condition were performed within the specific time intervals of 56 seconds. Each case recorded and analyzed the morphology and magnitude of tool wear.

- Initial tool wear was lower at lower cutting speed ($V_c = 25$ m/min) and feed rate ($f_r = 0.15$ mm/rev).
- In most cases, BUE was identified as a phenomenon alongside adhesion, which were the predominant wear mechanisms observed during the transition period ($t = 4$ s).
- In the steady-state cutting conditions, BUE was identified as a phenomenon, while both adhesion and abrasion were consistently observed. These observations could be attributed to the strong interactions between the hard particles of the Inconel 718 material and the cutting tool.
- When the V_{Bmax} of $300\text{ }\mu\text{m}$ was reached at constant cutting speed (45 m/min), increasing the initial feed rate decreased the tool life by around 67%.
- Applying the lower initial cutting speed, i.e., 25 m/min, increased the tool life by about 50% when the insert reached the V_{Bmax} of $300\text{ }\mu\text{m}$, compared to those at higher initial cutting speeds.

- In general, it can be concluded that using optimum cutting parameters in the transition phase of the cutting process can lead to a better life for the ultimate tool.

The knowledge gained in this work can study the initial condition and behavior influence on the service life for further development and progress. Moreover, the results achieved in this work can pave the way for new machining strategies focusing on the development of tool life in broader industrial sectors and processes.

In addition to these findings, the results clearly demonstrate significant potential for increasing tool life and boosting machining productivity when using optimized cutting parameters. By applying a lower initial cutting speed of 25 m/min and a feed rate of 0.15 mm/rev, the tool life was increased by approximately 50%, compared to higher cutting speeds, when the insert reached a VBmax of 300 μm . This considerable extension of tool life not only reduces the frequency of tool changes but also increases machining uptime, leading to a substantial improvement in overall productivity. Furthermore, the extended tool life directly translates into economic benefits for machining superalloys like Inconel 718, as fewer tool replacements and less downtime result in cost savings. The optimization of cutting parameters could enhance tool performance, reduce material waste, and ultimately improve the economic efficiency of manufacturing processes involving difficult-to-machine materials.

CHAPTER 9 REFERENCES

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CHAPTER 10 APPENDIX A

CONFERENCE 1 Initial Tool Wear Mechanism in Dry And Lubricated Turning of Inconel 718

Morvarid Memarianpour¹; Seyed Ali Niknam² Marek Balazinski¹ Sylvain Turenne¹

¹ Mechanical Engineering Department, Polytechnique Montreal, Canada.

² Sustainable Manufacturing Systems Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.

morvarid.memarianpour@polymtl.ca; saniknam@iust.ac.ir; marek.balazinski@polymtl.ca; sylvain.turenne@polymtl.ca

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Abstract

Tool wear mode and life are considered as critical machinability attributes. Three distinctive regions of tool wear, mainly known as initial wear, steady-state wear, and accelerated wear are understood to a large extent. The effects of cutting parameters on the initial tool wear have received less attention as compared to other two regions. Previous works by authors revealed that the cutting 4s could be considered as the transition period between initial and steady-state wear in turning of Inconel 718 with coated carbide tools. It is believed that adequate selection of cutting parameters in initial periods of cutting operation may tend to optimize the entire tool life. Therefore, in order to assess the effects of cutting parameters on tool wear morphology and tool wear modes at transition time 4s, various levels of cutting speed, constant levels of feed rate and depth of cut were used in dry and lubricated turning Inconel 718, which is generally considered as one of the most difficult to cut materials. The scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) were used for tool wear measurements as well as microstructural evaluation of the tool wear mode. Based on experimental observations, despite the lubrication mode and cutting speed used, adhesion and abrasion were found in almost all cutting conditions. It is believed that abrasion is initially taken place and removed the coated layer of the tool. Following this phenomenon, the adhesion is also taken place. The variation of cutting speed does not widely

change the tool wear results in transition time 4s. Moreover, although negligible, higher flank wear results were found under dry conditions.

Keywords: Tool wear; Inconel 718; Turning; Transition time; Machinability.

1. Introduction

Machining of superalloys is associated with high mechanical stresses and surface structure variations at high temperatures. Amongst, the Inconel 718 is generally known as one of the most difficult to cut materials due to its high hardness and prominent strength at elevated temperatures [1-3]. Inconel 718 is still known as one of the most highly used materials in aerospace and automotive industries. In addition, it can be highly used in numerous applications such as industrial gas turbines, space vehicles, rocket engines, nuclear reactors, submarines, stream production places, petrochemical devices, hot tools and glass industries [1, 4, 5].

Despite wide applications as aforementioned, machinability of Inconel alloys at high speed, in particular, Inconel 718, as well as an adequate selection of cutting parameters and suitable cutting tools are considered as delicate subjects. According to a review of the literature, the effects of machining parameters on steady-state wear period have been very well understood. However, surprisingly, the mechanism of initial tool wear, as well as effects of machining parameters on this phenomenon, have not been studied clearly. In fact, it is believed that accurate understanding of the initial tool wear mechanism and governing factors on initial tool wear rate may lead to better control and optimization of the machining process which eventually may lead to extended tool life [6-9] when machining hard to cut materials such as titanium metal matrix composites (Ti-MMCs).

As well as an accurate selection of cutting parameters, adequate selection of cutting tools play a significant role in machining performance. Several studies reported the machining of superalloys using ceramic tools [10]. However, at relatively low cutting speed, carbide tools are still considered as the prime choice when machining superalloys, including Inconel 718 [10-16]. According to the literature, the mechanism of initial wear in carbide tools within medium to high levels of cutting

speed is yet to be investigated. Furthermore, limited works were found on the effects of cutting parameters on initial tool wear mechanism when machining Inconel 718. In fact, the cutting time when the initial wear period is terminated and steady-state period may begin is referred to transition time. Previous works by authors [17] revealed that the cutting time 4s could be considered as the transition time when cutting Inconel 718 under similar feed rate and depth of cut as used in this work. Therefore, in order to assess the effects of various levels of cutting speed on the tool wear morphology as well as flank wear (V_{Bmax}) under both lubricated and dry conditions, the transition time 4s was used as the transition time.

2. Experimental Plan

The work part was a 140-mm diameter cylindrical Inconel 718 comprised of Ti-6Al-4V, 10-12% of TiC particles with uneven shapes and 10-20 μ m size. The CNC-MAZAK Nexus 200 was used in the turning tests. All cutting tests were conducted on the PVD carbide inserts CNMG 432-MF4 TM2000 coated with TiCN/Al₂O₃, manufactured with Seco (Figure1). This is to note that each insert's edge was used only in a single machining test. During this phase of experimental works and in order to observe the effects of different levels of cutting speeds (V_c) on the flank wear (V_{Bmax}), ten levels of cutting speed (25, 35, 45, 55, 65, 80, 100, 125, 175 & 200 m/min) were used at cutting time 4s under constant depth of cut 1 mm and feed rate 0.25 mm/rev within dry and lubricant condition. As aforementioned, to achieve a better understanding of the tool wear mechanism and to characterize the microstructural features of the wear region, SEM/EDS measurements were conducted (Figure 2). The V_{Bmax} was used as the measure of the flank wear on the insert flank side.

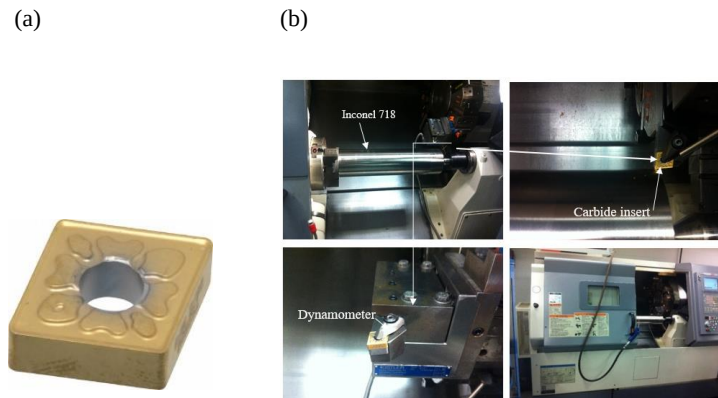


Figure 1. (a) The cutting insert used; (b) The machining set up used

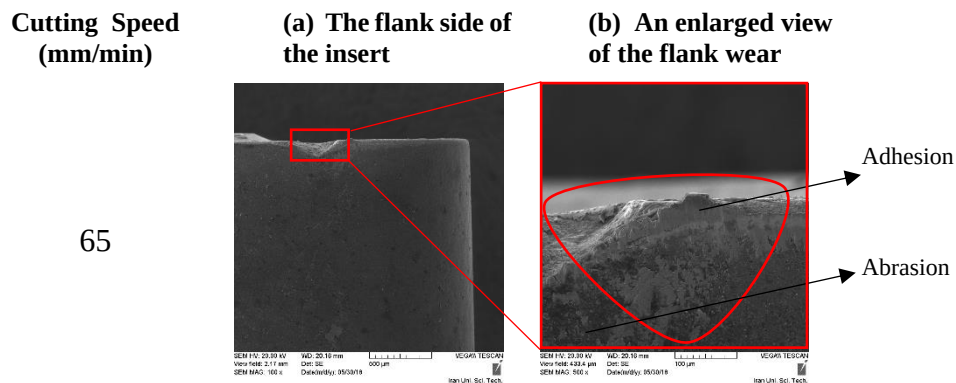
Table 10 Chemical composition of Inconel 718 alloy(wt%)

Element	(%W)	Element	(%W)
Ni	53.4	Si	0.12
Cr	18.8	Mn	0.07
Cb	5.27	Cu	0.07
Mo	2.99	C	0.03
Ti	1.02	P	0.01
Al	0.50	Fe	Balance
Co	0.17		

3. Results and discussions

The overview of the flank wear of the cutting tools used in machining operations are presented in Figures 2 and 3. Based on the experimental measurements by SEM/EDS, it can be expressed that despite the cutting speed used, the adhesion was found in all cutting condition. The chemical compositions of the highlighted area consist of mainly Al, Ti, Cr, Fe, Ni, Mo and which are

considered as the elemental compositions of the cutting tools and the work part used (Table 1). Presence of Ti is the evidence of the migration of the work part material to the cutting tool, which tends to generate adhesive layer on the flank side of the tested inserts. According to experimental measurements of V_{Bmax} (Table 2), expect minor cases at lower cutting speed where elevated V_{Bmax} is observed, the variation of cutting speed does not widely change the V_{Bmax} . The elevated V_{Bmax} at higher speed may attributed to edge hardening. In fact, at low cutting speed where constant cutting time 4s is used, less cutting length is resulted. Consequently, the chip formation may not happen adequately and it may stick to the work part edge when the cutting tool leave the work part. The non-separated chip may melt and attach to the work part and consequently higher V_{Bmax} is observed in the next experiment which need to cut more materials on the cutting edge. On the basis of experimental characterization (Figures 2 and 3). According to Table 2, lower percentage of tungsten (W) and higher percentage of Ni in the measured worn area of the cutting tools when higher levels of cutting speed is used confirm that worn area is mainly surrounded by Ni, which is the main element of the work part material. Lower percentage of the W at lower cutting speed indicates that at initial period of cut, abrasion is initially taken place which eventually removed the coated layer. Following this phenomenon, the adhesion is also taken place and the worn area is surrounded by presence of adhesive layers as well as built up edge. Despite the lubrication modes used, this phenomenon is strengthen at higher cutting speed used. The matrix behavior and hydrostatic pressure of the cutting edge play prominent roles at low levels of cutting speeds. In this case, the cutting tool acquires sufficient hardness to prevent abrasion and resists against the deflection forces.



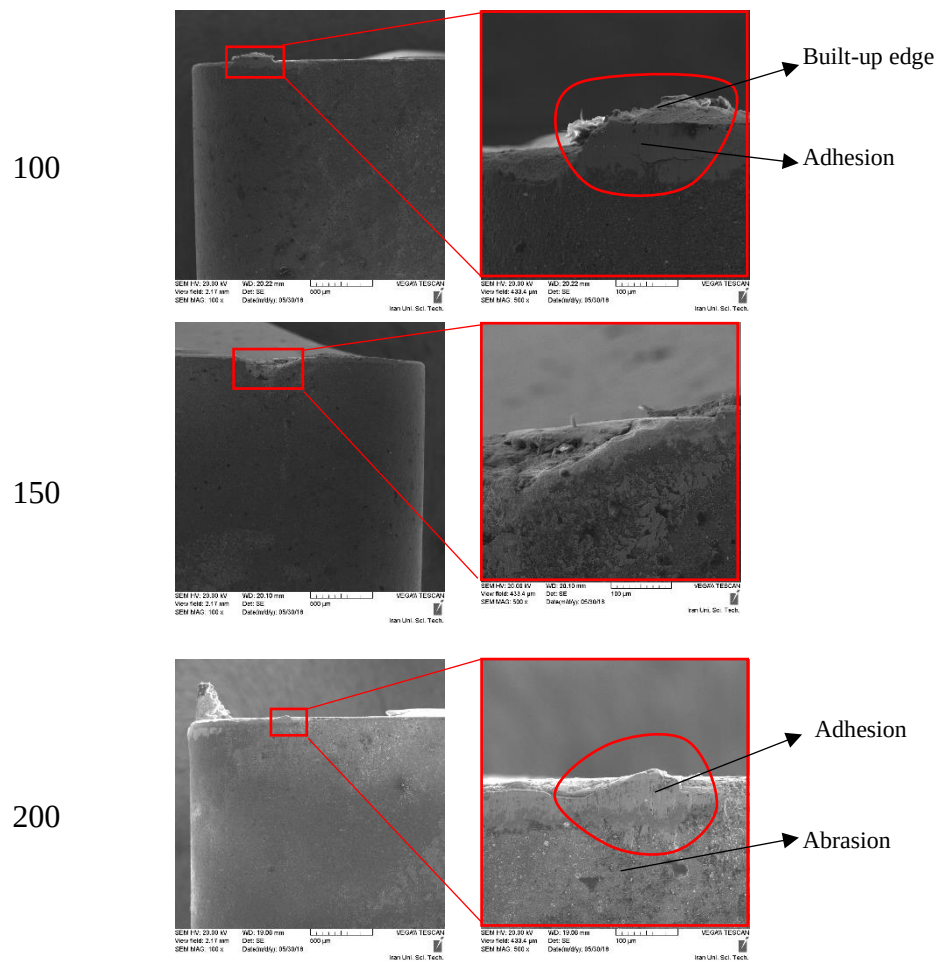


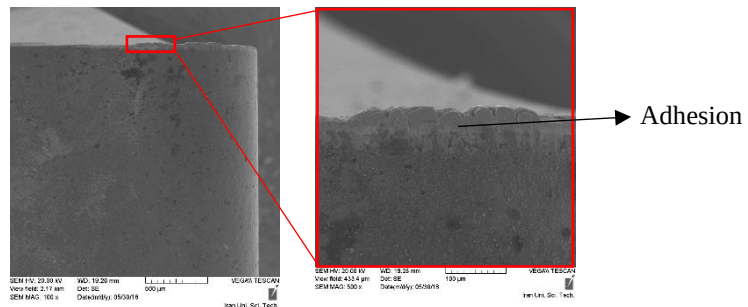
Figure. 2 SEM micrographs of flank face and tool wear region under dry condition

**Cutting Speed
(mm/min)**

**(a) The flank side of
the insert**

**(b) An enlarged view
of the flank wear**

25



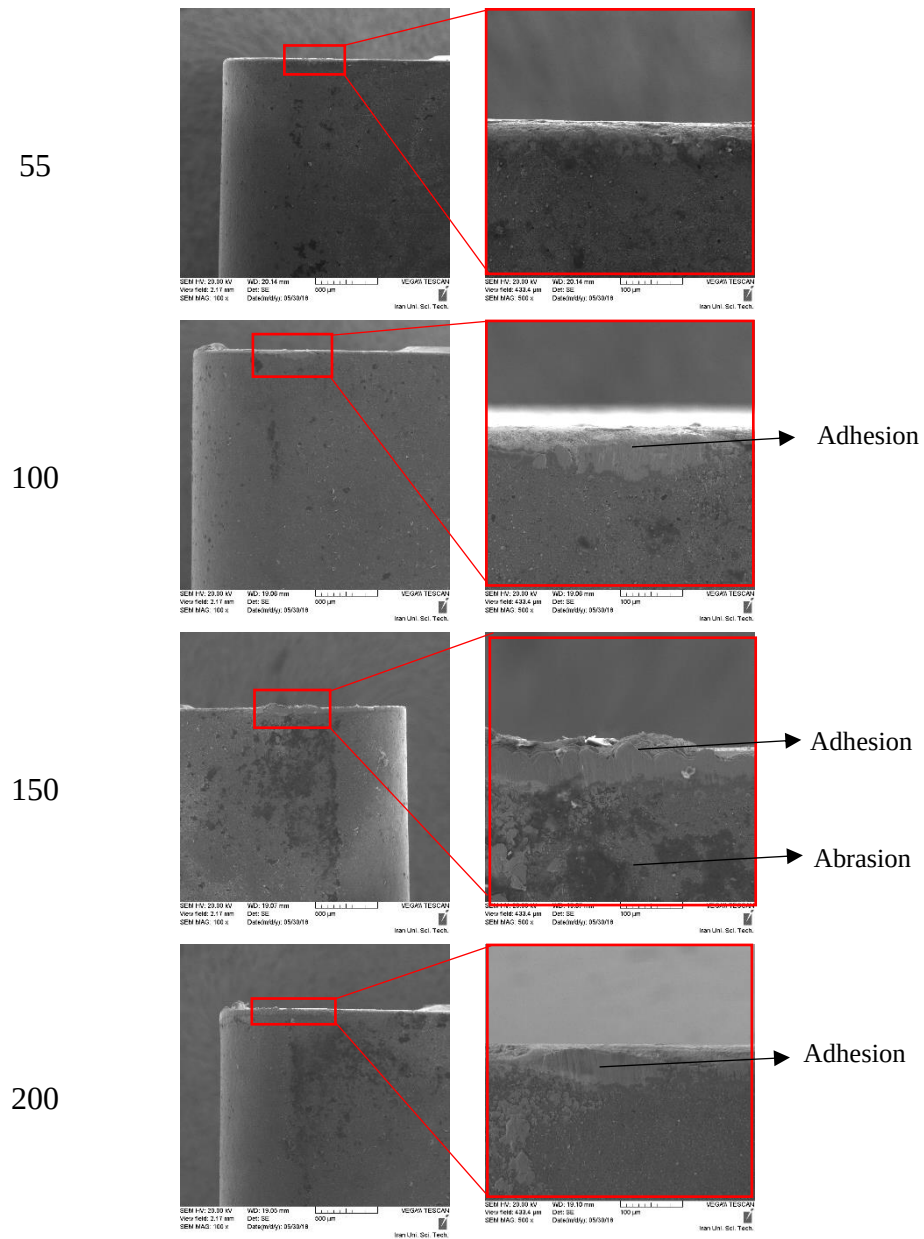


Figure 3 SEM micrographs of flank face and tool wear region under lubricated condition

Table 2. Flank wear results under dry and lubricated conditions

Cutting speed (m/min)	V_{Bmax} (mm)	
	Dry mode	Lubricated mode
25	X	0.06
35	X	0.05
45	X	0.06
55	0.33	0.05
65	0.13	0.10
80	0.17	0.19
100	0.09	0.09
125	0.29	0.10
150	0.19	0.08
175	0.09	0.12
200	0.10	0.06

Table 3 Variation of elemental composition on flank face wear (W%) at constant depth of cut 1mm and feed rate 0.25 mm/rev under at Cutting time 4s and different speed (a) Dry condition; (b) Lubricant condition

W%	Cutting Speed (m/min)			
	65	100	150	200
Al	3.35	2.32	2.7	9.72
Ti	1.8	2.06	1.7	9.59
Cr	17.23	18.21	12.05	15.45
Fe	17.23	16.91	10.76	14.8
Ni	45.34	50.28	50.38	40.97
Mo	11.54	7.81	9.5	7.2
W	3.52	2.41	2.91	2.27
Total	100.0	100.0	100.0	100.0

(a)

W%	Cutting Speed (m/min)				
	25	55	100	150	200
Al	13.92	12.43	5.48	1.82	4.2
Ti	15.58	14.41	5.43	1.27	6.24
Cr	10.12	9.15	14.35	18.41	17.14
Fe	9.23	9.42	13.41	18	15.96
Ni	27.21	27.31	39.36	50.92	46.84
Mo	7.95	4.93	6.63	9.57	7.66
W	25.99	22.34	15.34	0	1.96
Total	100	100.0	100.0	100.0	100.0

(b)

4. Conclusion

In this study and to achieve the best understanding of the correlation between transient time and tool wear morphology and ultimate tool life, a wide range of cutting parameters cutting were selected experimental parameters were selected according to industrial recommendations and cutting tool's manufacturer experimental works were conducted under both dry and lubricated modes. Based on experimental works conducted, the following conclusions can be made:

- Despite the lubrication mode, except for minor cases at lower cutting speed, which can be due to edge hardening, the variation of cutting speed does not widely change the flank wear results. Moreover, although negligible, higher flank wear results were found under dry conditions.
- Moreover, although negligible, higher flank wear results were found under dry conditions. This could be related to higher generated temperatures in the cutting zone. One major problem hindering the machinability of IN was the elevated temperature in the cutting zone which was shown as sparks and burnt chips. Thus, the tool/insert should resist high abrasion and thermal loads (i.e., CBN).
- It is believed that abrasion initially took place, eventually removing the coating on the worn area. Following this phenomenon, adhesion was also taken place. The variation of cutting speed does not widely change the tool wear resulting in a transition time 4s.

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