IMPROVING TOOL PERFORMANCE BY USING SOFT COATINGS DURING MACHINING OF INCONEL 718

IMPROVING TOOL PERFORMANCE BY USING SOFT COATINGS DURING MACHINING OF INCONEL 718

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Lay Abstract

Inconel 718 is considered to be a difficult-to-cut material due to its poor machinability. Significant tool failure at the early stage of cutting is the main challenge of machining this material and is the most significant contributing factor to its high manufacturing costs. Studies show that the common methods used to tackle this issue have not been completely successful. The goal of the present study is to tackle the machining challenges of Inconel 718 by developing tool coatings that meet the specific needs of the material to eliminate tool failure and thereby improve overall machining performance. For this purpose, a new tool coating material and a novel deposition technique that can be used as an alternative for commonly used coatings were developed in this study to improve the tool performance during the machining of Inconel 718. In addition, thorough studies have been carried out to gain a better understanding of the dominant wear phenomena and tool surface treatments that result in an improvement in the machinability of Inconel 718.

Abstract

Increasing tool life is a significant objective in production. Achieving this objective in a machining process poses a significant challenge, especially during cutting hard-to-cut materials such as superalloys, due to the severe tool chipping/failure at the beginning of the cut. Although numerous attempts have been carried out to improve tool performance and prolong tool life during the machining of difficult-to-cut materials over the past several years, researchers have not obtained sufficient control over sudden tool failure/chipping. The focus of this study is to prolong tool life and control tool chipping by developing an ultra-soft deposited layer on the cutting tool that can protect it during the machining of difficult-to-cut materials such as Inconel 718. In the current study, an ultra-soft layer of material is deposited on the tool through two different techniques; a typical physical vapor deposition (PVD) technique and a novel developed method called "pre-machining". In the PVD method, the soft layer is deposited under a high vacuum environment using a PVD coater. In the novel pre-machining method, the soft layer is deposited through a very short machining process involving Al-Si. It should be mentioned that soft coatings have never been used before for machining applications of difficult-to-cut materials including Inconel 718.

This study shows that in contrast to what is expected, depositing an ultra-soft layer on the cutting tool significantly improves tool performance, by reducing chipping, and improving the machined surface integrity during cutting of Inconel 718. The obtained results show up to a 500% ± 10% improvement in tool life and around a 150% ± 10% reduction in cutting forces. Significant reductions in work hardening, residual stress, and

surface roughness on the machined surface were other main achievements of the current study.

Keywords: Difficult-to-cut materials, Inconel 718, Soft coating.

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Table of Contents

List of Figures

List of Tables

Declaration of Academic Achievement

This dissertation was written to fulfill the requirement for the degree Doctor of Philosophy in Mechanical Engineering at McMaster University. The research project was undertaken between September 2017 and October 2020. In this study, new soft, lubricious layers were deposited on the cutting tool and used for the machining of Inconel 718. It should be mentioned that the soft coating has never been used for the machining of difficult-to-cut materials such as Inconel 718. In addition, the proposed soft coating in this study was used in a machining application for the first time. In this study, soft/lubricous layers were deposited on the cutting tool with two different techniques: pre-machining, which is a method that was developed in the current study, and physical vapor deposition (PVD), which is a common deposition technique used in the industry.

For developing the new soft, lubricious coating, detailed characterization studies were performed. In addition, detail machining performance and surface integrity studies were carried out during the machining of Inconel 718. The results of my studies will be published in five journal articles. In four papers, I was as the lead author. These five journal articles comprise this "sandwich" thesis:

1. M. Aramesh, Saharnaz Montazeri, S. C. Veldhuis: A novel treatment for cutting tools for reducing the chipping and improving tool life during machining of Inconel 718, **Wear**, Vol. 414-415, pp: 79–88 (2018).
   https://www.sciencedirect.com/science/article/pii/S0043164818305994

2. Saharnaz Montazeri, M. Aramesh, S. C. Veldhuis: An investigation of the effect of a new tool treatment technique on the machinability of Inconel 718 during the turning

process. **International Journal of Advanced Manufacturing Technologies**, Vol. 100, pp: 37–54 (2019).

https://link.springer.com/article/10.1007/s00170-018-2669-3

3. Saharnaz Montazeri, M. Aramesh, A.F. M. Arif, S. C. Veldhuis: Tribological behavior of differently deposited Al-Si layer in the improvement of Inconel 718 machinability, **International Journal of Advanced Manufacturing Technologies**, Vol 105, pp 1245–1258 (2019).

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4. Saharnaz Montazeri, M. Aramesh, S. C. Veldhuis: Novel Application of Ultra-Soft and Lubricious Materials for Cutting Tool Protection and Enhancement of Machining Induced Surface Integrity of Inconel 718 , **Journal of Manufacturing Processes**, Vol 57, pp 431-443 (2020).

   https://www.sciencedirect.com/science/article/abs/pii/S1526612520304278

5. Saharnaz Montazeri, M. Aramesh, S. Rawal, S. C. Veldhuis: Characterization and Machining Performance of a Chipping Resistant Ultra Soft Coating Used for the Machining of Inconel 718, **Wear**, Submitted.

1 Chapter 1

1.1 Introduction

A significant requirement in machining is to increase tool life and machining productivity. Achieving these objectives in a machining process poses a significant challenge for industry, especially when cutting hard-to-cut materials such as Inconel 718 (IN718), due to its poor machinability and the severe tool chipping/failure experienced early on in the cut. Although numerous attempts have been carried out to improve tool performance and prolong tool life during the machining of difficult-to-cut materials over the past several years, none have obtained sufficient control over sudden tool failure/chipping and short tool life. The focus of this study, in general, is to prolong tool life and control tool chipping by developing a soft/lubricious layer deposited on the tool that can protect it during the machining of IN718.

1.2 Literature Review

A literature review has been conducted on the metal cutting process, tool wear mechanisms, challenges of machining IN718, and previous studies on improving the machinability of IN718.

1.2.1 Overview of Metal Cutting and Tool Wear Types

Metal cutting is a process of component manufacturing that uses a tool to remove a thin layer of material, in the form of chips, from the bulk material through shear deformation. Tool wear is a major problem in the cutting process that leads to low productivity, high tooling costs, and the production of excessive scrap. The chief cause of tool wear is relative sliding and adhesive interaction between the tool and the workpiece during the cutting process. There are various types of tool wear such as flank wear, crater wear, depth-of-cut notch wear, built-up edge (BUE) formation, tool chipping, and tool fracture. Different mechanisms are responsible for the formation of tool wear that can be observed on the tools after the machining process. Typically, the dominant tool wear mechanisms are abrasive wear, adhesive wear, diffusion wear, and oxidation wear [1]. These mechanisms vary in accordance with cutting conditions. Also, during most cutting processes, tool wear is formed by a combination of several wear mechanisms. Temperature plays a key role in affecting certain tool wear mechanisms and tool wear types. Figure 1-1 shows the effect of temperature on the occurrence of different tool wear mechanisms at the tool-workpiece interface. As can be seen in Figure 1-1, each tool wear mechanism manifests at a specific area on the tool due to the temperature and pressure distribution.

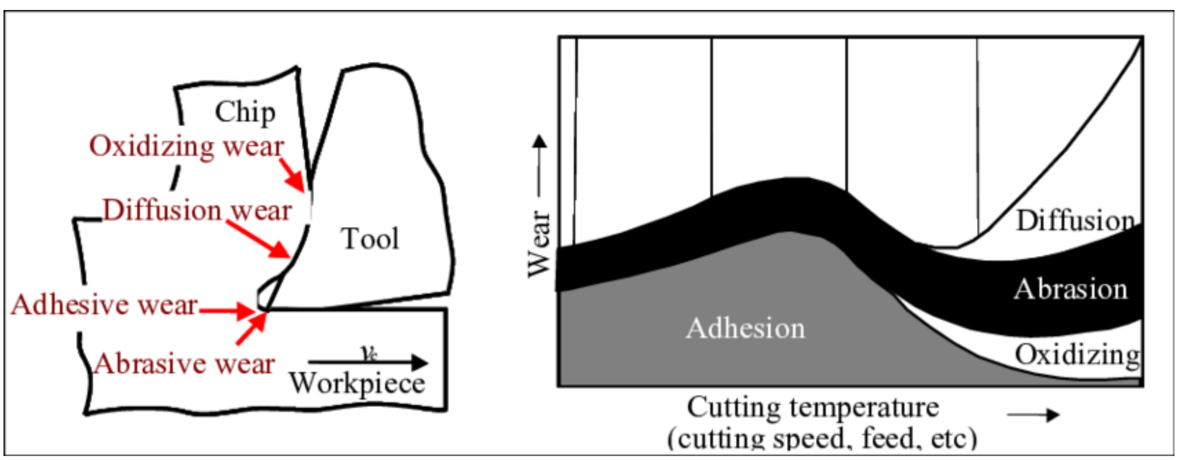

Figure 1-1. Wear mechanisms formed on the tool at different cutting temperature [1]

1.2.2 Overview on Machinability of Inconel 718

1.2.2.1 Inconel 718

Worldwide demand for nickel alloys has increased over time. Inconel718 (IN718) is the most common nickel-chromium-iron based alloy used to produce components that operate under extremely high temperatures, such as turbine blades in power generation and aircraft engines, pressure vessels, and nuclear reactors [2]. A study shows that more than 75% of high-temperature aerospace engine components are made of IN718 [3]. IN718 has high strength and good ductility up to 704°C and features good weldability, formability, and excellent cryogenic properties compared to other nickel-based alloys. The main reasons for using IN718 are its high oxidation resistance, high corrosion resistance, and high mechanical strength at high temperatures.

Gamma (γ) as a face-centered cubic (FCC) austenitic phase which contains a specific amount of solid solutions such as Fe, Cr, and Mo is the matrix phase of IN718. Nickel aluminum titanium [Ni_3(Al Ti)], known as a gamma prime (γ′), and nickel niobium (Ni_3Nb), known as gamma double prime (γ″) are two strengthening phases precipitated in the grains. The microstructure of the IN718 also contains hard carbide particles that are precipitated at the grain boundaries. These hard carbide particles are mostly niobium carbide and titanium carbide [4]. Figure 1-2 shows the different phases of IN718.

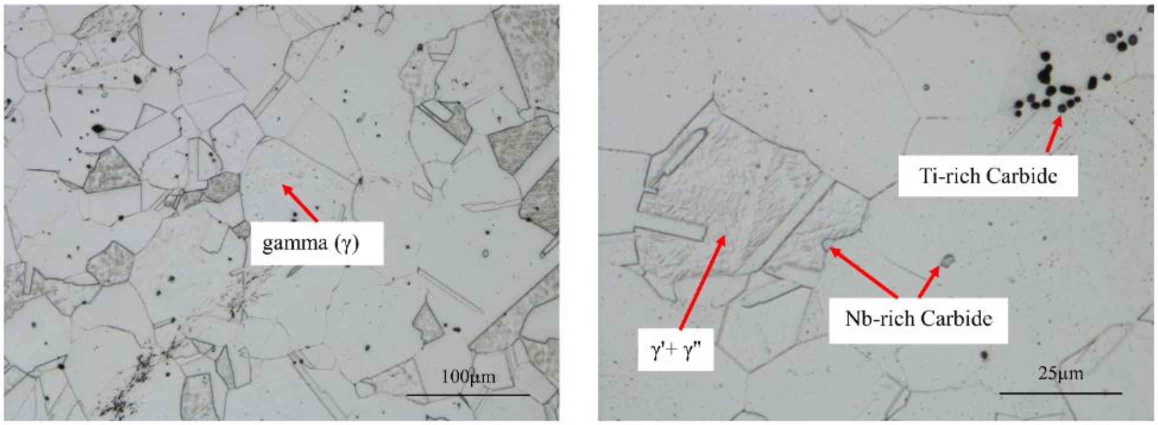

Figure 1-2. Microstructure of IN718

1.2.2.2 Machining Challenges of IN718

Although in recent decades IN718 was extensively used for aerospace and jet engine components, the machining of these alloys is very challenging. This alloy is generally considered to be a difficult-to-cut material. The reasons for the poor machinability of IN718 are listed below [5]–[9]:

1- High strength at elevated temperatures during the machining process due to its excellent thermal properties.

2- High temperature generation at the cutting zone due to its low thermal conductivity (up to 1200 °C).

3- High sensitivity to strain rate and rapid work hardening occurring during machining, which cause severe notch wear.

4- Abrasive wear during machining because of the hard, abrasive carbide particles present in the microstructure of the material.

5- The high tendency of IN718 to weld to the tool material and form an adhesive layer that can cause built-up edge (BUE) formation and wear. Periodic build-up and breakdown of the unstable BUE on the tool edge can result in severe tool failure or tool chipping.

6- The generation of high cutting forces during the cutting process due to high strength at high temperatures of IN718 can result in poor surface quality (residual stress and surface and subsurface damage) of the finished material.

Many studies have tried to tackle these machining challenges and lengthen the overall tool life by improving the chipping resistance of the tool during the machining of IN718. To achieve this objective, researchers have attempted to introduce different methods, which will be discussed in the following section.

1.2.2.3 Proposed Methods of Improving the Machinability of IN718

As mentioned, researchers have used various ways to improve the machinability of IN718. The methods proposed in previous studies for the machining of IN718 can be divided into four categories: machining strategies, tool designs/materials, coolant delivery, and tool coatings. However, low cycle times, high tooling costs, and the production of excessive scrap still present challenges. Figure 1-3 shows the different categories and some examples of studies related to each one.

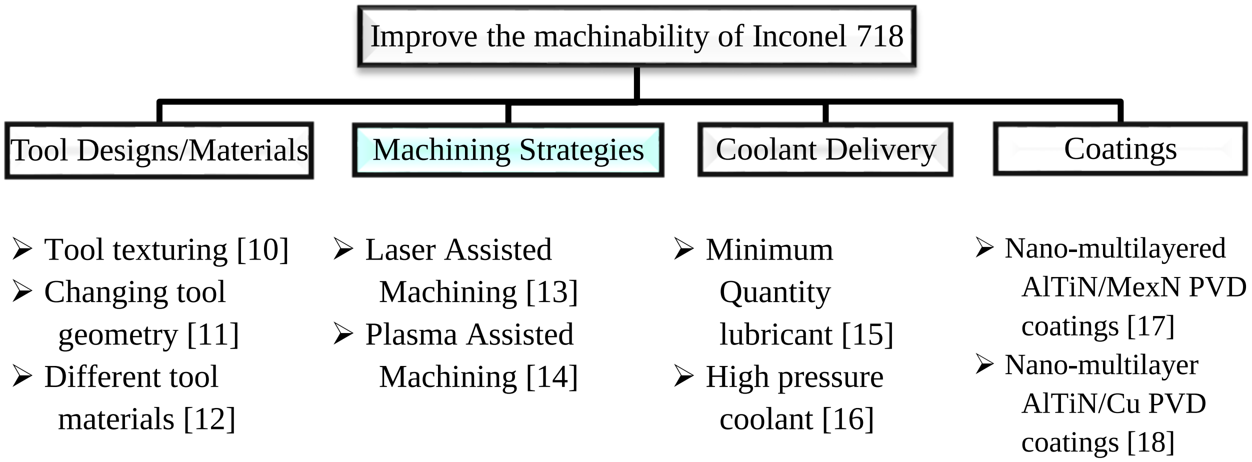

Figure 1-3. Different common methods applied previously for improving the machinability of IN718

The related studies in each category are introduced below in more detail.

1.2.2.3.1 Tool Designs/Materials

Various studies show that the performance of a tool during machining is affected by tool geometry, material, and design. The tool material used for IN718 machining should incorporate good wear resistance, high strength, high toughness, and excellent thermal shock properties. Many studies investigated the machining performance using CBN, ceramic, and coated carbide tool materials [19]–[21]. In addition to selecting different tool materials, researchers tried various tool geometries and tool designs. For instance, Pawde et al. [11] investigated the effect of tool geometry on the machined surface. They compared three types of tool geometries and recorded the results of the residual stress, microhardness, and cutting forces to find the best cutting condition and tool geometry for achieving the best surface integrity. A conclusion was drawn that the highest cutting speed, minimum feed rate, and average depth of cut can have the most effect on generating compressive residual stress at the machining surface with a chamfer plus honed cutting edge. To improve the performance of the CBN cutting tool, Sugihara et al. [10], introduced a novel texture on the flank face of the insert when machining IN718 at a high cutting speed as a way to entrap more lubricant in the cutting zone. By comparing three different types of tool textures, they discovered that texturing the flank and rake faces improved the wear resistance of the tool due to the superior lubricating behaviour. The creation of micro grooving on the flank face is a necessary condition for the lubricant to permeate the chip-tool interface. As a result, the amount of flank wear and adhesion were lower in the developed CBN insert than in a conventional insert. The studies showed that the maximum tool life improvement from using these techniques was not very high; they were around 13% to 33% [13], [14].

1.2.2.3.2 Machining Strategies

Using different machining strategies to cut materials can also be helpful in some cases. Using external heat to preheat the material before cutting is a method proposed recently to facilitate the cutting of difficult materials. In this method, a heat source installed in the machine applies localized heat to the unremoved material to soften it up before it reaches the cutting edge. Several researchers have used thermal enhanced machining to improve the tool performance during the process of cutting IN718. As an example, Navas et al. [13] tried to improve the machinability of IN718 by using laser-assisted machining (LAM). With this method, they significantly reduced the cutting forces and improved the final surface roughness. They found that the cutting forces and machinability benefited from three mechanisms: reduction in material yield strength, material hardness, and work hardening generation. Although the study showed a decrease in the cutting force (maximum 10%) along with better control of tool chipping/failure and significantly improved surface roughness, the overall tool life achieved with LAM was lower than the conventional method due to excessive heat on the tool surface. Venkatesan [22] used Laser Assisted Machining (LAM) of IN718 with a multi-layered (TiCN/Al2O3/TiN) coated carbide tool to improve the machinability of this alloy. They obtained the optimal cutting condition using the Taguchi method to control the cutting force and temperature. The results show that the cutting force was reduced by 60% with the LAM method.

1.2.2.3.3 Coolant Delivery

The objective of delivering the coolant to the cutting zone is to lower the temperature as much as possible and in some cases assist with chip formability and breakability to minimize the effect of chip rubbing on the tool and workpiece. For this purpose, researchers utilized various coolant delivery systems such as minimum quantity lubrication (MQL) and high pressure coolant, as well as coolant types like vegetable oil and semi-synthetic oil. Zhang et al. [15] compared the dry cutting and MQL cutting with biodegradable vegetable oil in terms of tool wear and cutting force. The use of MQL in the TiAlN/TiN coated carbide tool improved the tool life 1.57 times in comparison with the dry condition. In addition, the cutting force lessened due to the reduction in friction achieved by the MQL method with biodegradable vegetable oil as a lubricant. Behera et al. [23] investigated various coolant strategies, including high pressure jet, cryogenic, and MQL during the machining of IN718. They analyzed cutting force, tool wear, and surface finish to determine the effects of different coolant methods. The results indicated that cryogenic coolant has an excellent effect on surface quality improvement and tool wear reduction (around 50%).

1.2.2.3.4 Tool Coatings

Selecting a suitable coating to deposit on the tool is the most popular method for improving the machining performance of hard-to-cut materials. The most common tools used for cutting IN718 are coated carbide tools due to a solid combination of both fracture toughness and resistance [24], [25]. The techniques used to deposit the thin layers of hard wear-resistant materials on the tool include chemical vapor deposition (CVD), physical vapor deposition (PVD), and plasma-enhanced chemical vapor deposition (PECVD). Researchers use a variety of coating types and designs to improve tool performance. Almost all of the coatings recommended for the machining of IN718 are hard coatings. Biksa et al. [17] investigated tool wear behaviour, tool life, and chip formation with a nano-multilayer AlTiN/MexN coating where Mex is a transition metal of V–VI groups of the periodic table (V, Nb, Cr, Mo, W) and compared it with a monolayer AlTiN coating during the machining of IN718, for the purpose of finding a new adaptive coating that enhances lubrication and wear behaviour. They measured the microhardness and the friction coefficient of the coating and found that the developed coating is not only capable of forming a tribofilm for thermal protection but also possesses lubricating properties when exposed to oxygen. The results show that the AlTiN/MoN nano-multilayer has a longer tool life due to its ability to reduce wear and BUE formation on the tool. The tool life of the AlTiN/MoN coated tool was around 30% higher than that of the commercial coating used in this alloy’s machining. Fox-Rabinovich et al. [18] investigated the effect of a nano-multilayer AlTiN/Cu PVD coating on tool life and wear behaviour during the machining of IN718. In addition, they analyzed the coating structure and topological behaviour in their study and discovered that a nano-multilayer exhibits self-lubricating behaviour and provides thermal barrier properties which improve the tool life by 140%. They also found that the formation of beneficial tribofilms in the AlTiN/Cu coating reduced friction and improved thermal properties, resulting in less BUE formation.

1.2.2.4 The Limitation of the Proposed Methods of Improving the Machinability of IN718

As mentioned above, several attempts were made to tackle the machining challenges, reduce tool chipping/fracture and thereby improve the overall tool life. However, even with these innovations, IN718 is still considered to be a difficult-to-cut material. The reason is that the aforementioned methods did not offer a solution for eliminating the sudden tool chipping/fracture that occurs after a short period of cutting. This is because control of the tool chipping will only be achieved when most of the machining problems are solved simultaneously. Previous studies were ineffective in accounting for the sudden tool chipping occurrence. For example, using the optimal coolant in a machining process can have a significant effect on temperature reduction in the cutting zone, but it cannot minimize hardening of the workpiece material due to cyclic cooling and heating issues. Therefore, there exists no single method that can solve the machining challenges of a difficult to cut material on its own.

In addition, most of the mentioned methods are costly, complex, and need additional equipment. For instance, in the laser-assisted machining method, installing the laser source in the CNC machine to heat the workpiece material before cutting is very costly and difficult to maintain. Also, poor setup conditions related to angle, distance, and beam energy have been found to damage the tool and tool holder. Furthermore, although some studies have indicated that laser-assisted machining may greatly reduce cutting force, it did not succeed in improving overall tool life.

Although various researchers have proposed different ways to enhance IN718's machinability, there is still an essential need to develop a novel method for preventing premature tool chipping/failure and thereby increase tool life. However, of all the methods mentioned, developing various type of coatings is the most successful at improving the tool performance during the machining of IN718.

1.3 Research Gap

Studies show that mainly hard coatings were selected for the machining of hard-to-cut materials due to their wear resistance and high hardness properties. Table 1-1 shows the different coatings that have been used in various studies and their hardnesses. As can be seen, all coatings recommended for IN718 machining are hard coatings and having a hardness of higher than 20 GPa. It should be mentioned that coating materials are classified as soft and hard coatings according to their hardness [26], [27]. Generally, a coating with a hardness lower than 10 GPa is considered to be a soft coating while one harder than 10 GPa is considered a hard coating.

Table 1-1- Different recommended coatings and their hardnesses at room temperature

	Coatings	Hardness (GPa)		Coatings	Hardness (GPa)
1	TiAlN [28], [29]	29	**7**	CrN [30]	22.5
2	TiAlCrSiYN/TiAlCrN [31]	30	**8**	TiN [30]	24.5
3	AlTiN [17]	24.64	**9**	TiCN [29]	26.9
4	AlTiN/MoN [17]	26.13	**10**	CrN/TiN [30]	26.9-36.2
5	AlTiN/VN [17]	25.48	**11**	TiN/AlTiN [30]	29.4-38.2
6	TiAlCrN [32]	28.2	**12**		

Although researchers have tried to increase the hardness of coatings to improve wear resistance, excessive hardness itself can lead to coating failure, especially during the cutting of difficult-to-cut materials. The reason for this is that excessive hardness will increase the brittleness of the cutting tool, which can cause tool failure while cutting hard-to-cut materials such as IN718. It should be mentioned that IN718 is rapidly being work hardened during the machining processes. Cutting the work-hardened material is much harder than cutting the original material, especially with a hard, brittle tool. As mentioned before, severe work hardening results in tool notch wear during the cutting of IN718 which is considered to be a machining challenge of this alloy. Severe notch wear results in catastrophic tool chipping and tool failure, especially after a short period of cutting when the hard tool is very sharp. Therefore, tool chipping/tool failure is still considered to be the main challenge in the machining of IN718.

In addition, studies show that lack of lubricity is one of the problems of hard coatings [18], [33]. Typically, hard coatings used for the machining of IN718 have high hardness and a high coefficient of friction (COF). However, having a low COF of the coating allows the material to be removed easier and flow more easily on the rake face of the tool during the cutting process. As mentioned, studies have shown that most of the coatings recommended for the machining of IN718 are hard coatings, typically with a high COF. Therefore, because of their lack of lubricity and excessive hardness, these coatings are not able to tackle most of the machining challenges of this alloy and eliminate the sudden tool chipping or tool failure. A new method is still required to overcome all of the machining challenges mentioned in section 1.2.2.2. and eliminate tool chipping during the machining of IN718. Furthermore, the various developed methods that are recommended for improving the machinability of Inconel 718 have their own limitations and are able to control only one or two of the challenging aspects of machining. For example, they are not able to control sudden tool chipping/fracture during machining of Inconel 718 because tool chipping elimination will be achieved by controlling most of the challenging aspects of machining simultaneously.

1.4 Motivation and Research Objectives

Tackling the machining challenges of IN718 and eliminating the sudden tool chipping during the machining process to increase productivity and decrease the machining cost in industries are the main general motivation for the current study.

The ultimate goal of this study is to provide a better understanding of the machinability issue of this class of alloy. This current study attempts to provide a solution that will tackle the machining challenges and increase tool performance during the machining of IN718.

The proposed method for easing the material removal and reducing the initial shock on the tool during the cutting process is applying a novel soft coating on the cutting tool. Because of the slip plane in their microstructure, soft coatings can reduce contact friction significantly. There is no study that uses a soft, lubricious coating on a tool for machining a difficult-to-cut material such as IN718. Moreover, an easy and cost-effective method, refered to as pre-machining technique by the authors, was introduced, for depositing the soft coating on the tool.

The specific research objectives of the current study associated with improving the overall machinability of IN718 are as follows:

1. Investigate the role of pre-machining techniques on the tool life of uncoated carbide tools for the turning of IN718 and explain in scientific terms how the new pre-machining method impacts the performance of the tool (particularly chipping resistance) and the quality of the workpiece.
2. Compare different deposition techniques for preparing the lubricious layer on the tool. Compare layers deposited using PVD coating techniques with a sacrificial layer deposited through a pre-machining technique for better performance and industrial acceptance.
3. In-depth study on developing and designing a soft PVD coating to improve tool performance and surface integrity during the machining of IN718.

1.5 Thesis Outline

The format of the current dissertation is based on a sandwich thesis format. The results of the current study, published in five research papers, and also the idea of this thesis are protected by a patent filed under reference number US20190314900A1. This dissertation contains several chapters, and descriptions of the contents of each chapter are provided below:

1.5.1 Chapter 1

Presents a literature review of the current state of knowledge related to IN718 machinability studies. In this chapter, the causes of the poor machinability of IN718 are mentioned. In addition, common past attempts that have been made to tackle these challenges are explained in this chapter. The relevant literature review, research gaps, and research objectives are also provided.

1.5.2 Chapter 2.

This chapter includes an article that was published in **Wear**. I was the second author of this article which was related to the first objective of the current study. In this study, the developed new cost-effective method (pre-machining method) was used to deposit a soft layer on the cutting tool in order to eliminate tool chipping during machining of Inconel 718. In this study, the mechanisms that are responsible for this significant improvement are explained in detail. In addition, machining performance including, tool wear mechanisms, tool life, cutting forces, work hardening during machining of Inconel 718 were discussed and the results compared with the uncoated tool (this chapter covers objective 1 of the current study).

1.5.3 Chapter 3.

The results of this chapter were published in the **Journal of Advanced Manufacturing and Technology**. In this study, a new, simple, and cost-effective method was developed to deposit a soft layer on the cutting tool to improve the overall tool performance and eliminate tool chipping during machining of IN718. In this study, the developed method was used to deposit various types of soft/lubricious materials on the cutting tool. The criteria for material selection for deposition were explained in detail. Discussions were also provided on the main mechanisms that are responsible for the tool life improvements observed. Detailed investigations also have been done on tool life, cutting force, tool wear mechanisms, work hardening, tribofim formations, chip formations, and frictional behavior at the tool-chip interface (this chapter covers objective 1 of the current study).

1.5.4 Chapter 4.

This chapter represents an article that was published in the **Journal of Advanced Manufacturing and Technology**. In this study, the deposition of the soft layer on the cutting tool through the commercial physical vapor deposition technique (PVD) was compared with the deposition of a soft layer on the cutting tool through the developed deposition technique. In this study, the mechanisms of both methods were investigated and compared. Furthermore, the machining performance of these techniques was also discussed in detail (this chapter covers objective 2 of the current study).

1.5.5 Chapter 5.

This chapter includes an article that was published in the **Journal of Manufacturing Processes**. In this study, the performance of the proposed pre-machining technique and conventional physical vapor deposition technique (PVD) method on the surface integrity of IN718 were investigated in detail. For this purpose, an in-depth surface integrity analysis is performed to study their effect on improving the integrity of the machined workpiece surface including the work-hardening and residual stresses and enhancing the surface roughness.

1.5.6 Chapter 6.

This chapter consists of an article that was submitted to **Wear**. In this chapter, the effects of the main deposition parameters on the new soft PVD coating were investigated. For this purpose, different deposition parameters were selected and coating characterization was carried out in detail. In addition, a machining study on the newly developed soft PVD coated tools was investigated (this chapter covers objective 3 of the current study).

1.5.7 Chapter 7.

The summary and main conclusions of the current study are outlined in this chapter. Moreover, suggestions for future work are also listed in this chapter.

1.5.8 Appendix I:

Appendix A consists of Transmission Electron Microscopy (TEM) results to support the hypothesis about the formation of tribofilms on the cutting tool during the machining of IN718.

1.6 Note to Reader

This thesis consists of a series of research journal articles to achieve the goal of the current study. Therefore, there might be some repetition in some sections of the papers, especially in the introduction and experimental procedures. Although the main goal of all the research articles is to improve the machinability of Inconel 718, the focus of each research paper is different.

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2 Chapter 2

A Novel Treatment for Cutting Tools for Reducing the Chipping and Improving Tool Life During Machining of Inconel 718

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Stephen. C. Veldhuis:	Supervisor of the paper.

A novel treatment for cutting tools for reducing the chipping and improving tool life during machining of Inconel 718

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2.1 Abstract

Chipping and high tool wear are considered the most challenging issues associated with machining of superalloys, including Inconel 718. Despite numerous attempts in this area, it is still considered a critical drawback of this class of materials for application in different industries. A new tool treatment technique is proposed for improving the tool wear and reducing the chipping during machining of Inconel 718. The treatment involves less than two seconds of machining on an aluminum-silicon (Al-Si) workpiece prior to the actual machining of Inconel. In this way, the "pre-machining process", deposited a very thin layer of Al-Si on the tool face. During the subsequent machining of the Inconel bar, the Al-Si was melted due to the high temperatures of Inconel machining. The molten material channeled itself through the microcracks on the tool surface and seized their propagation. The sliding of the tool on the low friction Al-Si layer resulted in much lower forces, less

sticking, seizure and built-up edge formation and, thereby, in less tool wear and chipping. Several beneficial lubricious and thermal barrier tribo-films were also formed on the tool face, which further protected the tool from chipping and severe tool wear. Reducing the contact pressure, friction and temperature during machining resulted in considerable reduction in the machining induced work-hardening of the workpiece material, which is considered as one of the most important factors affecting chipping during machining of this class of materials. Moreover, the ductility of Al helped to dampen the vibrations during machining and helped in tool chipping prevention. Finally, the preconditioning of the tool itself through this process resulted in tool performance improvement by lowering the tool wear at the running-in stage. The new method resulted in a significant reduction in tool chipping and an overall improvement in tool life. Considerable improvements in the surface integrity of the machined part were also obtained. The contributing mechanisms are discussed using detailed material characterization techniques.

Keywords:

Machining of Inconel; Chipping; Machining induced work-hardening; Tool treatment

2.2 Introduction

Superalloys have become an important part of our modern lives, enabling us to overcome heights of space and depths of oceans. Owing to their desired thermal and mechanical properties, they perfectly meet the crucial requirements of different high-tech industries. It has been reported that they are employed in up to 75% of modern engine jet components, including turbine blades, which are constantly exposed to very high temperatures and pressures [1]. Inconel 718, a category of nickel-based superalloys, possesses superior properties such as high strength at elevated temperatures, corrosion and creep resistance and high strength to weight ratio. Thus, it is considered as one of the best materials to use in applications where extreme conditions of stress, temperature and pressure apply. Yet, these properties make it very hard to cut [2]. Severe tool wear, large built-up edge (BUE) formation, cracking and chipping occur during the machining of this class of material and its machining is still considered as a significant challenge for manufacturers.

Chipping can occur suddenly and yield severe damage to the machined surface making it highly undesirable. Yet, controlling chipping is still considered an important challenge in tool design, especially for machining of very difficult to cut materials such as Inconel 718. Several factors, such as poor thermal properties, hot hardness and work-hardening of this material, existence of hard carbide particles inside the material, in addition to the brittleness of the cutting tools and mechanical impacts and vibration imposed by the cutting action, result in severe tool wear and crack propagation, especially around the notch area, where the tool is in contact with the hardened surface layer of the material. Exposure to the atmosphere, especially to oxygen, can also affect the physical and chemical properties of the material in this area and promote further cracking, tool wear and, finally, tool chipping. Severe friction, seizure, and formation of excessive built-up edge at the rake face can further facilitate the chipping phenomenon [3] [4] [5].

Several attempts, including different tool geometries and materials [6], coatings [7]–[10] and machining strategies [11]–[13] have been employed for improving the chipping resistance and overall tool life of the tools during machining of Inconel. However, the challenge has not been resolved yet resulting in low cycle times, high tooling costs and the production of excessive scrap. Thermally induced stresses at extremely high temperatures generated during machining of Inconel reduce the tool strength and can break the interfacial bonding between the tool hard particles and their binders, including even super hard tool materials such as CBN [2]. Most coatings also cannot withstand the high thermal and mechanical loads. Furthermore, severe seizure makes lubrication ineffective and coolants have been shown to be unsuccessful in reducing the temperature to the levels required.

In this study, a new tool treatment technique is employed with the aim of controlling the chipping and improving the overall tool performance during turning of Inconel 718. In this method, a thin layer of Al-Si was deposited on the tool faces through a couple of seconds of pre-machining of Al-Si with the same tool. The results show that this method addressed the majority of the problems, enabled the tool to better withstand high loads and reduce tool chipping and premature tool failure. The observed improvements were attributed to a combination of several factors, such as tool edge protection and crack arresting, better lubricating properties, reduced contact pressure and consequently less abrasion wear, the formation of several beneficial tribofilms on the tool faces, reduced sticking, seizure and BUE formation, better damping properties and improving the running-in stage performance of the tools. The corresponding mechanisms are discussed in more detail in the following sections of this paper.

2.3 Experimental Set-up

The work-piece material used for this study was a bar of Inconel 718. The chemical composition of Inconel 718 was measured by Varian Vista Pro Inductively Coupled Plasma (ICP) instrument linked with Expert II software. The material properties are provided by the supplier. The mechanical and chemical composition of the Inconel 718 material are listed in Table 2-1 and Table 2-2, respectively. The pre-machining process is performed on an Al-Si bar with 10% silicon content. Uncoated carbide tools were used for this study. The machining tests were performed on a Boehringer CNC turning center.

Table 2-1. Material properties of Inconel 718

Property	**Value**
Density (kg/m^3)	8190
Young's Modulus (GPa)	200
Ultimate Tensile Strength (MPa)	1375
Yield Tensile Strength (MPa)	1100
Thermal Conductivity (w/mK)	11.4
Specific Heat Capacity (J/kg ˚C)	435
Melting Point (˚C)	1260-1336
Hardness (HRC)	32-34

Table 2-2. Chemical composition of Inconel 718

Material	**Ni**	**Cr**	**Fe**	**Mo**	**Nb**	**Ti**	**Al**	**Cu**	**Mn**	**Si**	**C**	**S**	**Co**	**P**	**Ta**	**B**
Weight %	55.6	17.2	15.65	2.9	5.24	1	0.6	0.3	0.35	0.35	0.08	0.015	1	0.015	0.05	0.006

Microstructural and elemental analyses were performed on a Tescan Vega II LSU Scanning Electron Microscope (SEM), equipped with an Oxford X-Max 80 Energy-Dispersive X-ray Spectroscopy (EDX) detector and Inca software Version 4.14. A 10-kV accelerating voltage was used to record the peaks. The spatial resolution of the EDS data is

1–5 μm^3 for low atomic numbers (Z) and 0.2–1 μm^3 for high Z, and the energy resolution is 132 eV. The EDS is capable of efficiently detecting elements heavier than Beryllium.

Formation of different kinds of tribofilms for different cutting strategies was verified by performing X-ray photoelectron spectroscopy (XPS) on the tool worn surfaces after each machining cycle. The XPS is equipped with a Physical Electronics (PHI) Quantera II spectrometer with a hemispherical energy analyzer, an Al anode source for X-ray generation, and a quartz crystal monochromatic for focusing the generated X-rays.

The X-ray source was from a monochromatic Al K-α (1486.7 eV) at 50 W–15 kV and the system base pressure was between 1.0×10^{-9} Torr and 2.0×10^{-8} Torr. The samples were sputter-cleaned for 4 min with a 4 kV Ar+ beam before collecting the data. The beam for data collecting was 200μm and all spectra were obtained at a 45° take off angle. A dual beam charge compensation system was utilized to ensure neutralization of all samples. The pass energy to obtain all survey spectra was 280 eV, while to collect all high-resolution data it was 69 eV. The instrument was calibrated with a freshly cleaned Ag reference foil, where the Ag 3d5/2 peak was set to 368 eV. All data analysis was performed in PHI Multipak version 9.4.0.7 software.

For a better understanding of the interfacial phenomena in the tool/chip interface such as friction and wear, nanotribological studies were performed, including nano-indentation and nano-wear tests. The tests were done using a Micro Materials NanoTest system. Nanoindentation was performed in a load controlled mode with a Berkovich diamond indenter calibrated for load, displacement, frame compliance, and indenter shape, according to the procedure outlined in ISO14577-4.

For the nanoindentation testing on the workpiece sub-layer, the peak load was 40 mN and three sets of 40 indentations were performed for each sample. Nanoindentation was performed at room temperature. The accuracy of the hardness measurement was around 10%. Micro-wear (low cycling repetitive unidirectional sliding wear) tests were performed using the NanoTest Scratching Module with a 25µm radius diamond probe. The 5-scan micro-wear procedure involved an initial topography scan, followed by 4 scans where, after a 200µm leveling distance, the load was ramped quickly (100 mN/s) to the peak load of 0.5, 1 or 2 N, and then followed by a subsequent topography scan. The scan speed was 5µm/s and the total scan length was 800µm. On-load and post-load probe penetration depth data in the constant load region (last 600µm of each scan) were determined automatically after correction for the sample slope and frame compliance in the instrument software.

The generated temperature during turning of Inconel 718 was measured with a VarioCAM HD 1024 infrared camera with a resolution of 1024 × 768 pixels and video frame frequency of 30 Hz.

2.4 Experimental procedure

In order to assess the performance of the proposed treatment, machining tests were performed without (benchmark) and after the “pre-machining” treatment (actual machining) and machinability analyses followed. For the *benchmark* testing, sequential machining tests on Inconel 718 were performed using an uncoated carbide tool until the tool failure criterion was reached. For the "*pre-machining*" treatment, prior to the actual machining of an Inconel bar, a turning pass was performed on an Al-Si workpiece for a few seconds. The same tool was then used for *actual machining* of Inconel until the end of tool life, defined by the tool failure criterion. For both benchmark testing and actual machining after treatment, the same cutting conditions were selected. Detailed information about the tools and cutting conditions and failure criteria for the two cases are provided below.

Uncoated carbide tools were selected for the tests. Carbide tools are the most commonly used inserts for machining of nickel-based super alloys including Inconel 718. Due to poor machinability of these materials, relatively low cutting speeds in the range of 20-30 m/min are commonly applied in industry for uncoated and also for PVD coated carbide tools. Chipping and rapid tool failure were reported when applying higher speed around 50 m/min even with coated tools. Conversely, high feed rates and depth of cuts are recommended to avoid the chipping and notch wear that occur when machining of the work-hardened layers of the workpiece in shallow cuts [3]. In this study, the cutting conditions are intentionally pushed to their practical limits in order to test the performance of the proposed treatment under severe conditions. Thus, a high cutting speed of 50 mm/min and relatively low feed rate and depth of cut are employed in this study. The cutting conditions are listed in the first row of Table 2-3.

As mentioned before, for the pre-machining treatment, a very short turning pass (total cutting time equal to around 1-2 seconds) was performed on an Al-10 Si alloy bar. A relatively high cutting speed and a low feed rate were chosen in order to attain a thin and uniform built up layer on the tool. A very thick or non-uniform built up layer can itself be detrimental for the cutting tool and result in chipping. Therefore, selecting a proper condition for this process is very important. The cutting conditions were selected after some trials. An important purpose of this study is to reduce chipping, which mainly happens at the notch area, located at a distance equal to the depth of cut from the tool tip. In order to make sure that the whole contact zone, especially the notch area, was covered and protected with Al-Si before the actual machining with Inconel, the depth of cut for the pre-machining process was selected to be larger than the depth of cut of actual machining. The corresponding cutting conditions are provided in the second row of Table 2-3. A layer formed on one sample tool is presented in Figure 2-1. As can be seen, the generated Al-Si layer on the tool surface with thickness of around 40 ± 5 μm is very uniform and has covered a large area of the tool edge. It should be mentioned that the cutting time of pre-machining of Al-Si is too short that, as can be seen in Figure 2-1, it did not induce any wear on the tool before the actual machining of Inconel.

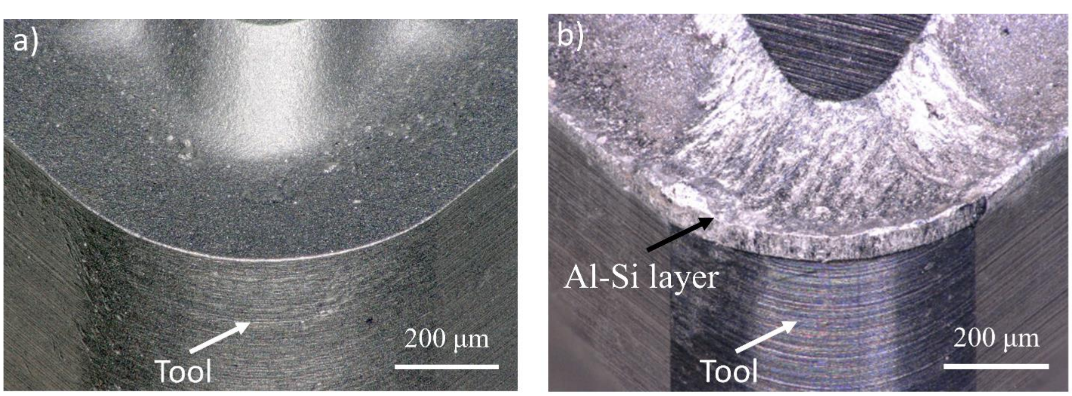

Figure 2-1. a) The benchmark b) the layer formed on the tool through the pre-machining process

Table 2-3. Cutting conditions for different strategies

Cutting Parameters	**Cutting Speed (m/min)**	**Feed Rate (mm/rev)**	**Depth of Cut (mm)**
Benchmark/Actual machining of Inconel after the treatment	50	0.1	0.15
Pre-machining with Al/Si	450	0.05	1

For benchmark and actual machining after the treatment, tool wear and cutting forces were monitored after each pass, and the tests were continued until the tool wear failure criterion was reached. Chipping or a maximum flank wear length of VB_{max} = 0.3 mm, whatever happened first, was considered as the tool failure criterion.

Machinability analyses, including tool wear and force monitoring, wear surface analysis, microstructural and tribological studies of the worn surfaces in addition to surface integrity analysis of the machined surfaces followed the machining tests. The results are provided in the upcoming section.

2.5 Results and discussions

2.5.1 Machining results

The tool wear and force results for the benchmark (without the pre-machining treatment) and the treated tools (after the pre-machining treatment) are presented in Figure 2-2 and Figure 2-3 respectively. Each test was repeated at least three times.

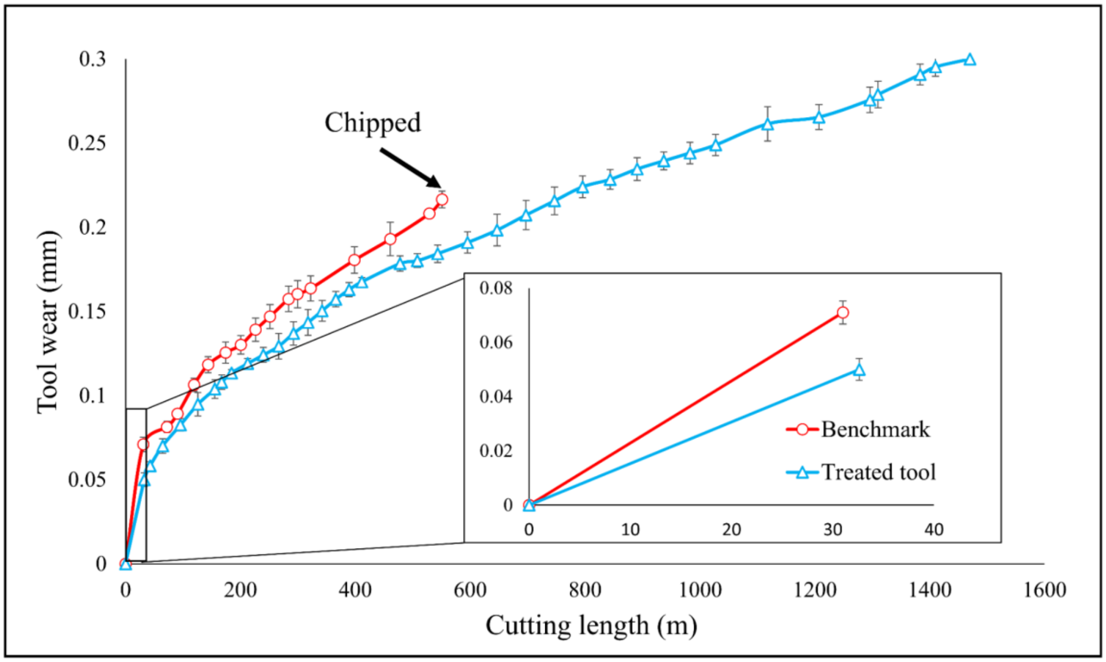

Figure 2-2. Tool wear data for benchmark and the treated tools

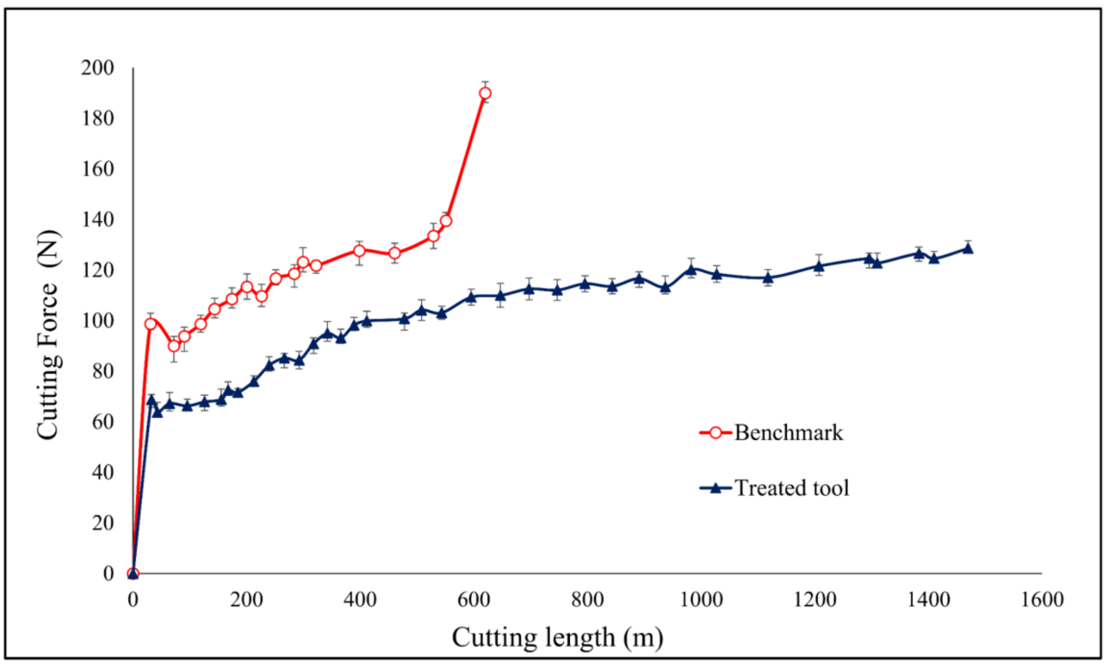

Figure 2-3. Cutting forces for the benchmark and treated tool

The untreated tools used for benchmark testing were all chipped between 400 to 600 m of cut. Yet, chipping was successfully prevented with the proposed treatment and an average of 300% tool life improvement was achieved through this process. After applying the treatment, the cutting forces were also reduced by 40-50 % in comparison with the benchmark. The same procedure was performed using another uncoated tool. Very similar results were obtained.

Images of flank surfaces of worn tools are shown in Figure 2-4. As can be seen, relatively deep grooves are formed on the un-treated tool surface, indicating severe abrasive wear. Considerable notch wear has already formed on the tool after only 68 m of cut, making it more susceptible to chipping. Also, an excessive built-up edge is formed on the tool rake face, which is very detrimental for the tool and can result in tool chipping and premature failure. These phenomena were not seen on the treated tool surfaces and tool wear exhibited a uniform morphology.

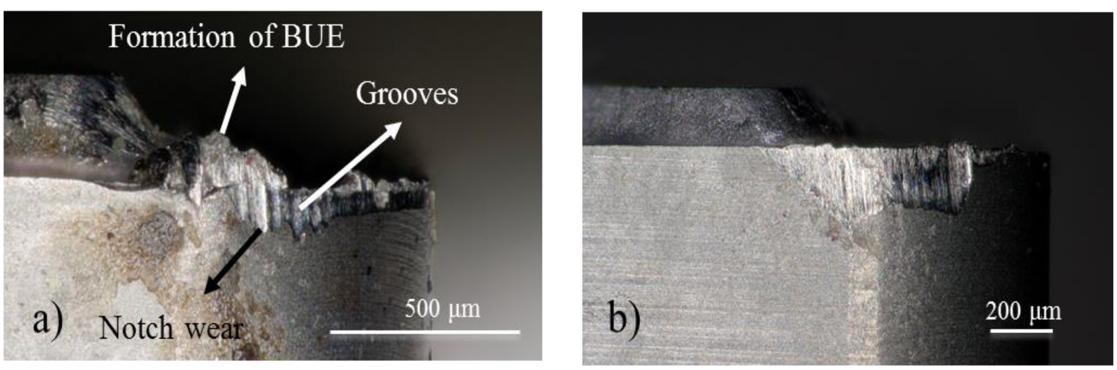

Figure 2-4. a) Tool flank wear after 68 m of cut without pre-machining b) Tool flank wear after 730 m of cut after pre-machining

2.5.2 Mechanisms resulting in chipping prevention and tool wear improvements

The proposed method was successful in reducing chipping and improving tool life significantly through different mechanisms. In this section, an attempt is made to discuss these mechanisms in details. The contributing factors and their effects on controlling the chipping and tool wear in the proposed treatment are shown in Figure 2-5 schematically.

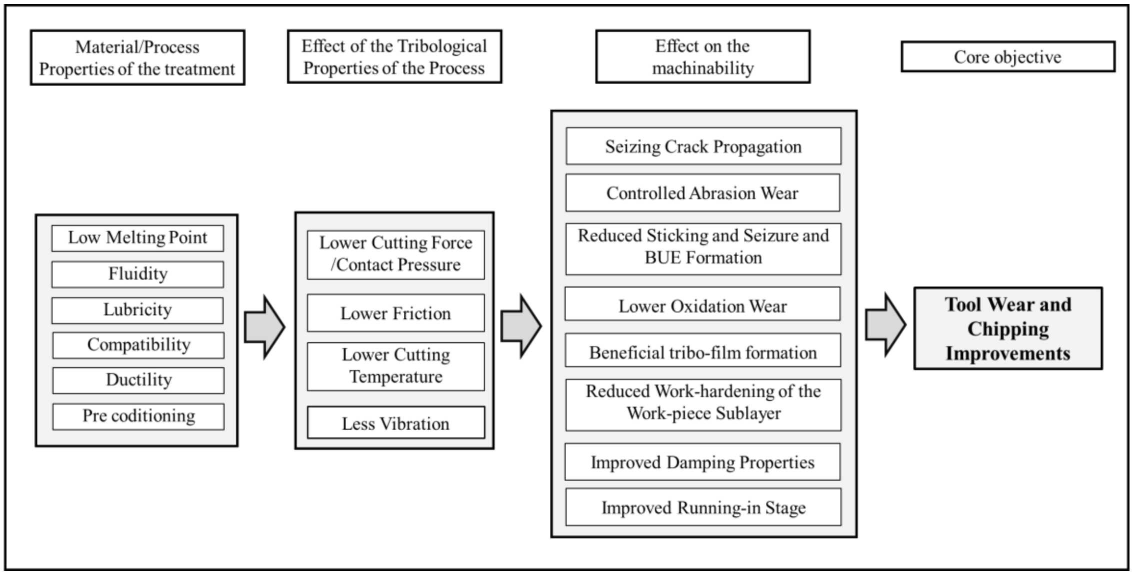

Figure 2-5. Contributing factors and their effects on controlling the chipping and tool wear in the proposed treatment

2.5.2.1 Crack propagation prevention

Chipping usually develops from different defects, especially microcracks on the surface of the tools. These small defects can be formed and propagated during the machining process due to different reasons such as the build-up edge formation and subsequent tearing off, leading to tool chipping and ultimately to the final tool failure. This is very crucial for machining of superalloys and, more specifically, for machining of Inconel 718.

In general, during machining of Inconel 718, very high temperatures of around 1000°C are generated in the cutting zone [13]. In this study, the cutting temperature during machining of Inconel under mentioned conditions were found to be 820°C. An image of the temperature profile obtained from the measurements with the infrared camera is provided in Figure 2-6.

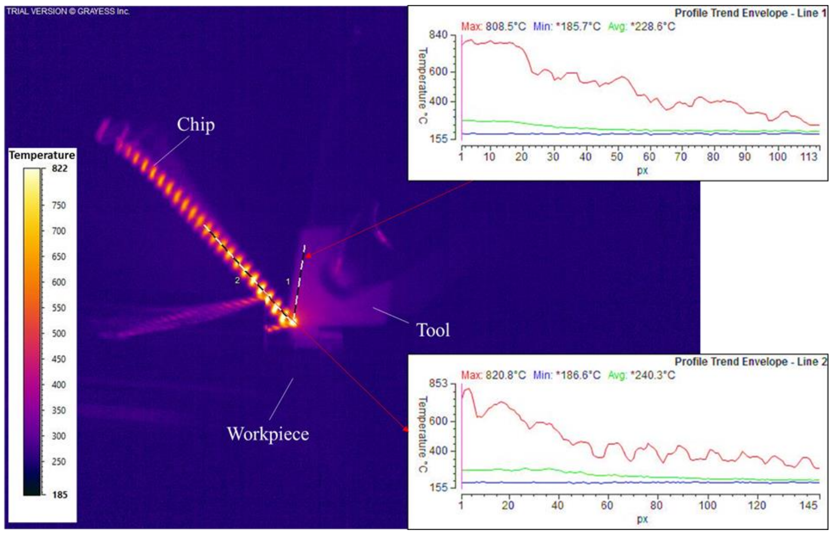

Figure 2-6. Temperature distribution on the tool and chip during machining process of Inconel

Al-Si which is chosen for the premachining process possesses a very low melting temperature of around 577°C [14]. Thus, the Al-Si which is deposited on the tool face during the premachining step melts during the actual machining of Inconel. The molten material can easily channel through the microcracks which are formed on the tool surface and fill them thus preventing them from propagation and weakening the tool. High fluidity and low viscosity of Al-Si are important factors contributing to this process. SEM images of the tool cross section showed that even before machining of Inconel and after just a few seconds of machining of Al-Si, the Al-Si had penetrated and filled the small defects on the tool surface. An example is shown in Figure 2-7.

It should be mentioned that the cutting pressure and forces during machining of Inconel are so high that any imperfection and pre-existing crack on the tools can cause chipping during the machining. Thus, filling the cracks and seizing their propagation can significantly reduce the chance of chipping.

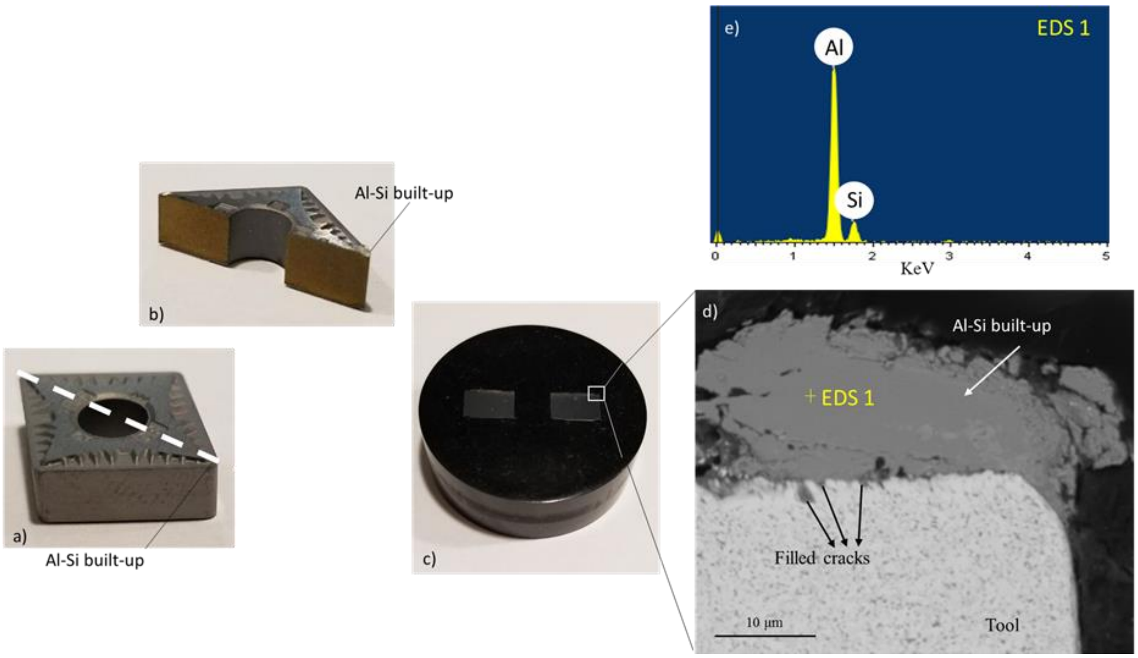

Figure 2-7. a) and b) images of the tool cross-section, c) image of the mounted tool-cross section showing the position of built-up layer on the tool rake face, d) the Backscattered image of the tool cross-section, e) EDS analysis of the built up layer, showing that the bult-up layer consists of Al and Si. The small cracks on the tool edge are filled with Al-Si

2.5.2.2 Controlling abrasion wear via formation of a film between the contact surfaces

It is known that when a film is formed and channeled between the two contacting surfaces, it can reduce the normal force by developing a hydrodynamic pressure between the surfaces, resulting in lower friction and separation of those surfaces [15]. The consequence of this phenomenon in machining will be reduced pressure between the surfaces, represented by lower cutting forces. This phenomenon can be also clearly pronounced and confirmed considering its effect on the two and/or three body abrasion tool wear.

Two and three body abrasion wear occurs when hard particles of the tool or workpiece material abrade the tool surface while moving or rolling between the two surfaces. This results in the formation of scratches, cavities, and grooves on the tool surface. Higher contact pressure between the surfaces will result in a high intensity of particles embedding in the surface and, consequently, deeper grooves forming on the tool surface.

Different hard abrasive carbide particles are present in Inconel 718 resulting in tool abrasion wear [16]. As shown in Figure 2-4, severe grooving is observed on the tool flank face during machining of Inconel. Yet, the grooving is significantly reduced with the premachining treatment, confirming lower contact pressure on the surfaces, due to the presence of the Al-Si film between the two surfaces.

For a more detailed analysis of the two and three body wear mechanisms, the roughness of the tool flank surfaces for treated and benchmark tests were investigated with the Alicona microscope and the results were compared with each other which is shown in Figure 2-8. On average the R_a and R_z of the flank surface of the benchmark after around 500 m of cut were ~ 1 and 2.6 μm, respectively, while, the values for the premachined surfaces were ~ 0.3 and 1.5 μm. The results suggest that grooving and scratches were considerably less after the treatment.

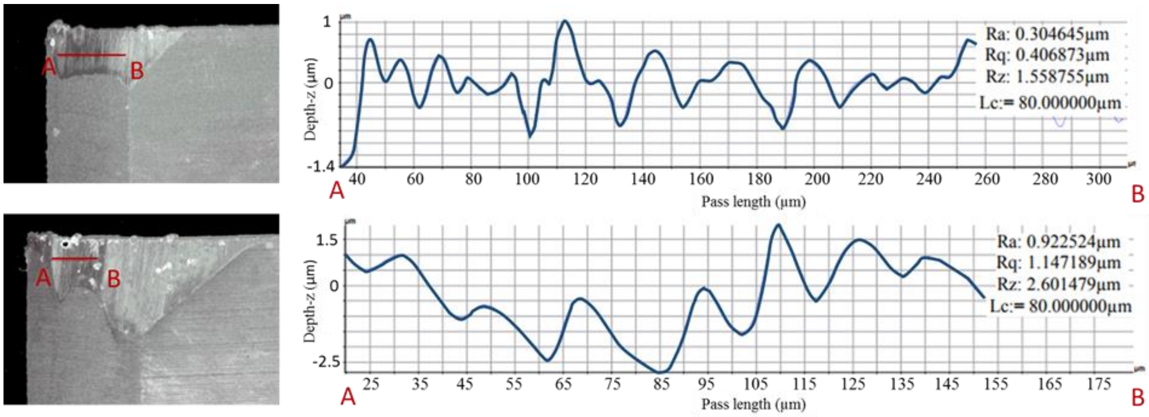

Figure 2-8. Roughness of the tool flank face of a) treated tool; b) benchmark tool

2.5.2.3 Controlling sticking, seizure and built-up edge formation

Sticking or high adhesion wear is considered as another issue of machining of Inconel material [7][17]. High friction and temperatures are responsible for this type of wear. Severe sticking can result in the formation of a built-up edge (BUE) on the tool/chip interface which is also very detrimental for the tool and can on its own result in tool chipping and premature failure.

This phenomenon can be controlled by increasing the lubricity, decreasing the temperature and load and by making an overall improvement in the tribological properties of the contact surfaces. The formation of a lubricious layer at the tool/chip interface, compatible with the tribosystem in place, can help tackle these problems. Thus, Al-Si was chosen for the pre-machining process due to its lubricity, thermal softening at high temperatures and high material compatibility with the materials present in Inconel 718 (this will be discussed further in section 2.5.2.5).

The lubricity and coefficient of friction (COF) of the Al-Si layer formed on the tool face was examined with nano-wear testing.

For this purpose, a series of nano-wear tests were performed on the cross-sections of the tools, passing through the built-up edge layer formed on the tool rake face and the tool core material, after benchmark and pre-machining tests. An image of the tool cross-section, showing the wear tests is presented in Figure 2-9. It is worth stating that the way the cross sections where obtained are shown in Figure 2-7.

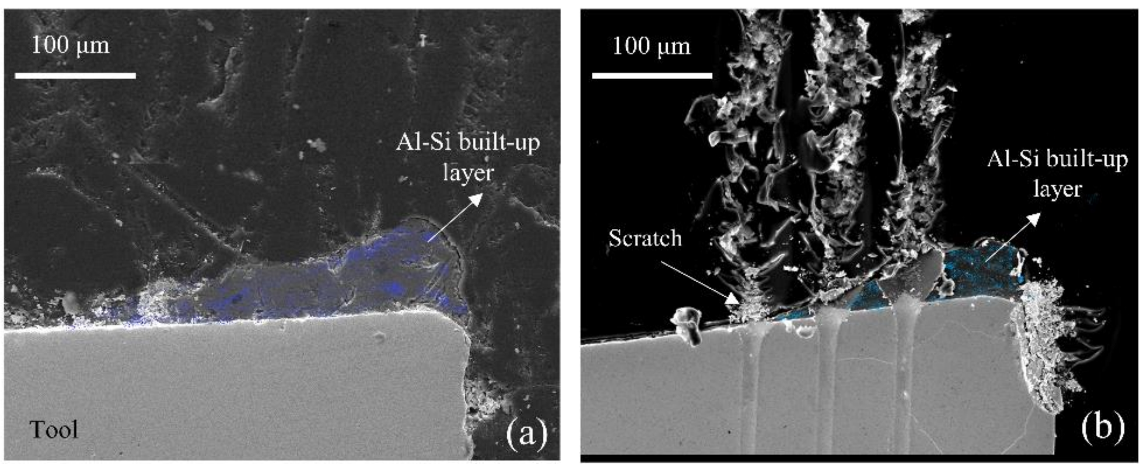

Figure 2-9. Nano-wear tests performed on the tool cross section after the premachining process – The blue layer in the image is the Al-Si layer formed on the tool rake face; a) before Nano-wear test b) after Nano-wear test

The COF corresponding to different built up layers (Al-Si in premachining and Inconel in benchmark testing) in addition to the COF of the tool base material were obtained from these tests and are reported in Table 2-4.

Table 2-4. COF of the tool material and different layers formed on the tool

Material	COF
Al-Si	0.06-0.08
Inconel 718	1.4
WC tool material	0.2

As presented, the COF of Al-Si layer is considerably lower than the corresponding values for the tool and Inconel. After the premachining process, and during the actual machining of Inconel, the low friction Al-Si layer located between the tool and the Inconel workpiece, makes the material flow much easier. This will result in lower friction and a correspondingly lower temperature.

It is worth noting that lubricious molten metals can be used in different tribo-systems as lubricants where high conditions of pressure and temperature exist. Machining of Inconel is one example of a situation where extreme conditions of pressure and temperature exist [18]. This results in severe sticking and seizure on the tool/workpiece interface. Since no lubricant can penetrate into the sticking zone, providing a lubricious layer on this zone before the start of machining can be very helpful. As the actual machining starts, the excess molten Al-Si will be pushed outside the contact zone. Yet, a thin film fills the voids and covers the tool/workpiece interface. The outcome of this phenomenon is clearly reflected in the machining results. As observed in Figure 2-3, the cutting forces are considerably lower for all the sequential machining passes, indicating lower friction and easier flow of material. Also, evidence of significantly lower sticking and seizure in addition to lower cutting temperatures is very clear considering the backscattered images of the worn surfaces of the benchmark and treated tools.

Figure 2-10 shows backscattered images of the flank faces of the benchmark and the treated tool. It should be mentioned that, in the backscattered images, the contrast in the image represents the difference in the atomic mass of the different elements.

The EDS results showed that the sticking zone in both cases is rich in Ni, Cr, Fe, Ti, Nb and Al which are constitutes of the Inconel 718 workpiece material. Though the length of cut in the benchmark is almost 1/3 of the one for the treated tool, the sticking zone is much larger, almost extending across the whole contact zone. As mentioned before, this is a phenomenon which is repeatedly reported in machining of Inconel. Interestingly the sticking zone in the treated tool is very small and only limited to a small area close to the cutting edge where the highest normal stress applies. The results show that the premachining process was very successful in controlling friction and preventing sticking and seizure during machining.

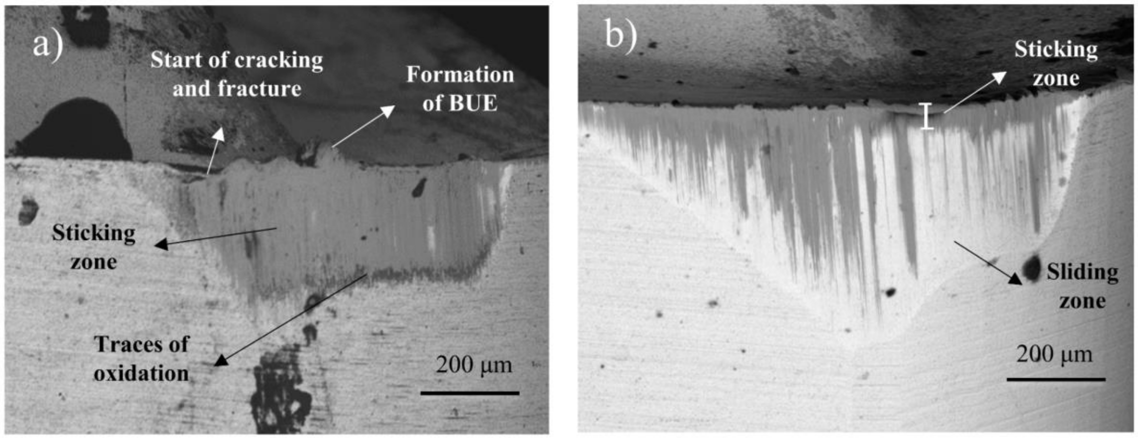

Figure 2-10. Backscattered images of the tool flank face of: a) benchmark after 500 m of cut; b) treated tool after 1550 m of cut

Seizure and severe sticking are often accompanied by the formation of built-up edge on the tool rake face. Formation of an unstable built-up edge can be very harmful to the tool. During the repeated formation and removal of this sticky material from the tool face, cracks and cavities can be formed on the tool progressing to the point where they result in tool chipping and failure. Especially if the material is very sticky and a large size BUE is formed on the tool edge, during its removal, it can break and fracture large pieces of the tool as well. Furthermore, this process can result in force instability that can also lead to tool chipping and premature failure [19]. As can be seen in Figure 2-10, relatively large BUE is formed on the tool rake face during the benchmark testing. Initiation of a crack and fracture on the tool face is also obvious in the image. When machining with the preconditioned tool the cutting length was three times longer than the benchmark tool, yet, no sign of BUE, crack formation or chipping was observed on the tool face.

2.5.2.4 Lower oxidation wear

High thermal compatibility of Al-Si with the tribo-system was expected to result in lower temperature and, thus, in less oxidation wear. This was examined by investigating the EDS images of the worn surfaces with and without the treatment.

In almost all the samples examined, the EDS and elemental mapping of the tool faces, revealed traces of oxidation around the contact area during benchmark testing (untreated tools) which was not observed for the tools prepared through premachining. An example is presented in Figure 2-11.

It should be mentioned here that in the elemental mapping images, the brightness and color contrast of the images represents the concentration of different elements; higher element concentrations are displayed with brighter contrasts in the images.

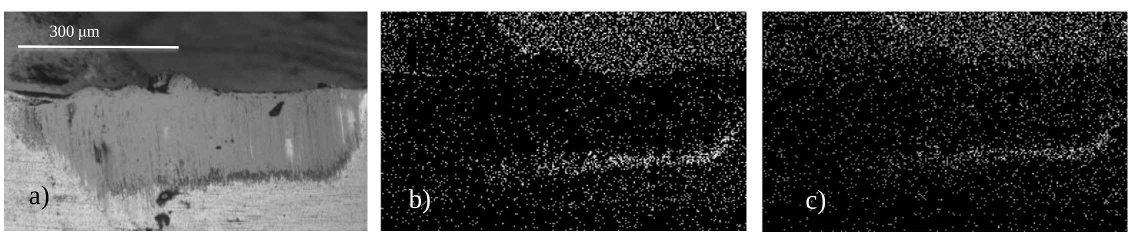

Figure 2-11. a) SEM image of the flank face of the benchmark tool after 500 m of cut; b) Map of Oxygen element performed on the same area; c) map of aluminum element performed on the same area

The oxidation occurring on the tool face is also a sign confirming the generation of higher temperatures during benchmark testing as oppose to the pre-machining process. It should be noted that the oxidation is dominant outside the contact zone, where it is exposed to oxygen.

2.5.2.5 Tribological compatibility and ability to form beneficial tribofilms

Another factor which was considered during the material selection for the premachining process, with the purpose of reducing the friction and temperature, was its compatibility with the tool/workpiece system and its capability to form beneficial tribo-films on the tool-workpiece interface. Thus, Al-Si was chosen, owing to its potential to form various beneficial triobofilms from both silicon and aluminum. Though the existence of silicon in the selected material may seem to impose some machinability concerns, if added to the system in right amounts, it can significantly improve the machinability by promoting various beneficial Si-based tribo films. Therefore, a cost effective grade of Al-Si with low Si content (10%) was selected for the premachining process.

In order to assess the formation of tribofilms, XPS analysis was performed on the worn rake surfaces of the pre-machined tool and the treated tool (received similar premachining process followed by actual machining of Inconel until the end of its tool life). The results are presented in Figure 2-12.

The pre-machined sample contained metallic Al and Al_2O_3 (sapphire) phases in addition to high temperature lubricant SiO_x-tribo-phases.

The treated tool after machining of Inconel contained an Al_2O_3 phase, a noticeable amount of $Al_6Si_2O_{13}$, a mullite tribo-phase, as well as a noticeable amount of SiO_x phase.

Both sapphire and mullite tribo-ceramic films have low thermal conductivity, and thus act as protective thermal barriers on the rake tool face and result in lower transfer of heat to the tool. On the other hand, lubricious SiO_x tribo-phases contribute to higher lubricity, lower friction and thereby to overall improved wear behaviour of the system.

Another important result obtained from the XPS study was the existence of high amount of the mentioned tribofilms forming on the treated tool surface till the end of its tool life. Though the thick layer of Al-Si formed on the tool face will be mainly removed from the tool after machining of Inconel, these results confirm that even after more than 1500 m of cut, a considerable amount of Al-Si is still present in the tribo-system. The XPS results of the tool after 1500 m of cut are presented in Figure 2-12.

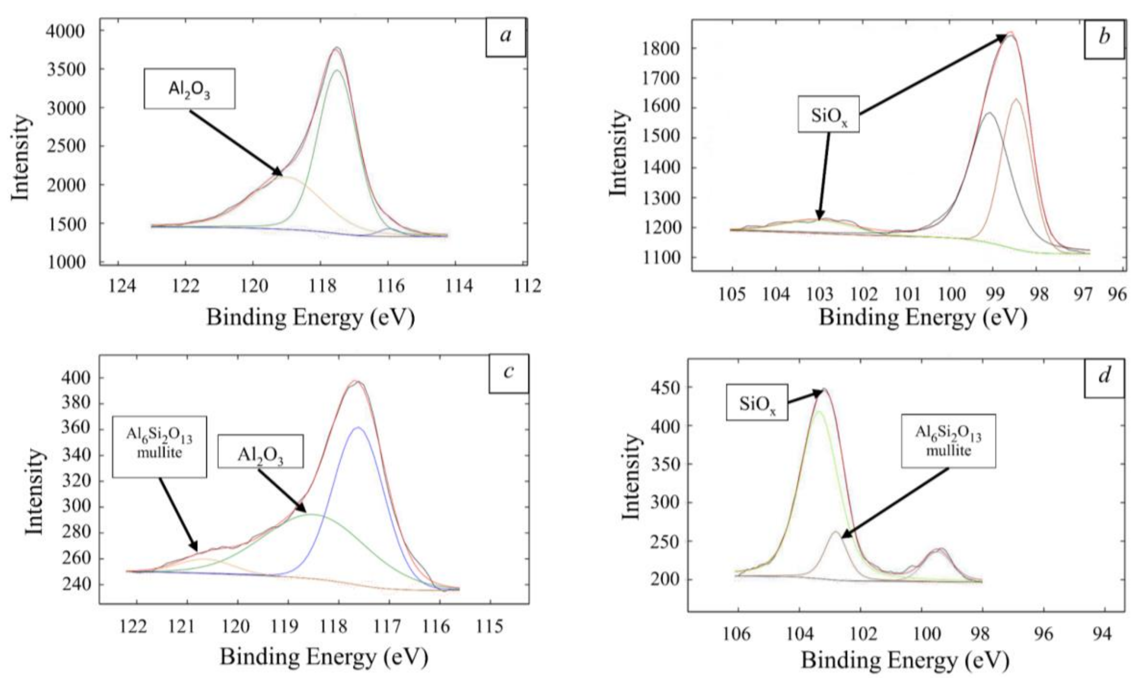

Figure 2-12. HR XPS spectra of the surface of tools. a-b) pre-machined; c-d) pre-machined and worn during machining of Inconel. a, c: Al_2s spectra; b, d: Si_2p spectra

2.5.2.6 Effect of pre-machining process on the work-hardening of the workpiece material

Near surface work-hardening of the workpiece material is still considered a significant factor negatively affecting the machinability of Inconel materials, resulting in severe chipping, notch wear, and tool fracture.

Another significant achievement of this study was reducing the work-hardening of the workpiece sub-layer through the application of the novel proposed treatment. As discussed above, the new method was very successful in improving the tribological properties of the cutting process, including improving the lubricity and friction, lowering the contact pressure and temperatures. These improvements, in turn, result in less work-hardening of the workpiece material during the machining process.

In order to assess the machinability induced work-hardening of the workpiece sub-layer, with and without the treatment, the nano-hardness profiles of the workpiece sub-surfaces were obtained, by applying nano-indentation tests on the different samples. Three series of nano-indentations, each consisting of a total number of 25 indentaions, were performed along a line perpendicular to the workpiece machined surface. The space between each indentation was 1µm.

The results showed a considerable reduction in the work-hardening of the workpiece material near the surface of the treated samples. The results are presented in Figure 2-13.

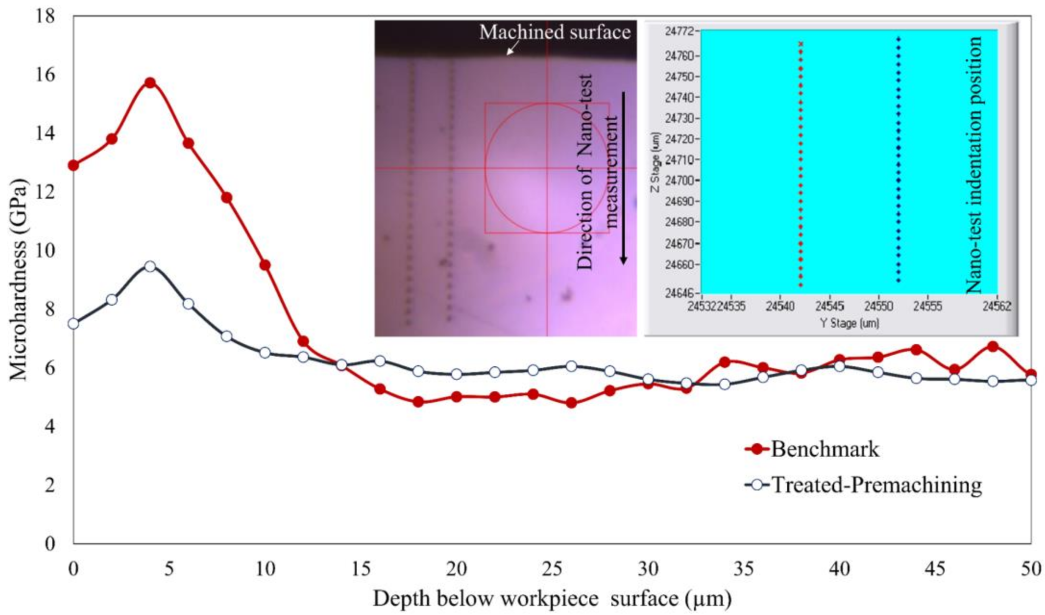

Figure 2-13. Nano-hardness profile of the machined subsurface after benchmark and treated testing

Reduced work-hardening of the sub-surface significantly affects the overall machinability of the material and results in reduced tool wear and chipping. Notch wear, which is typically developed due to the workhardening of the surface, will be considerably reduced resulting in less chipping occurring.

2.5.2.7 Improving damping properties

Chatter and vibration, especially in intermittent cuts, are also responsible for tool chipping and can be very detrimental for brittle tools.

Moreover, at the beginning of the cut, when the tool is very sharp, the shock of the initial contact can result in small defects on the tool which can result in premature tool failure [20]. This is very common for difficult to cut materials like Inconel 718. Thus, depositing a ductile film on the tool surface can help negate these phenomena, allow the tool to ease into cut and prevent the early onset of chipping and tool failure.

The Al-Si selected for the pre-machining process has a very high ductility and can act as a damping film on the tool and protect the tool from chipping, especially at the beginning of the cut, when a thick layer covers the whole cutting edge.

Premature failure of the uncoated tool after only a few machining passes was repeatedly observed during the experiments. An example of tool failure after only 120 m of cut is presented in Figure 2-14. This phenomenon was significantly reduced after the pre-machining process.

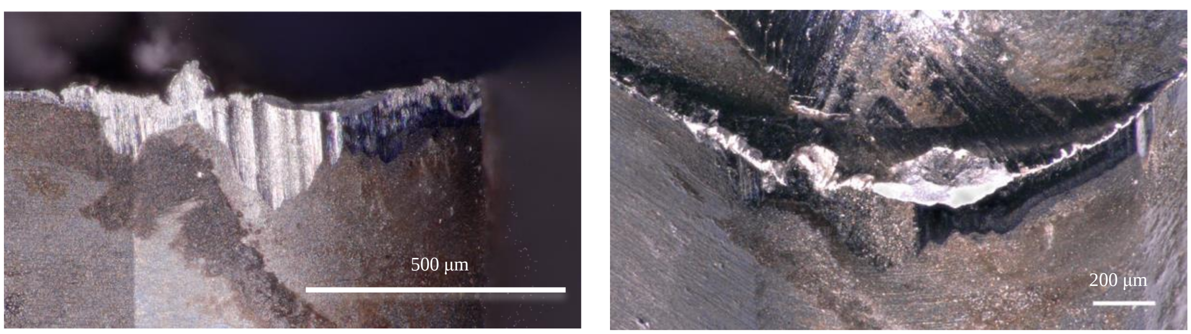

Figure 2-14. Tool failure in a benchmark tool after around 120 m of cut (Front and top views)

2.5.2.8 Preconditioning the surface and effect on the running-in performance

Pre-conditioning the contact surfaces, including prior sliding of the contact bodies before establishing full process conditions of heavy loads and high temperatures can affect the running-in stage performance of the tribo-system. Achieving an improvement in the tribological characteristics at the running-in stage is known to improve the overall tribological properties of the system and in machining this results in lower tool wear and cutting forces [21].

Improvements in tool wear and cutting forces in the running-in stage can be observed in Figure 2-2 and Figure 2-3. As seen in the results, both tool wear and forces in the first step for the treated tool are considerably lower than the corresponding values for the benchmark tests.

2.6 Conclusions

The purpose of this study was to introduce a novel, simple and effective tool treatment technique for reducing chipping and improving tool life during machining of Inconel 718. The treatment included "pre-machining" of Al-Si for around a second before using the same tool for the machining of Inconel 718. Through this process, a uniform and thin layer will be formed on the tool edges covering a large portion of the tool edges. During the subsequent machining of Inconel with the treated tool, the Al-Si layer will be molten due to the high generated cutting temperature. The excess material will be pushed out of the contact zone. However, a thin film forms between the tool and workpiece which protects the tool from chipping and contributes to the overall better machinability of the material in different ways presented as follows:

- Microscopy analysis of tool faces showed that as the Al-Si melts during the machining process, it fills the cracks and cavities on the tool and prevents them from propagation thus significantly reduces the chipping. Tool wear results showed significant reduction in chipping and around 300% tool life improvement over untreated tool.

- Comparing the roughness of the treated tools and untreated tools and analysis of tool surface morphology revealed that the two body and three body tool wear mechanisms were considerably reduced as a result of the presented treatment.
- EDS results showed oxidation wear was much less after the treatment compared to the untreated tool.
- Cutting forces were reduced by 40-50% compared to the untreated tool.
- SEM analysis of the worn surfaces showed that BUE formation was considerably reduced by the treatment.
- XPS analysis of the tool worn surfaces showed that several beneficial lubricious and thermal barrier tribo-films were formed on the tool surfaces that were present on the tool-chip interface till the end of tool life.
- The nano-indentation results performed on the workpiece sub-surfaces, showed around 45% reduction in work-hardening of the workpiece material through this process. This significantly affects the overall machinability of Inconel and results in tool wear and surface integrity improvements and chipping prevention.
- Tool wear studies showed that the tool wear at the running-in stage was reduced compared to the untreated tool which improves the overall performance of the tribo-system.

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3 Chapter 3

An Investigation of the Effect of a New Tool Treatment Technique on the Machinability of Inconel 718 During the Turning Process

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Relative Contributions:

Saharnaz Montazeri:	Writing – original draft preparation, Conceptualization, Methodology, Investigation, Perform all the experimental studies.
Maryam Aramesh:	Conceptualization, Methodology, Writing – review and editing.
Stephen. C. Veldhuis:	Supervisor of the paper.

An investigation of the effect of a new tool treatment technique on the machinability of Inconel 718 during the turning process

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3.1 Abstract

Though Inconel 718 alloy possesses excellent material properties and has various key applications in different industries. However, it still suffers from severe machinability issues and is considered one of the most difficult-to-cut materials. In this paper, a new and simple method is proposed to improve the machinability of Inconel 718 by forming different ductile and lubricious layers at the tool tip prior to its application for machining. Previous research showed that this method is very successful at improving the tool performance. In the current study, an enhancement of the proposed method is presented. Prior to the actual machining of Inconel, very short cuts of around two seconds were performed on an Al-Si and/or cast iron workpiece to form very thin layers of these materials on the tool rake face. During the subsequent machining of Inconel, the built-up material on the tool face has melted and the excess material was pushed out of the contact zone, with just a thin film remaining on the tool. This thin film protected the tool from chipping and considerably improved the tool life and the integrity of the machined surface. Results indicate that the tool treated with both cast iron and aluminum possessed a maximum tool life increase of 204%, a 45% lesser cutting force and a 59% reduction in machining induced work-hardening compared to the uncoated tool. All of the treatments displayed significantly reduced chipping. The following mechanisms contributed to these improvements: filling of the tool microcracks and prevention of their propagation, friction reduction enabling greater control over adhesion, seizure and built-up edge formation, improvement of the running-in stage of tool wear by preconditioning the tool surface prior to its main application, formation of various lubricious and thermal barrier tribo-films on the tool tip, control of different tool wear mechanisms such as adhesion, abrasion and oxidation. All these mechanisms are discussed in details using various characterization techniques.

Keywords: Inconel 718, Tool-treatment, Tool wear, Work-hardening.

3.2 Introduction

Inconel 718 is a type of nickel-chromium-iron alloy with superior characteristics such as high mechanical strength at evaluated temperatures, corrosion resistance, and high oxidation resistance [1]. It is widely used for producing parts operating under extremely high temperatures such as turbine blades, pressure vessels, aircraft engines, and nuclear reactors [2]. In recent decades, Inconel 718 was extremely used for aerospace and jet engine components [3], [4]. However, machining of these alloys is very difficult because of their low thermal conductivity, high shear strength, high hardness, work hardening tendency, the presence of abrasive carbide particles, and high reactivity with tool materials [5], [6]. The greatest machining challenge posed by these materials is their high-temperature strength and extreme toughness [7]. As a result, work hardening occurs rapidly during machining, leading to aggressive abrasive wear and rapid tool wear [8]. In addition, due to the low thermal conductivity of this alloy, the temperature at the cutting zone rapidly exceeds 900°C [9], [10]. The heat transferred to the tool leads to wear acceleration and thus tool life reduction [11], [12]. Also, at high temperatures, Inconel 718 has a tendency to weld to the tool material to form an adhesive layer that leads to built-up edge (BUE) formation [13]. The disintegration of the unstable BUE generated on the tool edge causes severe tool failure and chipping [14]. Due to their high strength and work hardening, the high cutting forces are responsible for extreme temperature and tool wear [15]. As mentioned before, hard carbide particles (HfC, NbC and TiC [16]) in the microstructure of Inconel 718 abrade the tool edge and cause severe abrasive wear [17].

Taking these factors into account, tool selection for this class of material requires special attention. The cutting tools should have good wear resistance, desired thermal properties, high hardness, and high toughness [10]. The most common tools for the cutting operation of Inconel 718 are carbide tools due to their good balance of fracture toughness and resistance [18]. Thus, carbide tools are commonly used for machining Inconel 718. However, because of their low thermo-mechanical stability, they still suffer from chipping and tool failure and cannot be used in high-speed machining processes. Many studies have been done to improve overall tool life and chipping resistance of the tool during machining of Inconel 718. To achieve this purpose, researchers tried different ways such as using different machining strategies [19], different tool design [20], different coolant deliveries [21], and different tool coatings[22]. Among mentioned methods, coating the tool itself is the most common method for improving performance by improving wear resistance and increasing the tool life. However, debonding of the coatings from their substrates, the high cost of coating preparation and tool edge fracture due to the disintegration of the hard coatings are listed as the main problems associated with the use of currently available coatings.

To deal with these problems, in our previous study Aramesh et al. [23] introduced a new tool treatment technique for the machining of Inconel 718. This technique consists of depositing a uniform and thin layer of a soft, lubricious, ductile, low melting point metal on the face of the tool. The proposed simple method for putting this thin layer in place is through the machining of the selected metal bar for a brief period of time, prior to the actual machining of Inconel 718. The previous study showed that Al-Si was a very suitable material for this purpose and was successful in tackling most of the listed machinability challenges of this material which included significant reduction of chipping, tool wear improvement, reduction of the chipping and enhanced integrity of the workpiece surface. In this study, the selected materials for the treatment technique are Al-10%Si and cast iron. The tool was treated with each material separately and also both materials were combined for another treatment. The results are compared with each other and the best combination was found to be that of Al-Si and cast iron.

Based on results obtained in this study, this simple method demonstrated a significant boost in tool life and chipping prevention through different mechanisms. To the best of our knowledge, the results achieved in this study in reducing the machined surface work hardening and cutting force as well as simultaneously observed significant tool life improvement are unsurpassed by any other similar study.

A complete machinability study was performed, including investigation of tool life, tool wear mechanisms, cutting forces, friction, sub-layer work-hardened layer, tribofilm formation and microstructural analysis of the contact surfaces.

3.3 Experiment setup and design

3.3.1 Microstructure and chemical composition of Inconel 718, Al-10Si and cast iron

The workpiece material of this study is a bar of Inconel 718 with a surface hardness around 32-36 HRC. The chemical composition of the workpiece material is presented in Table 3-1. The matrix phase of Inconel 718 is a gamma (γ) as a face-centered cubic (FCC) austenitic phase which contains the specific amount of solid solutions such as Fe, Cr, and Mo. There are two strengthening phases precipitated in the grains. These two precipitated phases are nickel aluminum titanium [$Ni_3(Al\ Ti)$] known as a gamma prime (γ′) and nickel niobium (Ni_3Nb) phase known as gamma double prime (γ″). The Inconel 718 also contains carbide particles such as niobium carbide and titanium carbide which are precipitated at the grain boundaries. Figure 3-1.a shows the different phases of Inconel 718 [24]. These carbide particles at the grain boundaries make machining of the material very difficult. They can result in severe abrasive wear and also result in high cutting forces [25].

The presented method, referred to in this paper as a "treatment process", which is performed prior to the actual machining of Inconel 718, a thin layer of soft and/or lubricious material was deposited on the tool tip through a short turning process. In this study, two different metals were examined during the treatment process: Al-Si 10% and ductile cast iron. The reasons for selecting these two materials will be explained below.

The microstructure of Al-10Si is shown in Figure 3-1.b. The microstructure of the Al-10Si alloy consists of eutectic Si particles (gray color), α -Al phase (white color), and few primary silicon particles (gray color). Al-10Si contains hard and brittle Si particles in a soft Al matrix [26]. Al-10%Si is selected because of the low melting point, low coefficient of friction, good ductility, and high reaction to oxygen. A cost-effective grade of Al-Si with a low amount of Si (10%) was selected for the treatment process. The Si in the Al-alloy promotes the formation of the beneficial Si-based tribofilms during the high temperature machining process. However, a low Si content is selected to avoid its machinability issues.

Cast iron consists of spheroidal graphite particles which are evenly distributed in a ferrite and/or pearlite matrix. Figure 3-1.c shows the microstructure of cast iron. Due to the presence of graphite nodules in cast iron's microstructure, it possesses high ductility, strength and also excellent wear resistance [27]. The graphite present in cast iron has a very beneficial effect on the friction coefficient as graphite is lubricious and is known to provide a self-lubricating metal base in many applications [28].

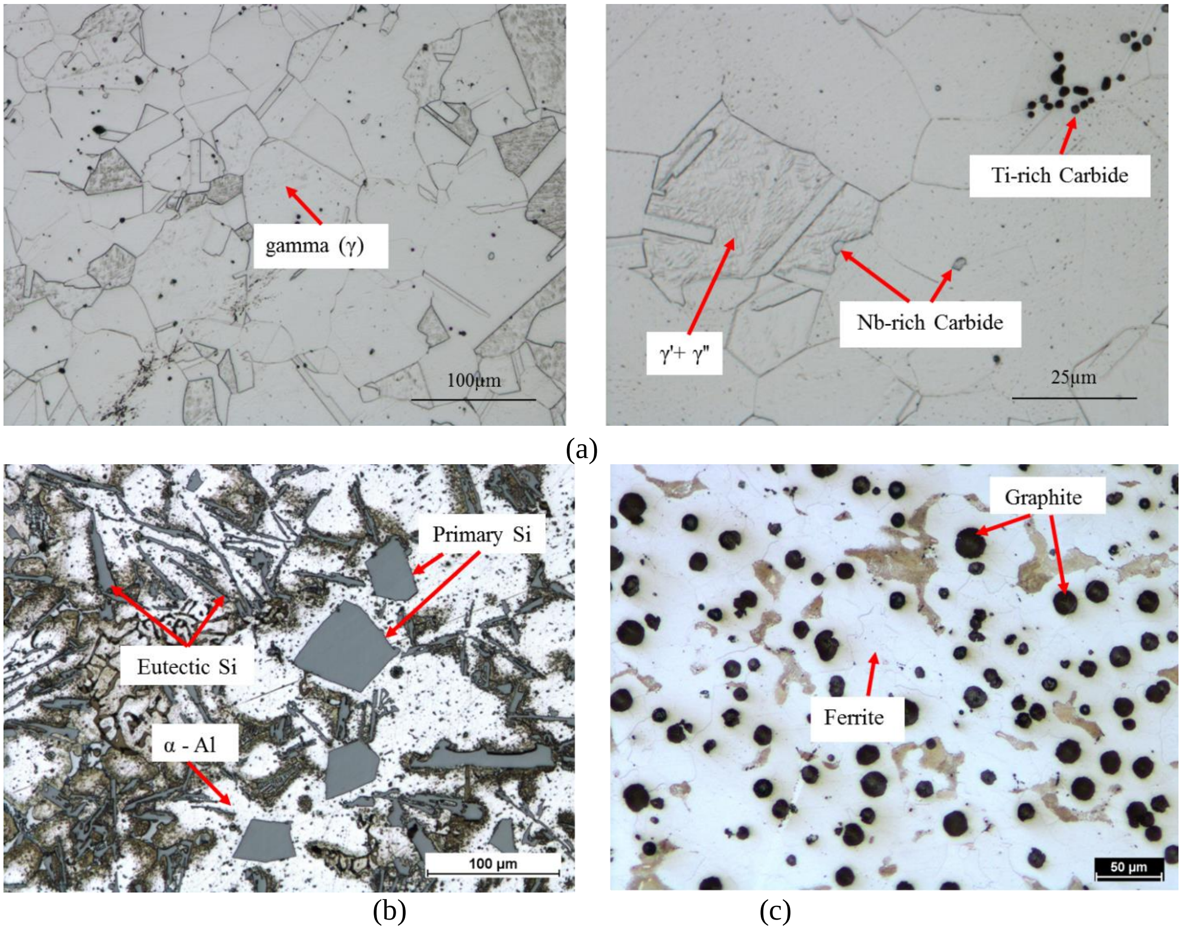


Figure 3-1. Microstructure of a) Inconel 718, b) Al- 10%Si and c) Ductile Cast iron

Table 3-1. Chemical Composition of Inconel 718

Material	**Ni**	**Cr**	**Fe**	**Mo**	**Nb**	**Ti**	**Al**	**Cu**	**Mn**	**Si**	**C**	**S**	**Co**	**P**	**Ta**	**B**
Inconel 718	55.6	17.2	15.65	2.9	5.24	1	0.6	0.3	0.35	0.35	0.08	0.015	1	0.015	0.05	0.006

3.3.2 Experimental methodology

Turning tests were performed on a Boehringer VDF 180 CNC lathe. The experimental setup is shown in Figure 3-2. For the wet machining tests, a semi-synthetic CommCool HD water-based coolant with a concentration of 5% and pressure of 7 bar was applied. Tungsten carbide tools of grade K313 and specifications of CNGG120408FS (from

Kennametal) were used for the machining tests. The rake angle was 5° and nose radius was 0.4 mm.

There are two machining steps in this research:

Step 1) tool treatment process: a very short turning pass of around two seconds is performed on the workpiece bar (Al-Si and/or ductile cast iron) with the uncoated carbide tool under dry conditions.

Step 2) actual machining: the tool used in the previous step is utilized for machining Inconel 718 under wet conditions.

During the tool treatment step, a thin and uniform layer (Al-Si and/or ductile cast iron) is formed on the carbide tool surface. This process effectively coats the tool surface with materials of Al-Si and ductile cast iron. As will be discussed in the following sections, this is a very simple method for depositing a thin layer on the cutting edge but other methods more amenable to mass production could be developed to achieve the same result.

An example of the treated tool with Al-Si is shown in Figure 3-3. The thickness of the deposited layer is around 40 ±5 µm. In step 2, the treated tool is used for machining of Inconel 718, and its resultant performance is compared with the uncoated tool.

The tools used for machining of Inconel, with a short description of their treatment method in step 1, are labeled below (summarized in Table 3-2):

T1: uncoated tungsten carbide; no treatment

T2: tool treated with Al-10%Si; a very short turning pass of about two seconds was performed on the AlSi bar.

T3: tool treated with cast iron; a very short turning pass of about two seconds was performed on the ductile cast iron bar

T4: tool treated with both Al-10%Si and cast iron. In this case, the tool underwent two turning tests before machining of Inconel 718. First, a thin layer of Al-10%Si was deposited on the tool material through one or two seconds of machining with Al-10%Si, followed by the same process for the cast iron.

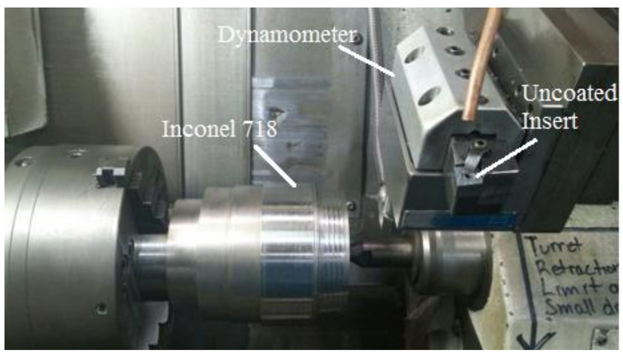


Figure 3-2. Experimental setup for machining of Inconel 718

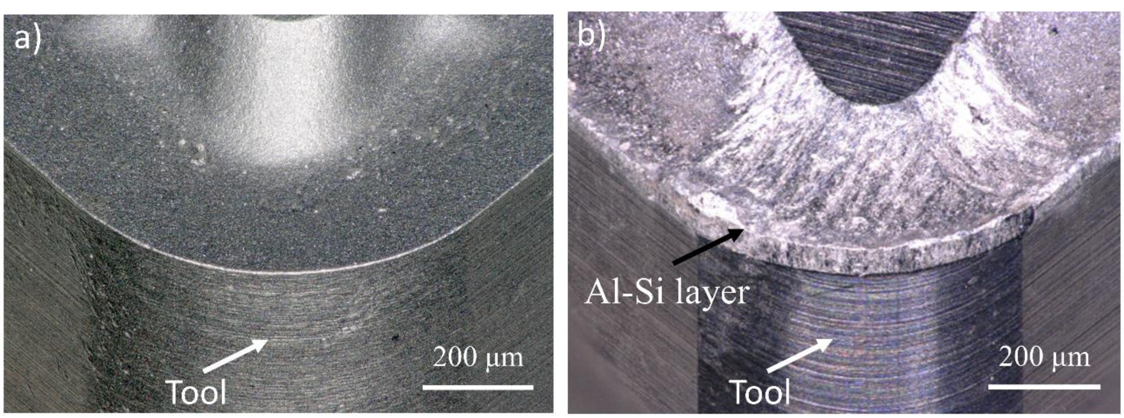


Figure 3-3-The layer formed on the tool through the treatment process: a) uncoated carbide, b) treated tool

Table 3-2. Carbide benchmark and treated tools used for the experiment

Cutting tools		Name
Uncoated carbide tool		T1
Treated tools	Treatment materials	
	Al-10%Si	T2
	Cast iron	T3
	Al-10%Si and cast iron	T4

Having a thick and non-uniform build up layer on the treated tool will increase the probability of tool chipping. Therefore, finding the proper conditions for the treatment process is very important. In addition, the thin layer should cover the entire cutting engagement zone on the tool when it is subsequently used to machine Inconel 718. Full coverage is important to ensure that the edge is protected from chipping and notch wear. To provide this uniform layer, a high cutting speed and a low feed rate were selected for the treatment process. A high depth of cut is also selected to assure the maximum coverage. The best cutting conditions for tools treated with Al-10Si and cast iron, as shown in

Table 3-3, were established after a few trial cuts were performed in order to achieve a smooth and uniform thin layer at the tool tip. Cutting speed for each selected material was based on the maximum speed at which proper build up layer form on the tool with the required properties. Since aluminum is softer than cast iron, the selected cutting speed for aluminum was higher. As mentioned, the total cutting time used for the treatment process was very short. The minimum cutting time which provides the thin build up layer with the requisite properties were selected to avoid wear affecting the tool. The minimum cutting time for the treatment process for both materials was around two seconds. It should be mentioned that during the treatment process of T4 (tool treated with both Al-10Si and cast iron), the cutting conditions for Al-10Si and cast iron treatments were the same as those used for T2 and T3 respectively.

In general, the range of the cutting speed for machining Inconel 718 with uncoated and coated tools, is around 20-30 m/min due to the poor machinability of this alloy [29]. Applying higher cutting speed around 50 m/min results in severe tool chipping and rapid tool failure. In addition, to avoid failure due to significant notch wear which is caused as a result of machining the work hardened layer of the workpiece surface, high feed rates and depth of cuts are recommended [30]. However, to observe the performance of the new technique under aggressive conditions and conserve material, a severe cutting condition (high cutting speed and low feed rate and depth of cut) was selected. The cutting conditions used for the tools treated with Al-10%Si, cast iron and the combination of both, as well as the Inconel 718 machining test, are shown in

Table 3-3.

Cutting, feed and radial forces during machining were measured with a Kistler dynamometer. Tool wear values were measured and tool wear pictures were taken using a Keyence VHX-5000 digital Microscope. In addition, material microstructure was obtained using a Nikon ECLIPSE Ni-U microscope. Material characterization of the tool and workpiece was done on a Tescan Vega II LSU Scanning Electron Microscope (SEM) which is equipped with an Oxford X-Max 80 Energy-Dispersive X-ray Spectroscopy (EDS) detector and Inca software. Wear test for the friction and nano-hardness tests of the work hardened surface were done on a Micro Materials NanoTest system. Nanoindentation was performed in a load controlled mode with a Berkovich diamond indenter calibrated for load, displacement, frame compliance, and indenter shape, according to the procedure outlined in ISO14577-4. The VarioCAM HD 1024 infrared camera with a resolution of 1024 × 768 pixels and video frame frequency of 30 Hz was used to evaluate the machining temperature during the turning of Inconel 718. According to the Keller et al [31], the emissivity for the current study was considered 0.27 for the temperature measurement. The temperature measurement was done on dry condition and an assumption was done for the wet condition. The identification of different tribofilm formations on the cutting tool was performed by X-ray photoelectron spectroscopy (XPS) equipped with a Physical Electronics (PHI) Quantera II spectrometer with a hemispherical energy analyzer.

Table 3-3. Cutting conditions used for different machining processes

Cutting Parameters		Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)
Benchmark/Actual machining		50	0.1	0.15
Treated tools	Al-10%Si	450	0.06	1
	Cast iron	250	0.06	1

3.4 Results and discussions

3.4.1 Tool life measurements

In this study, tool life was evaluated by measuring the flank wear and assessing edge quality. Since the tool chipping is the main problem during machining of Inconel 718, any tool chipping or flank wear exceeding 0.3 mm (according to ISO 3685), whatever occurred first, were considered for the end of the tool life criterion. The reason for considering the tool chipping as the end of the life is that all the tools faced complete failure after a pass or two after the occurrence of chipping. Figure 3-4.a shows the average flank wear vs cutting time and Figure 3-4.b shows the flank wear measurements at different cutting time of the benchmark without treatment (T1) and tools treated with Al-10%Si (T2), Cast iron (T3), and Al-10%si/Cast iron combination (T4) during the machining of Inconel 718. All the experimental tests were repeated at least three times at the same conditions.

The results show a considerable improvement for the treated tool as compared to an uncoated one. This method achieved an increase in tool life of 169% for T2, 114% for T3, and 205% for T4, which to the best of our knowledge is unsurpassed by the results of all other methods and coatings. In the following paragraphs, the main problems with machining Inconel and how this novel technique overcomes them, using each treatment material, will be discussed in detail.

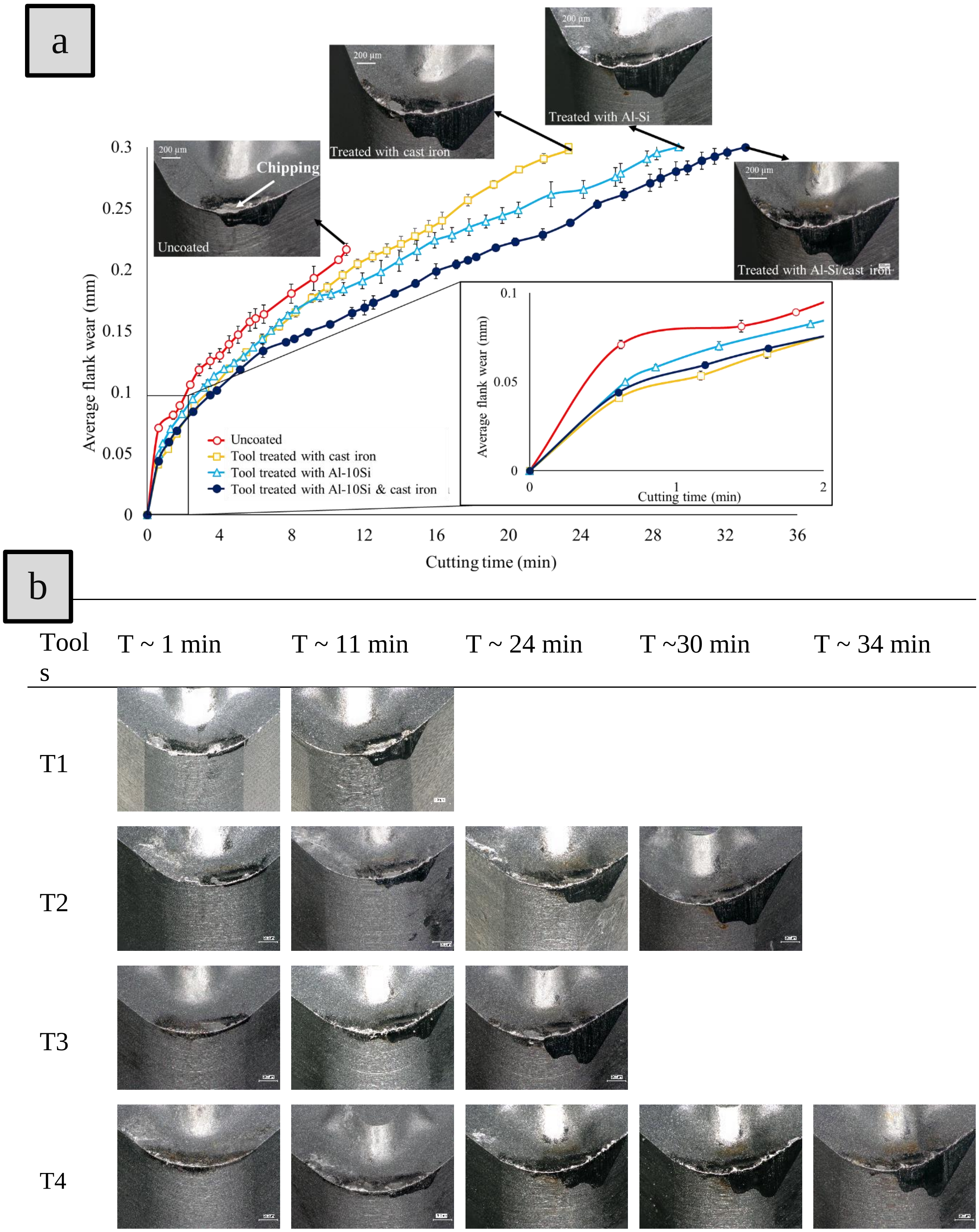
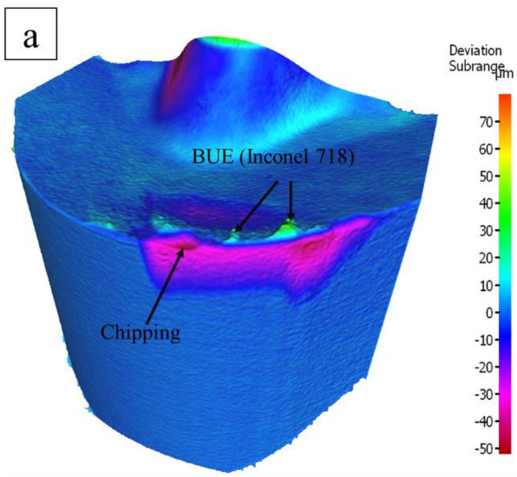


Figure 3-4. a) Flank wear vs cutting time, and b) flank wear measurement at different cutting time (T) for uncoated and treatment inserts during machining of Inconel 718

High temperatures and pressures at the cutting zone, combined with low cutting speeds during the machining of Inconel 718 leads to BUE formation. The BUE is an unstable structure that forms and breaks periodically. BUE breakage can result in crack formation and propagation in the cutting zone. The generated cracks result in the tool chipping after a few passes of the machining process. Inconel 718 is a material which has a high tendency to stick to the tool material and form BUE during the machining process. In addition, due to this tendency for work hardening, tool chipping and notch wear pose the main problems in machining of Inconel 718. The probability of BUE formation and breakage is high during machining of Inconel 718, especially if a lower depth of cut is selected. As mentioned, a low depth of cut was selected for machining of Inconel 718 to evaluate the new treatment technique at a severe condition, this concentrated the cutting load at the tip of the tool further promoting chipping. Furthermore, when the tool is sharp, tool-workpiece contact is low and the possibility of tool chipping and failure is higher. As can be seen in Figure 3-4.a the treated tools perform very well under these severe conditions, significantly better than the untreated tool. All the uncoated tools were chipped between 10 and 12 minutes of cut due to BUE formation on the tool and work hardening of the machined surface. Since the tool chipping was considered as the end of tool life criterion, the tests for the uncoated tools were stopped when the chipping was observed at the cutting edge. For chipping detection, all of the tools were assessed with a white light interferometer with a focus variation technology. For this purpose, the volume of the tool after chipping was compared with the new tool. An example is provided in Figure 3-5 where tool chipping occurred for an uncoated tool after a cutting time of around 11 min. The volume removed from the tool material (Vv) is provided in Figure 3-5.a. Moreover, the volume of the workpiece material sticking to the uncoated tool (Vp) can be also obtained with this technique, which was used in this study for comparing the adhesion of the built-up edge material to the tool rake faces after each treatment. Figure 3-5.b shows the SEM image of tool chipping occurred on the uncoated tool after 11 min of cut.



Name	Description	Value (µm³)
Vp	Volume of peaks above reference surface	1124524.552371
Vv	Volume of valleys below reference surface	4245502.606901

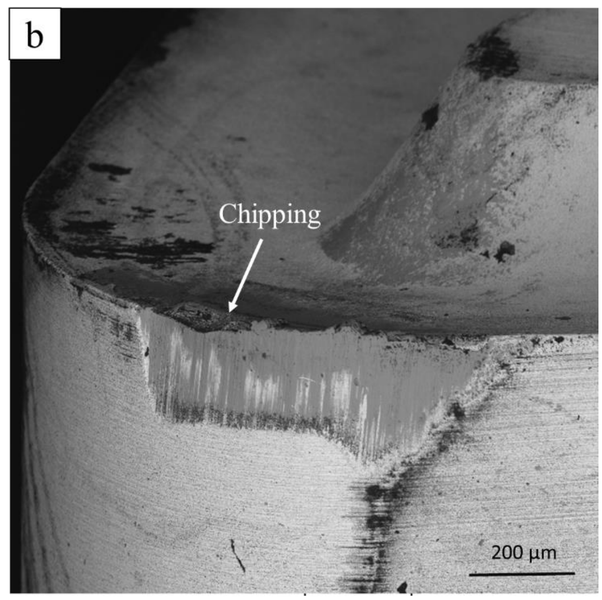


Figure 3-5. Chipping of the benchmark at the 11 min of cut (end of tool life) during machining of Inconel 718; a) volumetric measurements with white light interferometer with focus variation technology b) SEM image of the chipped tool

The machining temperature of Inconel reaches very high values. In dry machining conditions, our measurements with VarioCAM HD 1024 infrared camera (Figure 3-6) showed temperatures exceeding 820°C. Considering the similar works reported in open literature for machining conditions the temperature during machining of Inconel can reach the melting point of Al-10%Si (577 °C) [10]. Thus, the Al-Si deposited on the tool tip can melt at the high temperature generated during the machining of Inconel 718. Figure 3-7 shows BSE images of cracks filled with the molten Al-Si material at the tool cross-section. Filling the microcracks of the tool increases the tool's strength and prevents crack propagation, which reduces tool chipping significantly. A low coefficient of friction is the other property of the aluminum material which plays an important role in its selection for the tool treatment process. Reduced friction of the Al-Si layer located between the tool and Inconel interface during actual machining, improves the workpiece material flow. As a result, the probability of built-up edge formation and adhesion decreases, which leads to lower tool wear and tool chipping. Figure 3-8.a and 8-b show BUE formation on the uncoated tool and the tool treated with Al-Si after 1 min of cut. As can be seen, a lesser amount of BUE (Figure 3-8.b) compared to the benchmark (Figure 3-8.a) forms on the treated tool due to the lower friction of the deposited layer. As can be seen, a notch wear was formed on the benchmark, even after one minute of cut. Whereas, no sign of notch wear was observed on the other treated tools due to the lower forces and friction and controlling of work hardening (which will be discussed in section 3.4.5). Furthermore, Al-Si possesses high compatibility with oxygen to form beneficial tribo-films on the tool-workpiece interface. The XPS results shown in Figure 3-9, confirm the formation of beneficial tribofilms. The mullite ($Al_6Si_2O_{13}$,) and sapphire (Al_2O_3) tribofilm phases have a low thermal conductivity which can protect the tool from the high temperature generated during machining. Also, SiO_x tribo-phases provide lubrication at the tool-chip interface. Thus, formation of these beneficial tribofilms at the tool-chip interface results in lower temperature generation, wear reduction, and consequently lower tool chipping. Moreover, aluminum is a ductile and lubricious material which dampens the initial contact shock between the tool and workpiece, reducing initial flank wear and tool chipping. As can be seen in Figure 3-4.a, the life of the tool treated with Al-Si (T2) is more than two times higher than the benchmark (T1) due to the effect of all the parameters mentioned above. Tool chipping and work hardening are the main problems of Inconel machining which are both reduced with this novel treatment method.

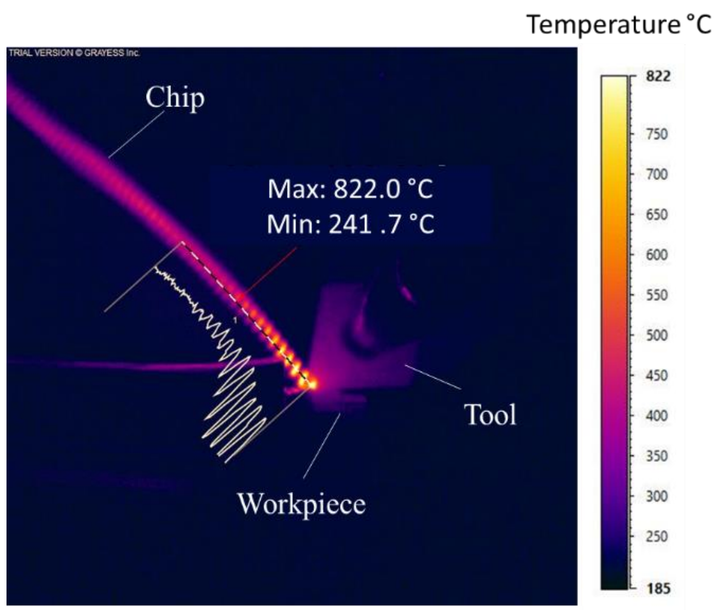


Figure 3-6. Temperature distribution at the tool-chip interface during machining of Inconel 718

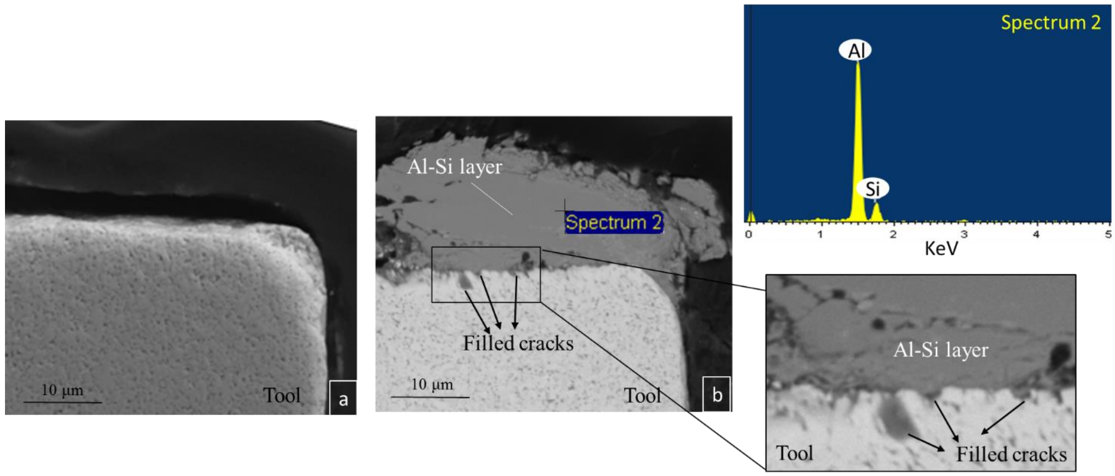


Figure 3-7. Back-Scattered images of the cross-section of a) benchmark and b) treated tool with Al-Si (T2)

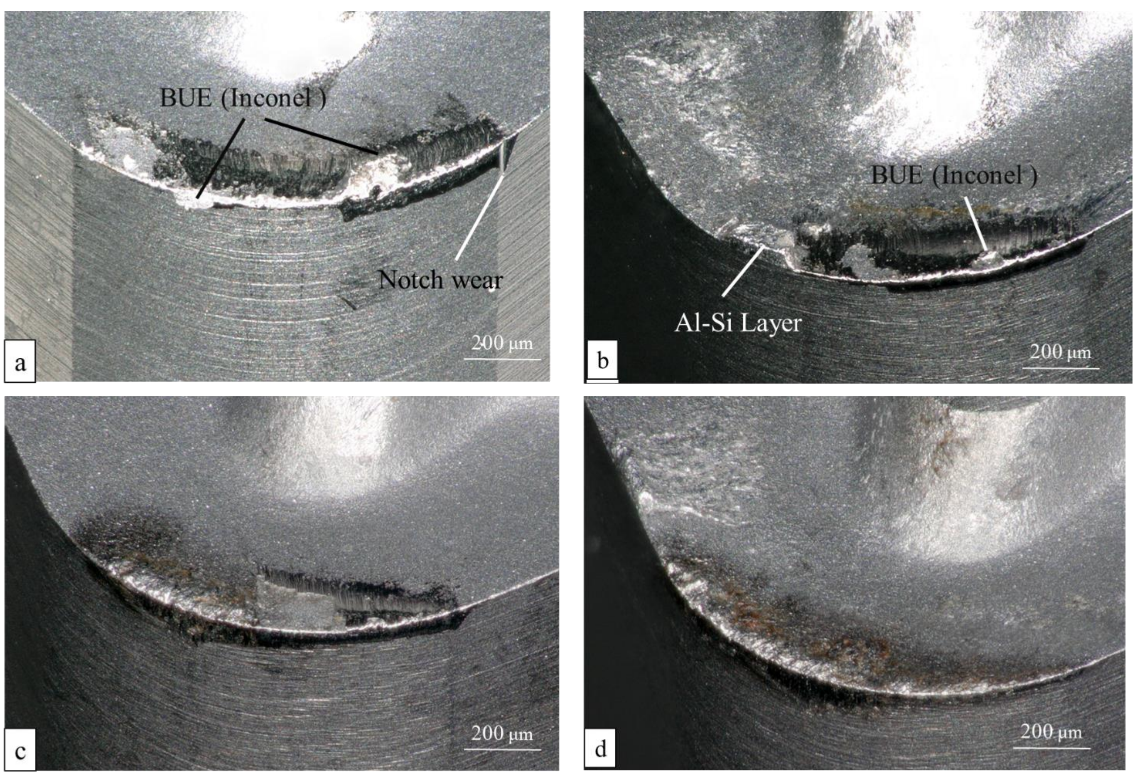


Figure 3-8. Tool flank wear after 1 min of cut a) benchmark (T1), b) tool treated with Al-Si (T2), c) tool treated with cast iron (T3), and d) tool treated with both Al-Si and cast iron (T4)

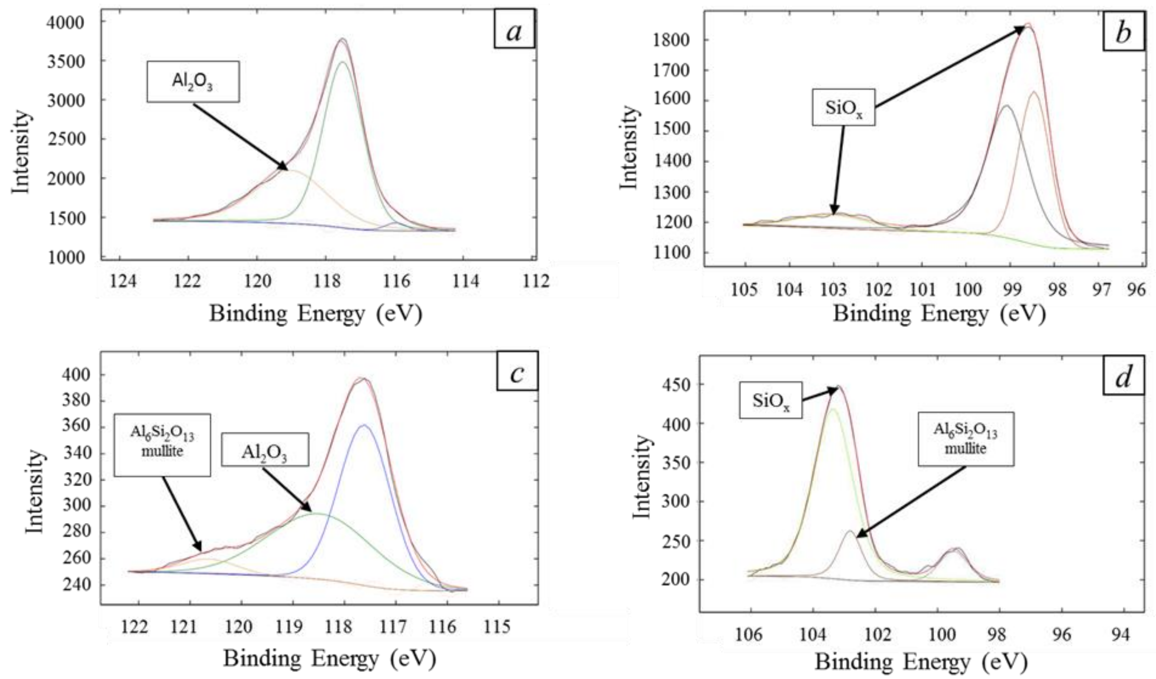


Figure 3-9. HR XPS spectra of the surface of tools. a-b) treated tool with Al-Si; c-d) treated tool with Al-Si which worn during machining of Inconel 718.

Cast iron was selected as another candidate material for this tool treatment process due to its high lubricity. As mentioned, depositing a thin lubricant layer can have a significant effect on reducing the BUE formation and improving the flow of the material. Thus, ductile cast iron, a material which possesses self-lubricating properties, due to the presence of graphite in its microstructure, was considered for the treatment process. When positioned between the tool and workpiece, cast iron makes their mutual movement and flow much easier. In addition, the coefficient of friction of the cast iron layer was found to be around 0.06. This measurement was performed with a nano-wear test (section 3.6). To better show the high lubricity of the cast iron and the effect it has on chip flow during the machining process, two very short cuts, each around one second, were alternatively performed on cast iron and Al-10Si (Figure 3-10). As can be seen clearly in Figure 3-10.b, the lubricious cast iron layer leads to aluminum material flow in the direction of chip formation. This result demonstrates how a lubricious material can have a significant impact on the material flow. Therefore, cast iron was selected as a tool treatment material prior to using the tool for the machining of Inconel material. Better flow of the material due to reduced friction results in lower cutting force and tool wear rate. In addition, low friction can considerably reduce the probability of BUE formation. As can be seen in Figure 3-4-a, the initial tool wear value of the tool treated with cast iron (T3) is around 50% lower than the benchmark. Therefore, the result shows a decrease in the probability of BUE formation, and consequently, the possibility of the occurrence of tool chipping during the initial cutting passes. Figure 3-8.c shows the BUE on the tool T3 after 1 min of cut. Although the thin layer of cast iron on the tool will noticeably decrease the tool wear and increase the tool life in comparison with the benchmark T1, the overall tool life of this tool (T3) is a bit lower than the T2 treated tool. The reason for this is because cast iron is not as sticky as aluminum, so it will be removed from the surface of the tool after several passes. Because of this, cast iron at the tool edge is not durable during the machining process. These examples demonstrate that finding a layer possessing both high lubricity and durability will have the most beneficial effect on tool life and wear.

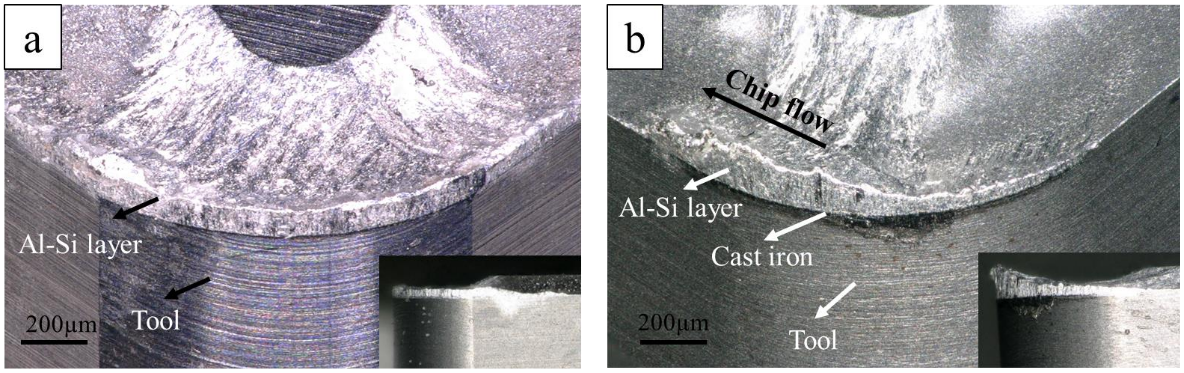


Figure 3-10. Material flow of the Al-10%Si; a thin layer deposit on the tool post treatment a) with aluminum (T2), b) with cast iron and then with Al-10Si

To demonstrate this phenomenon, a combination of lubricious and durable materials were selected for the treatment process. The selected materials were Al-10%Si (a durable and soft material) and cast iron (as a lubricious material). Thin layers of these materials formed at the tool on top of each other through the machining of an Al-Si bar followed by a short cut of cast iron. The reason for applying the Al-10%Si directly on the top of the tool is that not only does the Al-10%Si layer stay on the tool and form the beneficial protective layers during the machining process, but it can also fill the cracks and prevents them from propagating. While, the second lubricant layer of cast iron on the top of the Al-10%Si, which was found to not be as durable as aluminum during the process, will be in contact with the chip and reduce the friction and improve the material flow during the initial machining steps. As mentioned, the deposited cast iron will be removed from the tool after a few passes, however, XPS results showed that Al-Si was present on the tool even after 28 min of cut (Figure 3-9). Thus, the presence of cast iron at the initial step helps lower the initial tool wear and thus improves the initial running-in stage of tool wear.

In the following step, the treated tool (T4) was used for machining of Inconel 718. As can be seen, the highest improvement was achieved with a tool alternately treated with both Al-Si and cast iron. The result shows a 205% improvement in tool life without any tool chipping observed.

During the following step of machining of the Inconel alloy, the Al-10%Si present on the tool tip melted under the high temperature of machining filled the cracks and prevented their propagation (Figure 3-7). Also, because of the improved flow of the material and presence of a protective film on the tool, less BUE of Inconel was formed and no sign of notch wear was observed (Figure 3-8.d). As can be seen in Figure 3-4.a, the tool life of the T4 treated tool was considerably higher than T3, T2, and T1 due to the high lubricity, high compatibility, thermal barrier property and high ductility of the thin layer of both Al-10% Si and cast iron between the tool-workpiece surfaces.

3.4.2 Cutting force during machining of Inconel 718

Cutting force is another parameter that has a significant effect on tool wear. Increased tool wear generates higher friction and temperature due to a greater area of interaction between the chip and the tool [32]. Cutting forces associated with machining Inconel are high due to the work-hardened workpiece surface of the material, high pressures, and temperatures at the tool-chip interface. Finding a way to reduce the work-hardening, temperatures and pressures can reduce the force and in turn improve the tool life. The initial feed, radial and tangential cutting forces for different treatments are compared in Figure 3-11. As can be seen, the cutting forces of treated tools are lower than the uncoated tool. It should be mentioned that the main force which is the tangential cutting force is used for all the rest investigations in this study. Figure 3-12 shows the tangential cutting force variation compared to the cutting time for different treated tools and also for the benchmark tool. As machining time rises along with the tool wear, the cutting force gradually does as well. The cutting force of the uncoated tool was significantly higher than all the other treated tools. The reason for the high force value of T1 was that the benchmark's rate of flank wear was considerably higher than that of the other tools. At the initial step, the cutting force of the benchmark tool was around 100N and increased gradually to 140 N at a cutting time of around 11 min. The cutting force rapidly rose to 190 N at a cutting a cutting time of around 12 min, because of the occurrence of tool chipping at the cutting edge.

Since the proposed method added a thin layer that reduced the friction and decreased the contact pressure, in all treated tools the cutting force value was much lower than the benchmark tool. As can be seen in Figure 3-12, the cutting force of the T2 treated tool was considerably lower than the benchmark. During the initial passes of machining, the cutting force was around 70 N, which was 30% lower than the initial force of T1. The cutting force of the T2 treated tool ranged from 70 N to 120 N. At the cutting time of 31 min, it reached the maximum value of 120 N. Meanwhile, the cutting force of the T3 treated tool at the beginning of the machining was considerably lower (43%) than T1 due to the lower temperatures and friction at the cutting zone. However, the initial cutting force of the T3 treated tool was lower than in the T2 treated tool. As the cutting time grew, the cutting force of the T3 treated tool significantly increased to 140 N at cutting time of 28 min, which was higher than the cutting force of the T2 treated tool. This result demonstrated that the presence of cast iron on the tool at the beginning of the cutting process will be removed from the tool rake face quickly after only a few passes. The T4 treated tool was observed to have lower cutting force in the range of 57 N to 100 N. Cutting force after around 1 min of cutting with tool T4 was 57 N and gradually increased to 100 N after 34 min of cutting.

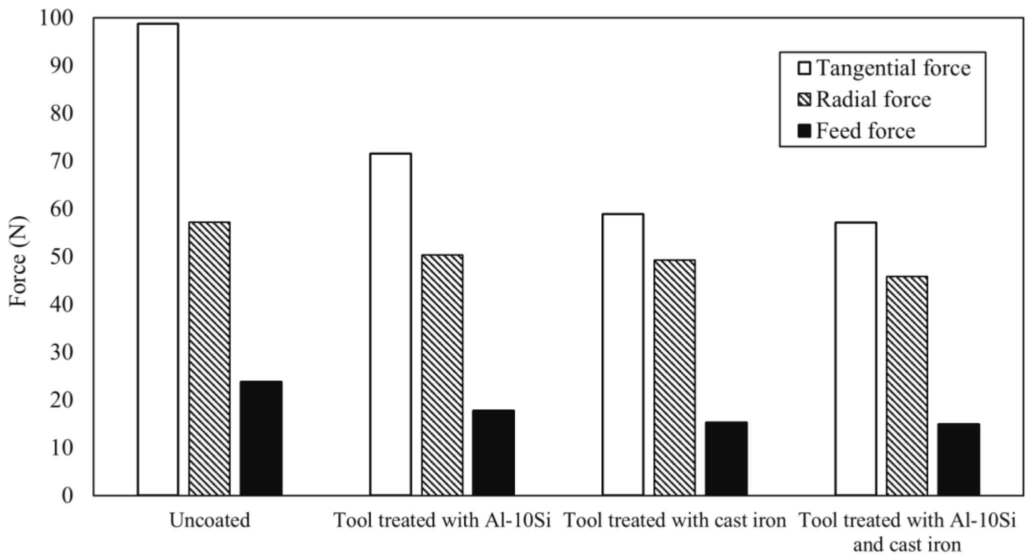


Figure 3-11. Feed force, radial force and tangential cutting force after around 1 min of cut for the benchmark (T1) and the treated tools (T2, T3, and T4)

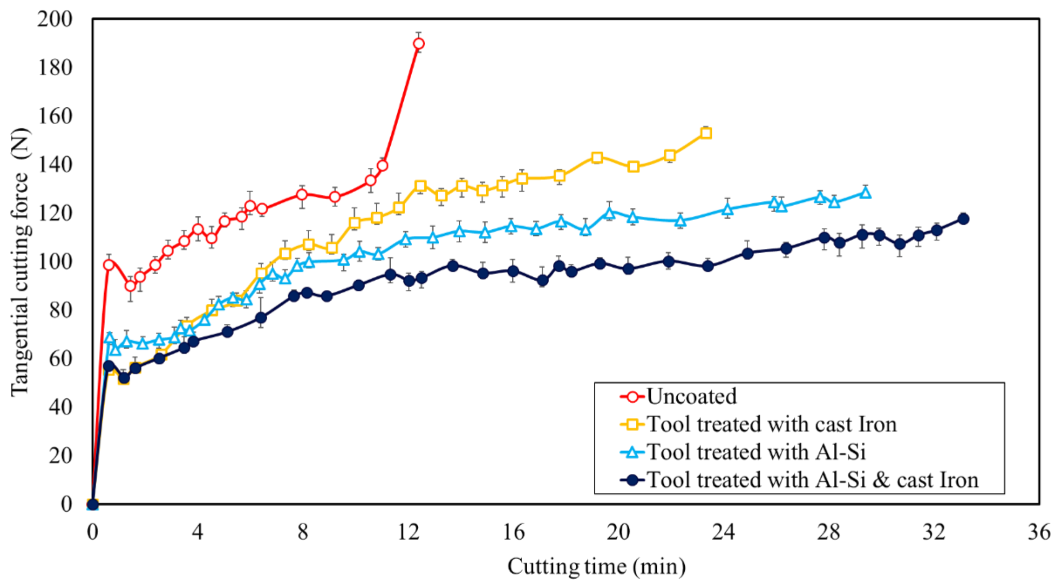


Figure 3-12. Tangential cutting force variations vs cutting time for the benchmark (T1) and the treated tools (T2, T3, and T4)

3.4.3 Tool analysis in the running-in stage (first pass after machining with Inconel 718)

Tool flank wear consists of three stages; initial wear (running-in), steady-state wear and accelerated wear stages. Studies show that controlling the initial wear stage significantly affects the overall tool life. In the initial stage of wear, microcrack formation and propagation is very high because of the high localized stresses in the tool [33]. Analysis of the tool wear mechanism at the initial pass of machining can help better understand the overall tool wear behavior.

To investigate the effect of the proposed treatment on tool wear behavior in the running-in stage, a single pass of around 1 min of cut was performed on the Inconel bar using all the treated tools (T2, T3, and T4) and the benchmark tool (T1). The worn tools were analyzed using the Back-Scattered Electrons Microscopy (BSE) and Energy Dispersive Electron Spectroscopy (EDS) to assess the tool surface after a short cut was made on the Inconel alloy (Figure 3-13).

For all the inserts, spectrum 1 in Figure 3-13 represents the tool base material and is used as the basis of comparison. As can be seen, it is mainly composed of W and C, which are the main components of the WC uncoated tools.

As shown in the EDS results for the benchmark tool (T1) and the treated tool T2 in Figure 3-13.a and 3-13.b, the traces of workpiece material were found on the tool flank and rake face (making the BUE). The high amount of Ni, Cr, and Fe in spectrum 2 and spectrum 3 indicate that Inconel 718 adhered to the cutting edge even after 1 min of cut. As shown in Figure 3-13.b, the thermal barrier properties of the Al-10%Si layer deposited between the tool-chip interface decreased the amount of BUE formation on the tool edge. The volume of the BUE in the T2 treated tool (region shown with spectrum 3) was lower than the benchmark (region shown with spectrum 2) after one pass. Poor thermal properties of Inconel 718 were the main reasons for the high temperature and pressure conditions that may result in BUE formation. Extensive adhesion was due to high friction, high temperatures, and contact pressures. The tendency of Inconel to form a large BUE in the initial stage of cutting plays an important role in tool failure and chipping during the subsequent passes. Lower BUE formation was associated with a decrease in the probability of crack development and propagation.

The BSE images and EDS analysis of the treated tools with cast iron (T3) and with both aluminum and cast iron (T4) after one pass of machining of Inconel 718 are also shown in

Figure 3-13.c and 3-13.d, respectively. As can be seen, a high amount of graphite is found on the tool, close to the tool tip and also on the tool flank face. The existence of graphite provides a lubricious film at the tool-chip interface due to its low shear strength [34]. This lubricious layer reduces friction in the cutting zone. Since there was almost no sign of the Ni, Cr in the EDS analysis of spectrum 4, it supports our assessment that cast iron prevented the sticking of Inconel 718 to the cutting edge and facilitated chip flow over the tool edge. Therefore, by depositing a cast iron layer on the tool tip before machining with Inconel 718, the formation of BUE was significantly reduced.

The tool wear behavior of the T4 treated tool was almost the same as the T3 treated tool (Figure 3-13.d). For the T4 tool, in addition to the graphite in cast iron improving the material flow, the presence of aluminum under the cast iron was found to protect the tool from the initial force and thus reduce the propensity of the T4 treated tool to chip.

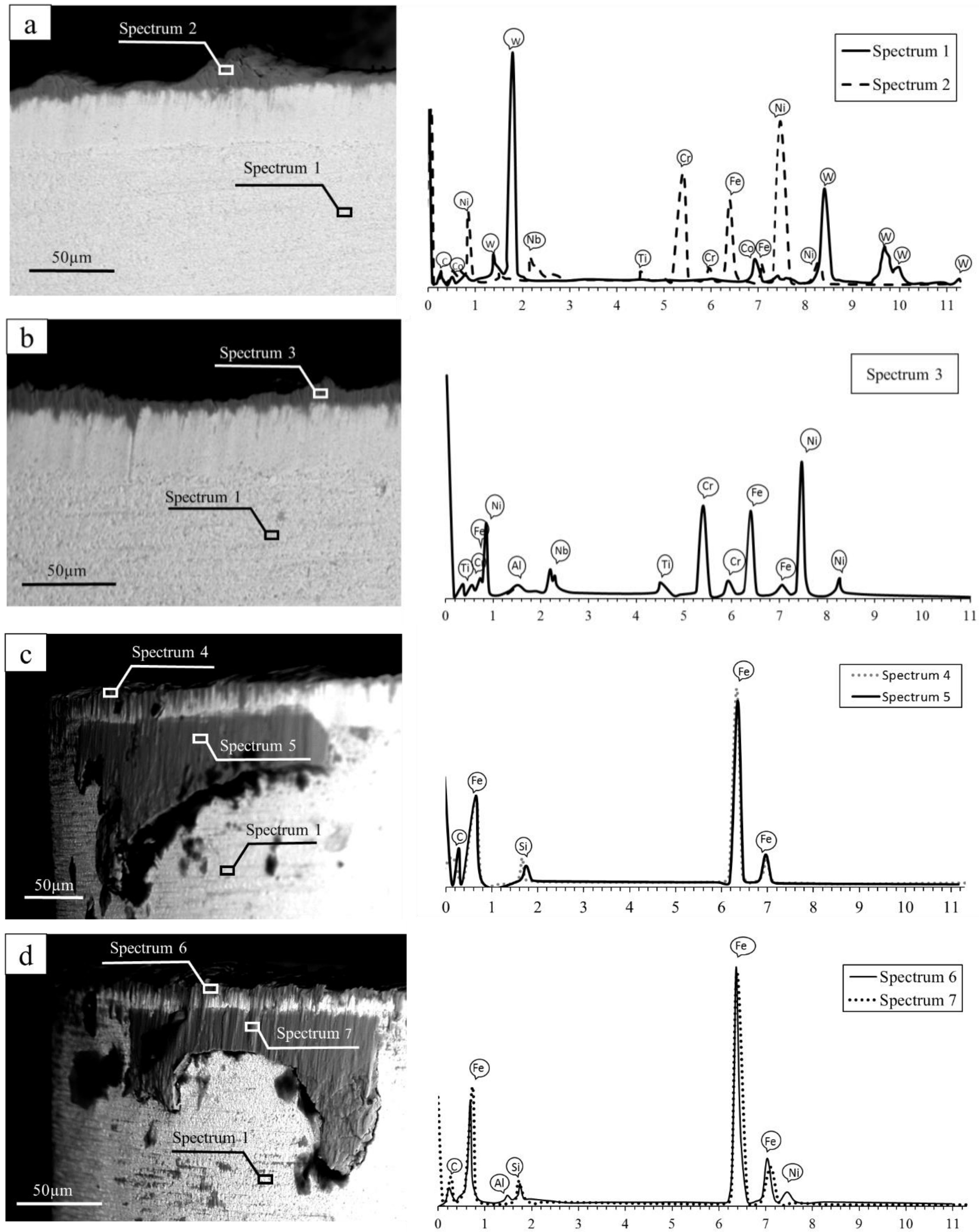


Figure 3-13- Backscattered images and EDS analyses of a) benchmark (T1) and treated tools with b) Al-10%Si (T2), c) Cast iron (T3) and d) Al-10%Si/Cast iron and (T4) after around 1 min of cut (36 m of cut) during machining of Inconel 718.

3.4.4 Tool wear analysis

In this study, the dominant tool wear mechanisms of Inconel 718 that cause tool chipping are classified as adhesion, abrasion, severe notch wear and chemical wear. This section discussed how the proposed treatment resulted in controlling these mechanisms and resulted in less chipping and premature tool failure.

The most common type wear mechanism during machining of Inconel 718 is abrasion. Abrasive carbide particles (TiC, NbC, etc.) present in the microstructure of Inconel 718 as well as built up and tool material fragments, roll between the workpiece and the tool and scrape severe scratched and grooves on the tool flank face and accelerate the flank wear. This has been considered as one of the most common problems experienced with machining of this class of materials [35] and [36]. Also, due to the abrasion of the work hardened layer of the work-piece surface on the tool, depth of cut notch wear occurs on the tool flank face [8]. Depth of cut notch wear causes localized damage on the tool and results in premature tool failure [37].

During machining of Inconel 718, the temperature at the tool-chip interface rose significantly. The temperature measured by VarioCAM HD 1024 infrared camera exceeded 820°C (Figure 3-6). At high temperatures, welding and adhesion of Inconel 718 onto the cutting tool caused severe sticking and adhesive wear. Because of the hardness of Inconel 718, high cutting forces and stresses increase the real contact area between the tool and chip, resulting in adhesion wear and sticking. As mentioned above, a large BUE can form at the top of the rake flank face of the tool due to the severe sticking of the workpiece material. This BUE material is known to be unstable and can cause tool detachment and chipping via particle removal from the tool edge due to the chip flow on the rake face and work hardened material flow on the flank face [8], [35]. Continuous formation and detachment of BUE leave small cracks on the tool material, which later results in tool chipping [38]. In addition, the chemical wear might be occurring on the flank surface of the tool due to the high temperature generation. Tool elements at high temperature can react with the environment and/or workpiece material and cause oxidation wear during machining of Inconel 718. Oxidation wear occurs at the outside of the contact zone, where it is exposed to oxygen.

Figure 3-14 shows different types of tool wear observed on the flank and rake faces of the treated tools and the benchmark tool. As shown in Figure 3-14.a, the benchmark (T1) was chipped before reaching a flank wear value of 0.3 mm. One main reason for tool chipping is adhesion of a high amount of workpiece material to the cutting edge under the conditions of high pressures and temperatures. As can be seen, a large volume of BUE material was formed at the cutting edge. Also, the area of the sticking zone on the flank face was too large and covers almost the entire area of the flank wear. The fracture of this adhered layer might cause tool tip breakage during the machining process. In addition, the uncoated carbide tool cannot withstand high temperatures and pressures. Since the tool is not protected, the probability of tool chipping will increase under these severe conditions. Moreover, our previous study on uncoated tool shows that the severe abrasion wear on the tool flank face occurs due to the rolling of hard carbide particles on the tool [23]. Whereas, less abrasive wear observed on the treated tools because the protective layer reduced contact pressure at the tool-chip interface.

Figure 3-15 shows the EDS image of the benchmark flank surface. A considerable amount of oxygen was found around the contact zone, where it was exposed to oxygen. The higher amount of the oxygen and aluminum at the tool flank surface confirm the occurrence of oxidation wear, a sign that a high temperature was reached, as shown in Figure 3-14.a.

In Figure 3-14.b, lower BUE formed on the T2 treated tool compared to the benchmark (T1). XPS results (Figure 3-9) demonstrated that the thermal barrier film protected the tool during machining. The zones of sticking and oxidation wear, highly affected by temperature, are considerably decreased. As a result, not only does the soft layer protect the tool from high temperatures and BUE formation, but it can also lead to the reduction of tool failure due to chipping by filling in the existing cracks on the tool surface. The results show that by depositing the thin layer of Al-10%Si on the tool, no chipping was observed on the tool edge. This was attributed to the protective layer forming between the tool and chip interface (Figure 3-14.b).

The experimental test was repeated multiple times to observe the effect of the cast iron tool treatment. Results reveal that, in some cases, only a small amount of chipping occurred at the end of tool life for the T3 tool (Figure 3-14.c), since the lubricious cast iron layer facilitated chip flow. Lower BUE formation and sticking zone on the cutting edge reduce the tool chipping at the initial step of machining. The reason for tool chipping at the end of tool life was attributed to the fact that the layer of cast iron is removed from the tool edge as cutting process. As illustrated in Figure 3-14.d, the sticking zone of the T4 treated tool was significantly lower due to the presence of both lubricious cast iron and ductile Al-10%Si on the surface of the tool. In addition, no chipping and oxidation were observed after machining with T4 treated tool.

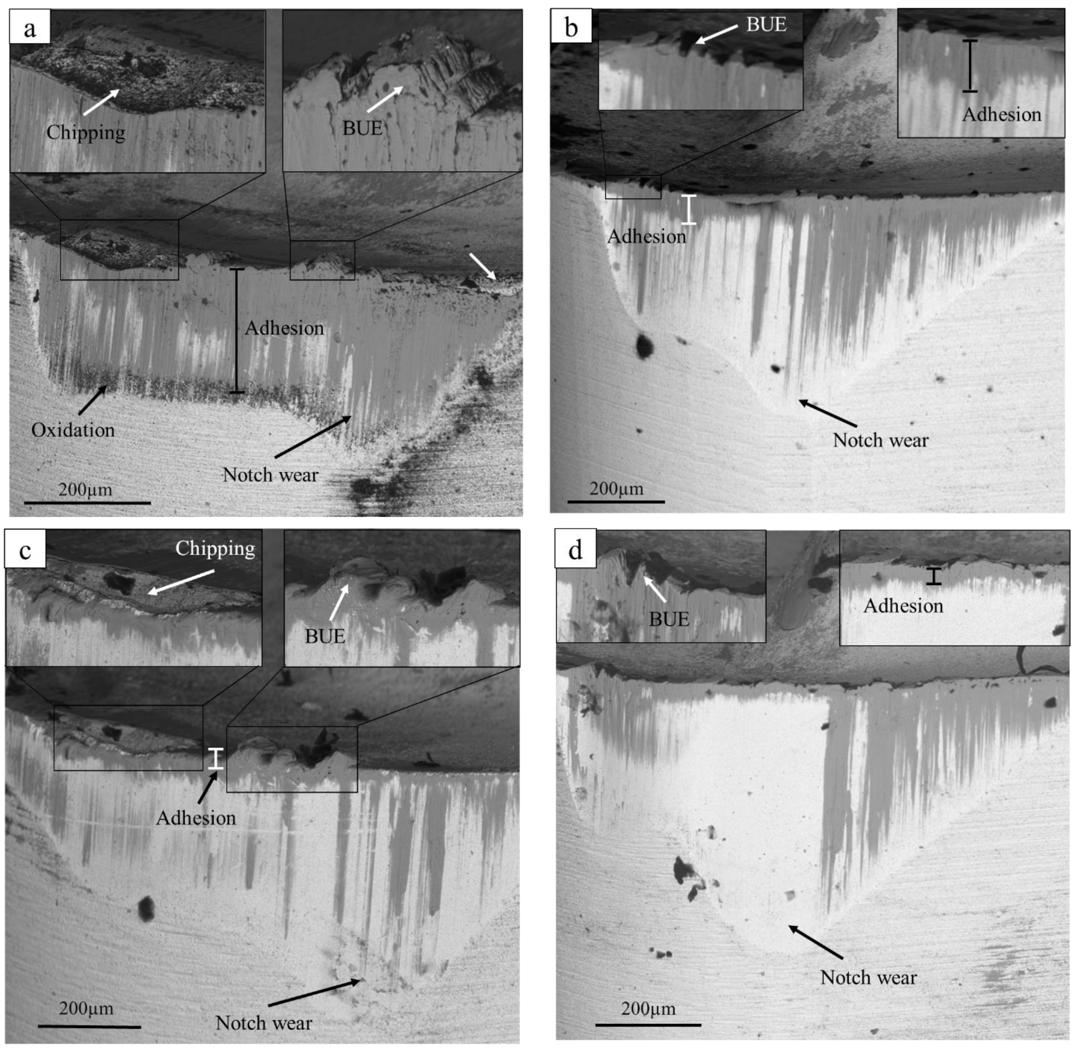


Figure 3-14. SEM images of tool wear of a) benchmark and treated tools; b) T2, c) T3 and d) T4 at the end of the tool life during machining of Inconel 718

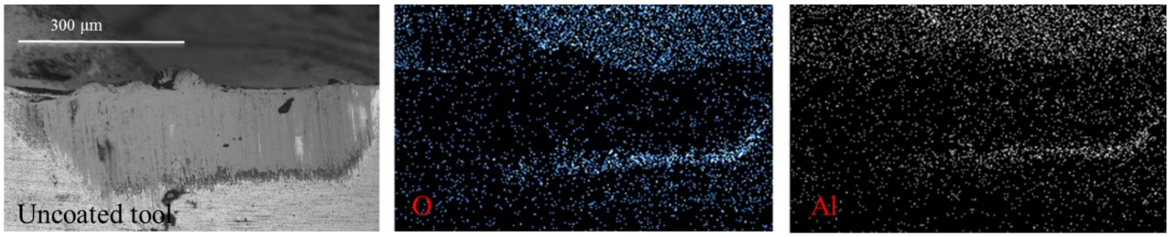


Figure 3-15. a) SEM image of the flank face of the benchmark tool after 10 min of cut; b) Oxygen map; c) Aluminum map

3.4.5 Machining induced work-hardening of the workpiece.

As mentioned before, high cutt1ing temperatures and pressures result in the formation of a work-hardened layer during the machining of Inconel 718 [39]. In addition, the rapid heating and cooling that happens during wet machining can also result in work-hardening of the surface [5]. Several studies show that the surface hardness of Inconel 718 is higher than that of the sub-surface [29], [18]. To date, many different coatings have been developed with the aim of reducing the work hardening of the machined surface. But to the best of our knowledge, they were not successful in significantly reducing the work hardening of the surface. However, the results of this study demonstrate a considerable reduction of surface work hardening with work hardening decreasing by 44% for T2, 50% for T3, and 59% for T4 as compared to the benchmark (T1).

Figure 3-16 shows the nano-hardness variation along the workpiece surface of different treated and uncoated tools. The hardness measurements were repeated three times for each machined surface. As can be seen, the depth of the work-hardened layer is less than 10 µm after machining with different treated tools and around 15 µm with uncoated tools. The surface hardness was measured to be higher than the bulk material for all the tools, while the hardness value reached the maximum as the distance from the surface became greater. Beyond this point, the hardness value decreased gradually from the maximum peak to the bulk material value. The reason for the lower hardness of the surface as compared to the subsurface was attributed to the thermal softening which occurred in the workpiece material at the tool-workpiece interface.

The hardness of the uncoated tool was measured to be 13 GPa at the surface, and it increased to 15.7 GPa at 4 µm below the surface. The hardness decreased gradually from 15.7 GPa at around 4 µm to 5.5-6 GPa at around 15 µm. As shown in Figure 3-16, the maximum hardness of the surface machined with the benchmark was around two times higher than the treated tools. The nano-hardness value of the Inconel subsurface machined with the T2 treated tool was found to be considerably lower than that machined with an uncoated tool (9.4 GPa) due to lower tool wear, force, friction, and temperature generation. The hardness value declined significantly around 44% in this case. The surface machined with the T3 treated tool had a maximum hardness of 7.9 GPa which is 50% lower than the hardness of the Inconel 718 surface machined with the T1 untreated tool which was attributed to the ease with which the material flowed. The maximum hardness value of the surface of the workpiece material was 6.5 GPa after cutting with the T4 treated tool. These results show that the removal of material was much easier when the soft, lubricious and durable film associated with this process form and remain present between the tool-chip interface. With a 59% reduction in the hardness value of the machined surface, the probability of tool failure or notch wear was observed to be significantly lower.

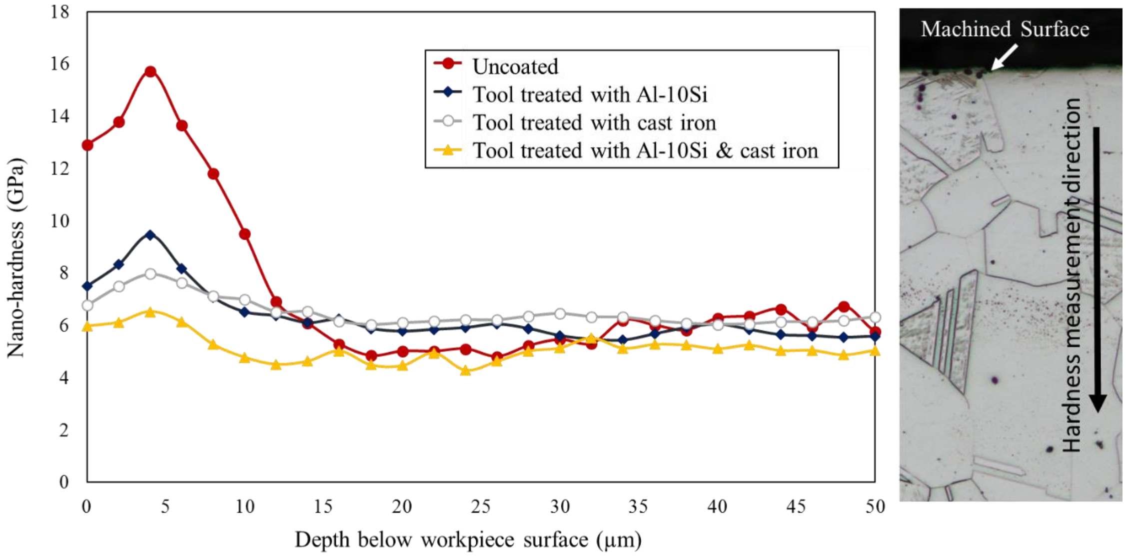


Figure 3-16. Nano-hardness profiles of Inconel 718 surface after turning with T1, T2, T3, and T4 tools, observed at machining time of 3 min

3.4.6 Coefficient of friction (CoF)

Friction has a significant effect on temperature and force generation. A nano wear test was performed to measure the coefficient of friction of the different treated layers. During the nano-wear test, the nanoindenter passed through the built-up layer on the tool rake face and the tool cross section material to obtain the coefficient of friction of each layer. Figure 3-17 shows different steps for preparing the nano-wear test sample. The coefficient of friction of the tool material and Inconel 718, Al-10%Si and cast iron on the tool tip after the turning process is performed is shown in Table 3-4. The coefficient of friction of the materials is obtained from the nano-wear test on the tool cross section after machining with Inconel 718, Al-10%Si and cast iron. The coefficient of friction (COF) of the Inconel material was measured to be 1.4, which is high. Thus, during machining of Inconel 718 with the uncoated tool, adhesion and BUE formation is high due to the high friction at the contact zone. As a result, high temperatures and high cutting forces are generated as well as an increased tool wear rate. The existence of a low CoF thin film at the interface between the tool and the chip, renders material flow easier, causing a drop in temperature and machining seizure. As shown in Table 3-4, cast iron and Al-10%Si, chosen as tool treated materials both show very low CoFs.

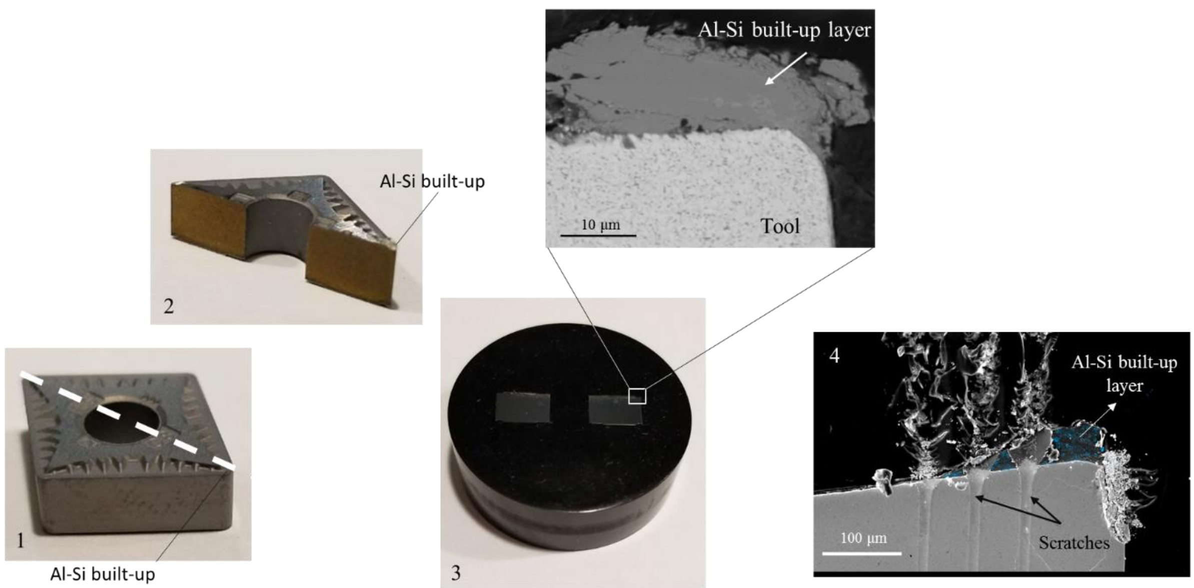


Figure 3-17. Different steps for preparing the sample for the nano-wear test; step1 & 2) preparing the tool and cutting the tool, 3) mount the sample and then polish it 4) the Backscattered image of the tool cross-section after the nano wear test on the built-up layer and tool material

Table 3-4. The coefficient of friction of different layer on tool after machining

Material	Coefficient of Friction
Inconel 718	1.4
Al-10%Si	0.06- 0.08
Cast iron	0.04-0.06
Carbide tool	0.2

3.4.7 Chip characteristics

Continuous chip formation was observed during the machining of Inconel 718 with both the treated and untreated tools but a large shear angle and corresponding reduction in chip thickness were observed during machining with the treated tools which were observed to facilitate chip breakability. In addition, a higher shear plane angle results in lower cutting forces and lower temperatures. For estimating and comparing the cutting temperature, the thickness of the deformed chip was measured after the first pass of the machining process. The shear angle of treated and untreated tools was estimated and are shown in Table 3-5. Higher temperatures at the primary deformation zone led to the thermal softening of the chip material, which increased the probability of adhesion and thus BUE formation. A greater amount of BUE caused friction to rise, which further complicated the sliding of the workpiece material on the tool.

Table 3-5. Shear angle during the machining process

Tools	Deformed chip thickness-t_c (mm)	Shear angle-Φ (°)
T1	0.1645	32.49
T2	0.1455	35.96
T3	0.1213	41.39
T4	0.1412	36.83

The summary of results concerning the use of the novel method in this study are shown in Table 3-6. As can be seen, a significant improvement in tool life, cutting forces, and work hardening have been achieved for the machining of Inconel 718 using this treatment. Further work still needs to be done to develop this treatment into a cost effective method for mass treating tools.

Table 3-6. The percentage of improvement of treatment tools in comparison with the untreated tool

Treated Tools	Tool life improvement (%)	Cutting force reduction (%)	Work hardening reduction (%)
Al-10%Si (T2)	173	30	44
Cast iron (T3)	120	45	50
Al-10%Si and Cast iron (T4)	204	45	59

3.5 Conclusions

Short tool life due primarily to excessive tool chipping together with high cutting forces and a high temperature in the cutting zone are the main problems associated with using carbide tooling to machine Inconel 718. This study introduces a new, simple and easy way to perform tool treatment concept to improve the machinability of Inconel 718. In this method, the performance of the new tool treatment technique with Al-10Si and/or cast iron were compared to the benchmark. For the treatment, prior to the actual machining of Inconel, a very short cut, around two seconds, was performed with the uncoated tool on selected workpieces. Al-10%Si and cast iron were selected as the workpieces for the treatment.

Al-10% Si was chosen due to its high ductility, low melting point, low coefficient of friction, and high reactivity to oxygen. Cast iron was selected because of its high lubricity. Thus, in this study for showing the performance of the new treatment method, tool life, tool wear mechanisms, cutting forces, friction, sub-layer work-hardened layer, tribofilm formation and microstructural analysis of the contact surfaces were investigated. The following conclusions briefly explain the achievements of the current work:

1. Tool treatment with aluminum resulted in a substantial tool life improvement, elimination of tool chipping and cutting force reduction. Although the treatment with cast iron can have a significant effect on tool life improvement, chipping

takes place over time because of the instability of the cast iron layer formed on the tool surface. To improve the durability and lubricity of the surface treated layer, and thus the tool's performance, both cast iron and aluminum were selected for last pre-treatment process. Results show that the tool treated with both cast iron and aluminum possesses a superior tool life improvement of 204%, a reduction of the tangential cutting force by 45% and less chipping and work hardening compared to the untreated tool.

2. Cracks are one of the most important factors resulting in chipping. The Al-Si deposited on the tool, treated with A-10Si and the tool treated with a combination of Al-10Si and cast iron, will be molten during the subsequent machining of Inconel. The molten material flows on the tool surface and fills the pre-existing defects in the tool and the small defects that are generated during Inconel machining, preventing propagation and, thus, preventing the tool from chipping.
3. Compatibility of the Al-Si with the tool-workpiece tribosystem resulted in the formation of various beneficial triboflms on the tool treated with A-10Si and the tool treated with a combination of Al-10Si and cast iron. The lubricious and thermal barrier films generated during machining protected the tool from seizure and BUE formation and contributed to reduced tool chipping and prevented rapid tool failure.
4. High friction, temperatures and contact force during machining result in severe sticking and formation of BUE on the tool surface. These are also considered important factors resulting in chipping and tool failure. Formation of an excellent

lubricious layer at the tool/chip interface through the proposed treatment, contributed in significant reduction of sticking and built-up edge formation in all the treated tools, especially for the tools treated with Al-10Si and treated with a combination of Al-10Si and cast iron.

5. Chip thickness analysis indicates that treated tools have a higher shear angle compared to the benchmark, which is a result of a lower cutting force, lower friction and better flow of the material at the cutting zone.
6. An important achievement of the new treatment was its ability to reduce the work-hardening of Inconel 718 during machining through controlling the friction, temperature and contact pressures. The nano-indentation results performed on the workpiece sub-surfaces, showed up to 59% reduction in work-hardening of the workpiece material for the tool treated with Al-10Si and cast iron. This significantly affects the overall machinability of Inconel and results in tool wear and surface integrity improvements and chipping prevention.

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4 Chapter 4

Tribological Behavior of Differently Deposited Al-Si Layer in the Improvement of Inconel 718 Machinability

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Maryam Aramesh:	Methodology, Writing – review and editing.
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Tribological behavior of differently deposited Al-Si layer in the improvement of Inconel 718 machinability

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4.1 Abstract

Inconel 718 suffers from very poor machinability which limits its application and causes very high machining costs. Therefore, maximizing the tool performance is of prime importance for improving its machinability and reducing the high costs. Physical Vapor Deposition (PVD) of coatings on the tool material, is the common method, suggested by many studies, to improve the tool performance during cutting of difficult to cut materials. Previously authors have introduced an easy and cost-effective process for depositing the target material on the tool as an alternative for PVD coatings. In the novel proposed process, referred to by the authors as the "pre-machining" method, the material is deposited on the tool surface during a few seconds of machining of the target workpiece. In the current study, the performance of the new proposed technique is compared with the conventional PVD method. The target material used for deposition is a very soft material (Al-Si) which itself has not been used before for coatings used for difficult to cut materials. Thus, for this study, a single layer of soft Al-Si material is deposited on the tool through two different techniques; a typical PVD technique under a high vacuum environment in a coater chamfer and the “pre-machining” technique. The comprehensive machinability analysis performed on the tools showed that application of Al-Si as the target materials through both techniques is very beneficial for the cutting tools used for cutting Inconel 718. Moreover, results showed that the performance of the new, easy to perform and cost-effective deposition technique is very similar to the performance of conventional PVD coatings, and even outperforms a PVD coating in some respects. The results showed that the tool life of the Al-Si coated tool with 1 and 0.7 µm thicknesses and Al-Si pre-machined tool are significantly higher than the uncoated tool by 321%, 231% and 205% respectively. They also outperform the conventional TiAlN hard coating used for machining of this class of material. The study also demonstrated that the cutting force decreased significantly by using Al-Si coated and pre-machined tools. Furthermore, chipping, abrasion wear, adhesion, BUE formation and machining induced work hardening of the workpiece material reduced significantly by using the Al-Si pre-machined/coated tools. Investigation of the chips produced during the machining process and coefficient of friction measurements also confirmed the friction reduction and better flow of the material at the tool-chip interface as a result of Al-Si deposition with both techniques.

Keywords: PVD coatings, Soft coatings, Pre-machining process, Al-Si coating, Inconel 718.

4.2 Introduction

Inconel 718 is a nickel-chromium alloy with high mechanical strength at elevated temperatures, high corrosion and oxidation resistance. It is widely used in components operating at high temperatures such as turbine blades, nuclear reactors and aircraft engines. However, machining of this alloy is extremely difficult and limits its applications due to a combination of several mechanisms including [1], [2]:

- Inconel 718 alloys do not lose their strength at high temperatures during the machining processes.
- Work hardening of the machined surface during cutting results in a severe depth of cut notch wear and leads to pre-mature tool failure.
- Abrasive wear appears during machining due to hard-abrasive carbide particles present in the material microstructure.
- A high temperature is generated on the tool-tip due to its low thermal conductivity.
- Adhesion and BUE formation occurs due to the high cutting stresses and temperatures.

Collectively these problems can result in severe tool wear and catastrophic tool fracture/chipping. Numerous machinability studies have been carried out over many years, aiming to overcome the machining issues associated with Inconel 718. These attempts can be mainly categorized into four groups; i) different machining strategies [3], [4], ii) various tool geometries and tool texturing [5], [6], iii) different types of cooling systems [7], [8], and iv) various tool material coatings [9], [10]. Although each method has its own pros and cons, coating is currently the most widely used method in industry and among researchers to prolong tool life during machining of Inconel 718. Coatings provide good lubricating and good abrasive behavior at the tool-workpiece and tool-chip interface, thereby improving tool life and performance. Typical coatings used for the tools for machining of Inconel 718 are TiAlN, TiC, TiN, TiCN, and Al_2O_3. Moreover, new designs and types of coatings such as multilayer, nanocomposite and self-adaptive coatings are also selected for tool materials. For example, the TiAlCrSiYN monolayer, TiAlCrSiYN/TiAlCrN multilayer, TiAlN/MexN multilayer, and TiAlN/Cu coatings were applied for the tools used in machining of Inconel 718 [9], [11]–[13]. Studies show that mainly hard coatings were selected for machining of hard to cut materials due to their wear resistance and high hardness properties. Moreover, there are a few studies which used a soft layer at the top of the hard coatings on the tool to decrease the friction behavior of the coating during machining of hard-to-cut alloys [12], [14]. Table 4-1 shows different types of hard coating used and suggested for machining of Inconel 718. As can be seen, the hardness of all coatings is higher than 20 GPa.

Table 4-1- Different recommended coatings and their hardness at room temperature

	Coatings	Hardness (GPa)		Coatings	Hardness (GPa)
1	TiAlN [15], [16]	29	**7**	CrN [17]	22.5
2	TiAlCrSiYN/TiAlCrN [18]	30	**8**	TiN [17]	24.5
3	AlTiN [9]	24.64	**9**	TiN/AlTiN [17]	29.4-38.2
4	AlTiN/MoN [9]	26.13	**10**	TiCN [16]	26.9
5	AlTiN/VN [9]	25.48	**11**	CrN/TiN [17]	26.9-36.2
6	TiAlCrN [13]	28.2			

Generally speaking, a coating with a hardness lower than 10 GPa is considered to be a soft coating while one harder than 10 GPa is considered a hard coating [19], [20]. The soft coatings tend to be lubricious due to the presence of slip planes present in their crystal structures. Thus, using a soft coating facilitates the flow of material at the tool-chip interface. As shown, there exists no study that uses a single layer of soft coatings for machining a hard-to-cut material. Our previous studies [21], [22] showed that the deposition of an ultra-soft layer of Al-Si on the tool via the proposed “pre-machining process” significantly improves the tool performance through resolving the main machining issues simultaneously. In the “pre-machining process”, prior to the machining of Inconel, a very short cut, around a few seconds, is performed on an Al-Si bar. Through this process, a thin layer of Al-Si is deposited on the tool, which will be used later for the machining of Inconel. According to our previously published data, the soft Al-Si deposited on the tool through the pre-machining process significantly improved tool performance in machining of Inconel 718. Since physical vapor deposition (PVD) is a common tool coating method used in industry the PVD deposition method was selected for deposition of Al-Si on the tool surface and the results are compared with the pre-machining process. To date there are no studies reported in the literature involving the deposition of Al-Si coating for machining applications specifically for hard to cut materials. To evaluate the tool performance, tool life, cutting forces, tool wear mechanisms, abrasion wear, friction behavior and work hardening of the machined surface were investigated. Moreover, to have a better comparison between the performance of soft and hard coatings, the tool life of the commercial hard TiAlN PVD coated tool under the same condition was investigated. The reason for selecting TiAlN is its widespread use in cutting hard to cut materials such as Inconel 718, due to its fatigue fracture resistance, low thermal conductivity and ability to form protective films [9], [23].

4.3 Experiment setup and design

In the current study, to evaluate the performance of the deposited Al-Si layer on a cutting tool, two different deposition methods were used, as explained below:

In the first method, the Physical Vapor Deposition (PVD) process was used to deposit an Al-Si monolayer with two different thicknesses of 0.7 µm and 1 µm on a Kennametal K313 cemented carbide grade with the reference number of ISO CNGG432FS. In this process, the sample was heated up to around 550°C and Ar gas was used for the deposition using the PVD method.

In the second method, the pre-machining technique, which was proposed by the authors in a previous study was used [21]. In this method, a single machining pass of around two seconds was performed on an Al-Si bar to deposit a thin layer of Al-Si layer on the tool before the start of machining with Inconel 718. Figure 4-1 shows the experimental steps of the tool treatment procedure in the pre-machining method. As can be seen in Figure 4-1, a thin layer of Al-Si is formed on the pre-machined tool after step 1. For deposition of Al-Si in the pre-machining process, a high cutting speed, high depth of cut and low feed rate were selected to produce the uniform thin layer that fully covers the cutting tool. The cutting conditions are shown in the first row of Table 4-2. These conditions were selected after some trials.

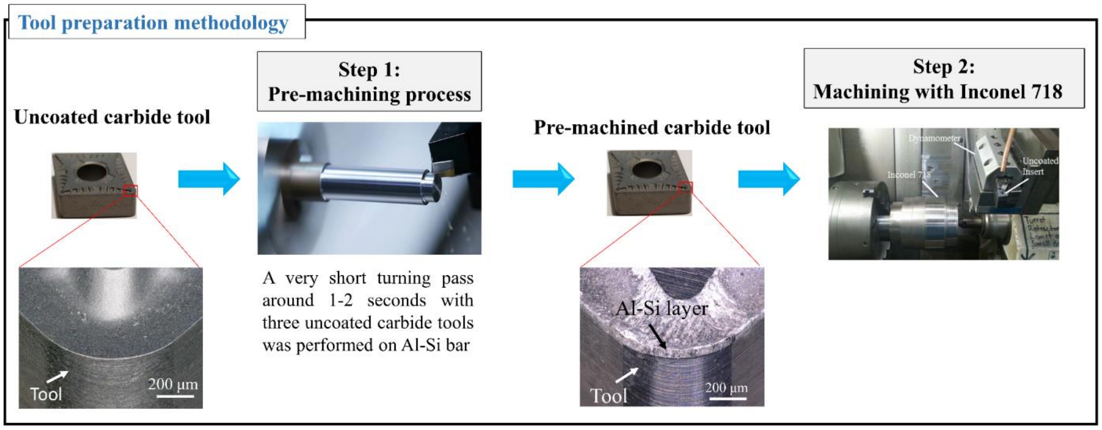


Figure 4-1. Pre-machining experimental steps

Table 4-2. Cutting conditions for different machining

Cutting Parameters	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	Coolant
Pre-machining process	450	0.06	1	Dry
Machining of Inconel 718	50	0.1	0.15	Wet

For machinability studies, the base uncoated tungsten carbide tool, which is a suitable grade for machining of Inconel, was considered as the benchmark tool. Also, a hard TiAlN PVD coated tool was considered as a commercial coated benchmark tool. The coated and pre-machined tools were further compared with the benchmark tools. Therefore, five different tool types were selected for the machinability analyses as listed below:

Tool 1: Uncoated tungsten carbide (WC) tool as a benchmark

Tool 2: TiAlN PVD coated tool as a commercial benchmark

Tool 3: Al-Si coated tool with the traditional PVD method with a coating thickness of 0.7 μm

Tool 4: Al-Si coated tool with the traditional PVD method with a thickness of 1 μm

Tool 5: Al-Si pre-machined tool with a thickness of 40 ± 5 μm

All properties and characteristics of coated and pre-machined tools are shown in Table 4-3. The thickness of Al-Si coated tools was measured with a ball crater system of a 25 mm diameter. The thickness of the Al-Si pre-machined tool was measured with a Keyence VHX-5000 microscope. The hardness of the deposited Al-Si on the pre-machined tool was measured by Micro Materials NanoTest system, with a constant load of 40 mN and a Berkovich diamond indenter. The hardness values are reported in GPa which is the SI unit typically used for reporting the hardness.

Table 4-3. Properties of the coated and pre-machined tools

Coatings	Composition (at%)	Process	Layer	Hardness (GPa)	Thickness (μm)	Edge radius (μm)
TiAlN	Ti (40), Al (60), N	PVD	Monolayer	35 [24]	4.5	8.12
AlSi	AlSi (10)	PVD	Monolayer	1.5 [25]	0.7 & 1	8.03
AlSi	AlSi (10)	Pre-machining process [21]	Monolayer	1.58 ± 0.21	40 ± 5	8.23

The workpiece material for this study was an Inconel 718 bar with a hardness of 32-34 HRC. The material properties and main chemical compositions of Inconel 718 are given in Table 4-4 and

Table 4-5, respectively. The material property was consistent before and after of cutting process. The chemical composition was identified using Varian Vista Pro Inductively Coupled Plasma (ICP) device equipped with Expert II software. The machining tests were carried out on an OKUMA CNC Crown L1060 turning machine. A semi-synthetic CommCool HD water-based coolant with a concentration of 5% and pressure of 7 bar was applied during the wet turning process of Inconel 718. Cutting forces during the experiment were measured with a Kistler dynamometer. The cutting conditions for Inconel 718 machining was shown in the second row of Table 4-2. Typically, a combination of low cutting speed, high feed, and depth of cut improve tool performance in Inconel 718 machining [26]. However, in the current study aggressive cutting conditions (high cutting speed, low feed and low depth of cut) were intentionally selected to evaluate the performance of the proposed coatings under the most severe conditions. The same conditions were selected in our previous studies, enabling the comparison of the current results with previous results on the proposed pre-machining method. The conditions used are presented in Table 4-2.

Tool wear measurements after each cutting pass were taken and chip thicknesses after the first machining pass were measured by a Keyence VHX-5000 digital Microscope. Chip undersurface roughness and flank wear surface roughness were measured with a white light interferometer microscope. Tool material characterization analyses were done on a Tescan Vega II LSU Scanning Electron Microscope (SEM) equipped with an Oxford X-Max 80 Energy-Dispersive X-ray Spectroscopy (EDS) detector and Inca software. X-ray photoelectron spectroscopy (XPS) equipped with a Physical Electronics (PHI) Quantera II spectrometer with a hemispherical energy analyzer was performed on the tool to verify the formation of different types of the tribofilms. The hardness of the machined Inconel bulk material measured by Micro Materials NanoTest system, with a constant load of 40 mN was assessed using 40 indentations. A Berkovich diamond was used as the indenter. The coefficient of friction (COF) of the Al-Si deposited layer on the tool through machining/PVD process measured by Anton Paar Revetest scratch tester. A Rockwell C diamond with 20 µm radius, a constant load of 2N, the velocity of 5 mm/min and length of 1mm were selected for the COF measurement.

Table 4-4. Chemical composition of Inconel 718

Material	**Cr**	**Fe**	**Mo**	**Nb**	**Ti**	**Al**	**Cu**	**Mn**	**Si**	**C**	**S**	**Co**	**P**	**Ta**	**B**
Weight %	17.2	15.65	2.9	5.24	1	0.6	0.3	0.35	0.35	0.08	0.015	1	0.015	0.05	0.006

Table 4-5. Material properties of Inconel 718

Property	Density (kg/m^3)	Young's Modulus (GPa)	Ultimate Tensile Strength (MPa)	Yield Tensile Strength (MPa)	Thermal Conductivity (w/mK)	Specific Heat Capacity (J/kg °C)	Melting Point (°C)
Value	8190	200	1375	1100	11.4	435	1260-1336

4.4 Results and Discussions

In this section, the performances of the pre-machined and coated tools are compared with the uncoated and coated benchmark tools, defined in the experimental set-up section, in terms of their tool life, tool wear mechanisms, chipping characteristics, cutting forces and their effect on the work-hardening of the workpiece material.

The Al-Si used possess numerous beneficial properties as a target material that has been overlooked till now and not been used as a coating material. However, in this section, results will be presented showing how the combination of these properties can improve the cutting performance in general. These properties include high lubricity and low coefficient of friction, high ductility and high compatibility. In contrary to what was expected, its low melting point is also a favorable property contributing to tool protection and chipping resistance. The contributions of these factors on improving the machinability of Inconel 718 are discussed in this section. More details can be found in our previous studies [21], [22].

Although the performance of the pre-machining process is very similar to the PVD coating, having the same target material, there are some unique features about the pre-machining process that makes this process very distinctive from the PVD process. The principal differences between the two processes are as follows. It should be mentioned that the pre-machining is a cost-effective method with approximately 4 times lower costs than the commercial available PVD method.

During the pre-machining process, the Al-Si is formed through cutting the Al-Si bar. Thus, the Al-Si layer is mainly formed on the tool rake face (Figure 4-2). While through PVD coating a uniform layer will be formed on both rake and flank faces.

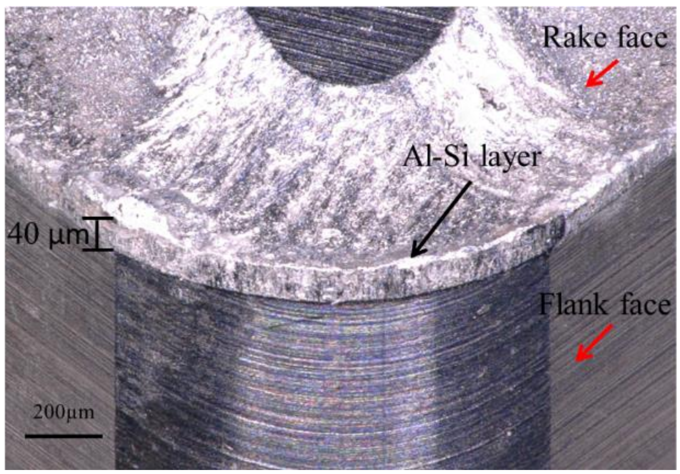


Figure 4-2. Al-Si layer deposited on the tool rake face through the machining process

The thickness of the Al-Si layer formed on the tool through the pre-machining process can be as high as 40±5 μm. Providing this thickness through the PVD process is almost impossible and if possible will induce many geometrical challenges. In this study, the thickness of the coating is around 1 μm, which is a typical value for a PVD coating.

During the pre-machining process, the Al-Si is deposited on the tool under high machining temperature and pressure, much higher than the equivalent values for the coating.

Moreover, as opposed to the PVD coating, the pre-machining process can be considered as a preconditioning process, where before using the tool for its actual machining performance, it is experiencing an intense load and temperature which effectively forms a built-up edge (BUE) level of material which is known to have a high level of adhesion to the tool substrate [21].

The main focus of this study is to investigate the effect of these differences in the deposition techniques on the performance of the tools used for machining of difficult-to-cut materials such as Inconel 718.

4.4.1 Results

4.4.1.1 Tool life comparison

Figure 4-3 shows the tool life of the uncoated, TiAlN PVD coated, Al-Si PVD coated with 0.7 and 1µm thicknesses and Al-Si pre-machined tools. It should be mentioned that in the current study, either maximum flank wear of 0.3 mm or excessive tool chipping, in the order of precedence, were considered to be the end of tool life criterion. As shown in Figure 4-3,tools coated with a 1 µm Al-Si, coated with a 0.7 µm Al-Si and Al-Si pre-machined tool and tool coated with TiAlN prolong tool life 321%, 231%, 205% and 122% respectively, compared to the uncoated tool. The results show that both pre-machined and coated tools with a soft Al-Si show significant improvements over the uncoated tool and the hard commercial TiAlN coated tools. Moreover, comparing our results with the existing results for the TiAlN reported in the literature, shows the Al-Si coated tool outperforms the TiAlN coated tool under almost all conditions reported [9], [10], [27]–[29].

The common trend in developing coatings for machining of difficult to cut materials is to develop as hard as possible layer on the tool to improve its wear and abrasion resistance.

However, this study for the first time showed that application of an ultra-soft material as a coating can be very beneficial and their performance can be even better than commonly used hard coated tools in the industry. Contrary to what is believed, this study also showed that the application of soft coatings was not limited to its low melting point. In the discussion section, it will be shown how the molten material acted as an in-situ lubricant and contributed to tool life enhancement. Significant improvement of the developed coated/pre-machined tool with a soft material used during machining of Inconel 718, will open a new window in the area of tool coating selection for demanding machining applications.

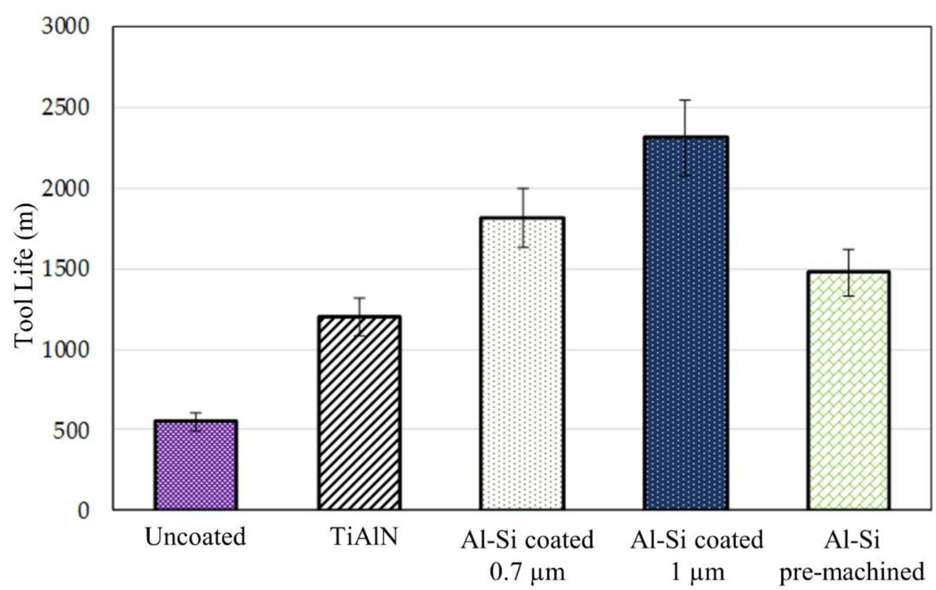


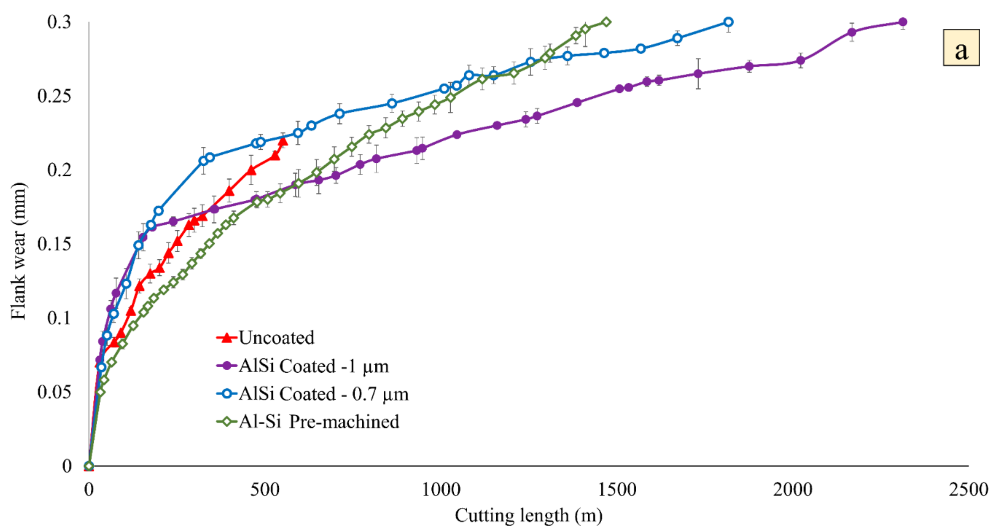
Figure 4-3. Tool life of the coated, pre-machined and uncoated cutting tools

4.4.1.2 Machinability study

Since the focus of this study is to examine the performance of the Al-Si coated tools in comparison to the Al-Si pre-machined tool, further investigations on machinability and performance of these tools are provided in this section.

4.4.1.2.1 Tool wear and cutting forces

Figure 4-4.a shows the tool flank wear and Figure 4-4.a shows cutting force as a function of the cutting length for the pre-machine and coated tools in comparison to the uncoated tool.



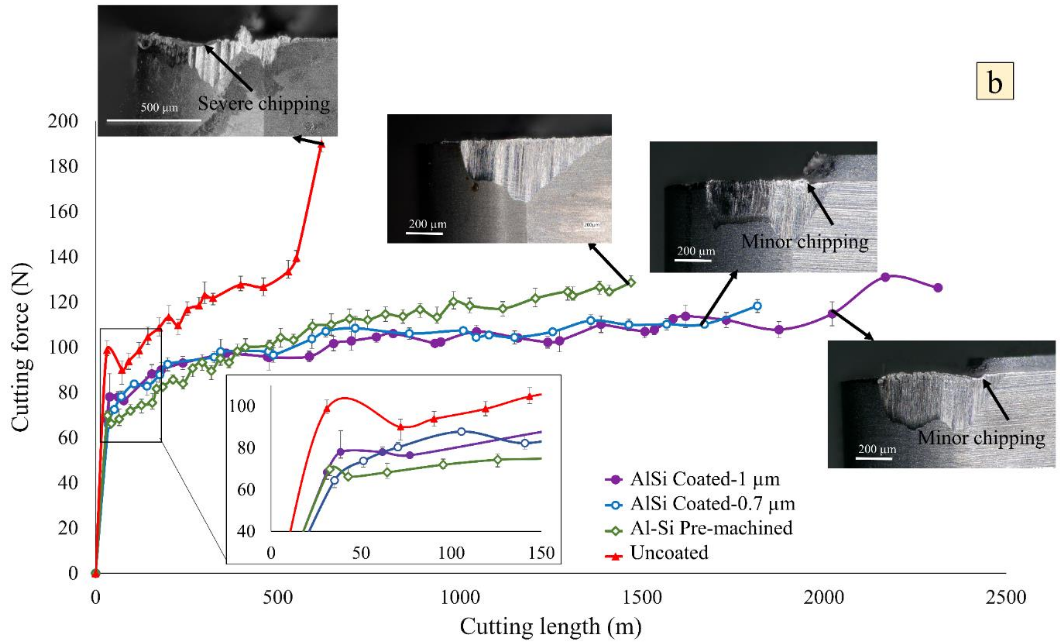


Figure 4-4. a) Tool flank wear vs. cutting length, b) cutting force vs. cutting length for uncoated, Al-Si pre-machined and Al-Si coated inserts during machining of Inconel 718

As can be seen in Figure 4-4.a, uncoated tool wear measurements were stopped prior to 0.3 mm flank wear due to aggressive chipping of the cutting edge occurring at around 550 m of cut. Since the uncoated tungsten carbide tool cannot withstand the high temperature and pressure generated during cutting of Inconel 718, severe chipping occurs at the cutting edge. The experiment was repeated more than 4 times and all the tools were observed to chip before 600 m of cut. Figure 4-5 shows an example of tool failure and severe chipping of the uncoated tool after 120 m of cut.

As illustrated in Figure 4-5.a, the tool life of the Al-Si pre-machined tool is much higher than the uncoated tool. While the tool life of the Al-Si coated tools are even much higher than the pre-machined tool. As can be seen in Figure 4-4.a, the tool flank wear trends for both Al-Si coated tools are similar to each other and show the highest improvement among the tools tested.

As the tool wear increases gradually, so does the cutting force (Figure 4-4). As demonstrated in Figure 4-4.b, the Al-Si coated tools and pre-machined tool were able to reduce the initial cutting force by around 25% and 40% respectively.

Similar to the tool wear results, the forces of the pre-machined tool at the running-in stage is the lowest among the tools tested.

Moreover, for the uncoated tool, the force values show a distinct rise as the tool severely chipped at around 550 m of cut. Minor chipping was also observed on the coated tools, corresponding to a small rise in the force data around the end of tool life.

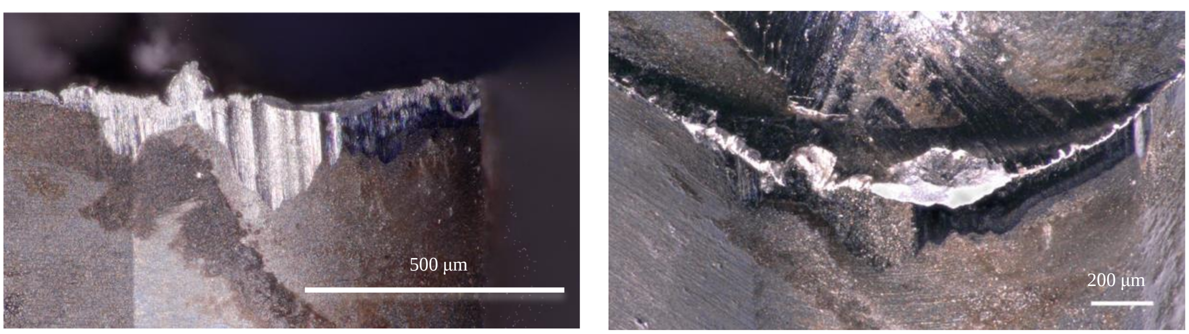


Figure 4-5. Uncoated tool after around 550 m of cut

4.4.1.2.2 Tool wear mechanisms

Figure 4-6 shows the images of the different worn tools at the end of their tool lives. The main tool wear mechanisms of all the tools can be classified as notch wear and chipping, abrasion, adhesion and built-up edge (BUE).

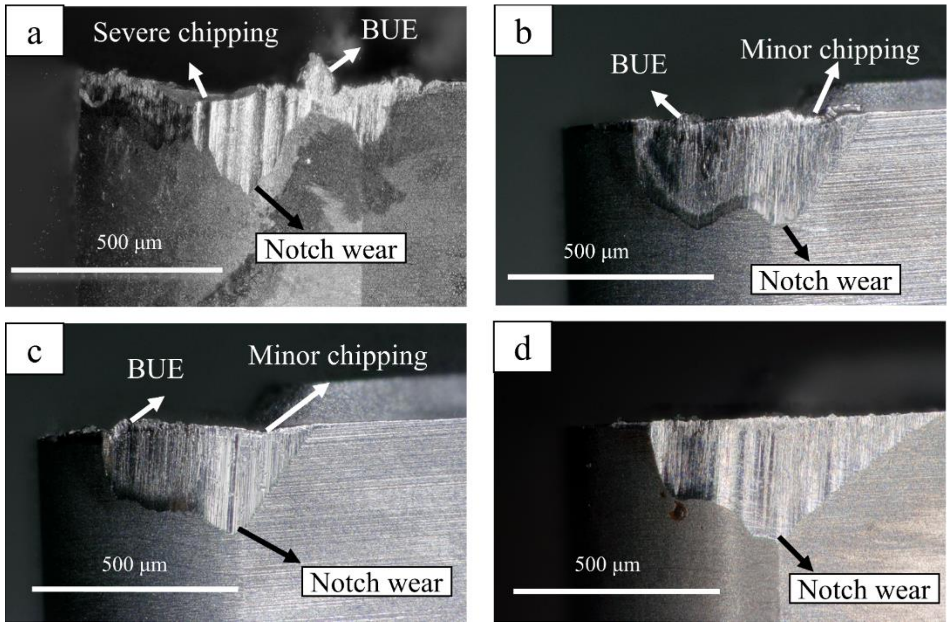


Figure 4-6. Images of the worn tools at the end of their tool life for a) uncoated tool after 120 m of cut, b) Al-Si coated with 1 µm thickness after 2350 m of cut, c) Al-Si coated with 0.7 µm thickness 1850 m of cut, and d) Al-Si pre-machined tool after 1470 m of cut during machining of Inconel 718

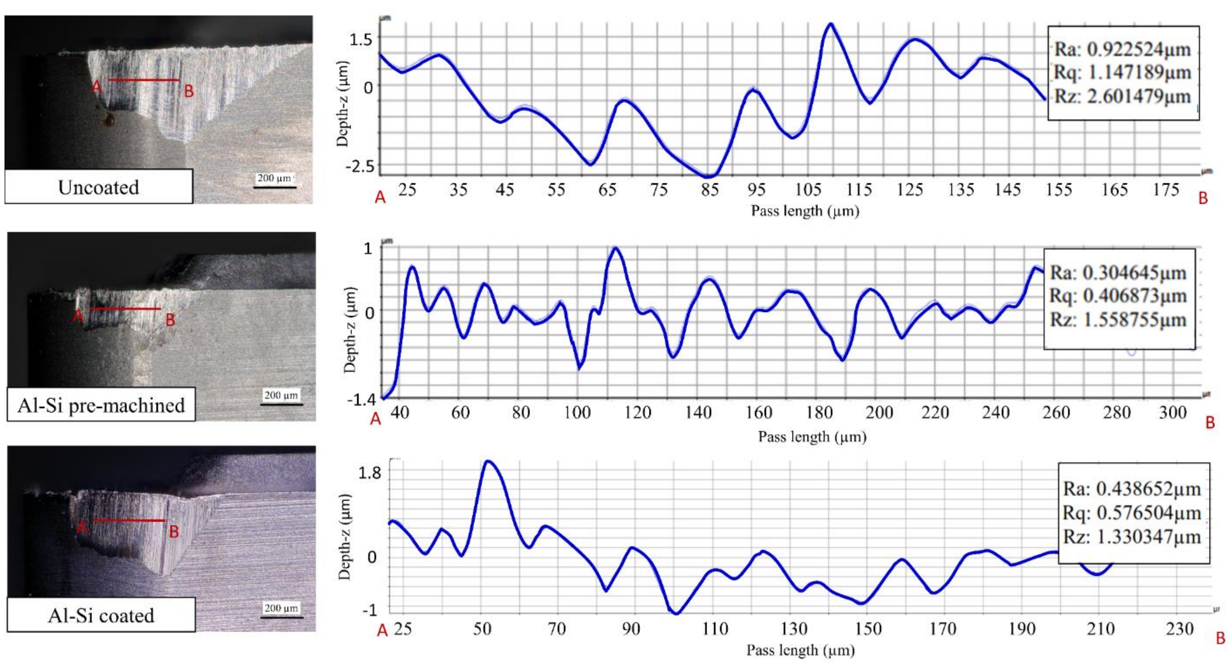
As mentioned before, severe notch wear and chipping occurred on all the uncoated tools. An example is provided in Figure 4-6.a showing severe chipping after 120 m of cut.

Minor chipping in the notch area were also observed on the coated tools close to the end of their lives; at around 2000m of cut for the 1 µm thickness coating (Figure 4-6.b) and at around 1600m of cut for the 0.7 µm thickness coating (Figure 4-6.c).

No sign of chipping was observed for the pre-machined tools. It should be mentioned that the test was repeated at least 10 times. Figure 4-6.d shows an example of a pre-machined tool after 1470 m of cut.

Adhesion and BUE formation is another main concern especially for the uncoated tools as shown in Figure 4-6.a. The BUE formation was controlled significantly by pre-machining with the tool (Figure 4-6.d). Coated tools also showed very good performance in reducing the BUE (Figure 4-6.b and 6.c).

Two body and three body abrasion wear is another mechanism occurring during machining of Inconel 718 due to the presence of hard carbide particles in the microstructure of the workpiece. The broken pieces of BUE may also get stuck between the tool and workpiece and result in severe abrasion wear. In order to compare the abrasion wear of the different tools, the roughness of the worn surfaces of different tools was measured using an Alicona Infinite Focus microscope and the Ra and Rz values were compared. The results are shown in Figure 4-7. As can be seen in Figure 4-7, Ra and Rz of the flank surface of the pre-machined/coated tool are around 2 times lower than the uncoated flank surface, pointing to significantly less grooves and consequently lower abrasion wear for these tools compared to the uncoated tool.



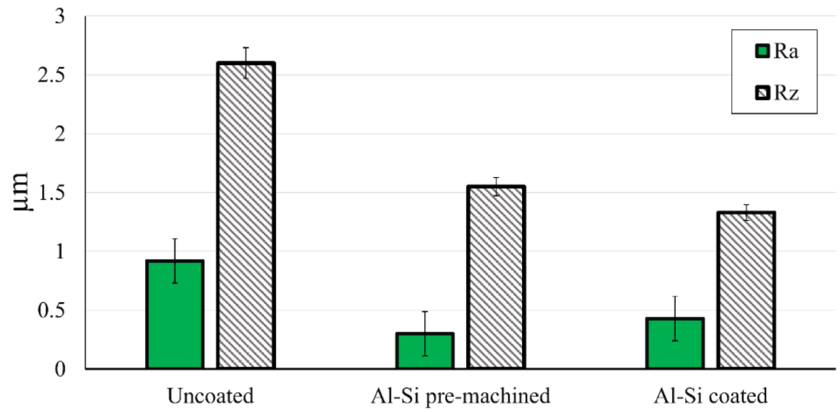


Figure 4-7. Flank surface roughness (Ra and Rz) of the uncoated, Al-Si pre-machined and Al-Si coated tools

4.4.1.2.3 Work hardening

The high work hardening tendency of Inconel 718 will result in high cutting forces, severe notch wear and tool chipping/failure during the cutting process. Due to the work hardening, the hardness of the surface layer of the material will change. Due to the work hardening, the hardness of the surface layer of the material will change. Therefore, reducing the work hardening will significantly improve tool performance. In the current study, to study the ability of the coated and pre-machined tools in reducing the machining induced work-hardening, micro-indentations were performed on the undersurface of the workpiece material after machining with these tools. As before, the same test was performed for the uncoated tool as the basis of comparison. As illustrated in Figure 4-8, the maximum hardness of the workpiece material machined with the uncoated tool is around 16 GPa. While this value was reduced to around 12 GPa after using the coated tool and to around 10 GPa after applying pre-machining. The 40% improvement reached by the pre-machining process is, to the best of our knowledge, the highest achievement reported for this phenomenon and the corresponding 25% improvement for the coated tool is also among the best values ever reported for different tools/strategies. Since work-hardening is one of the most important issues of machining of Inconel 718, this significant improvement can be itself considered as one of the main success factors in employing soft coatings for machining this material.

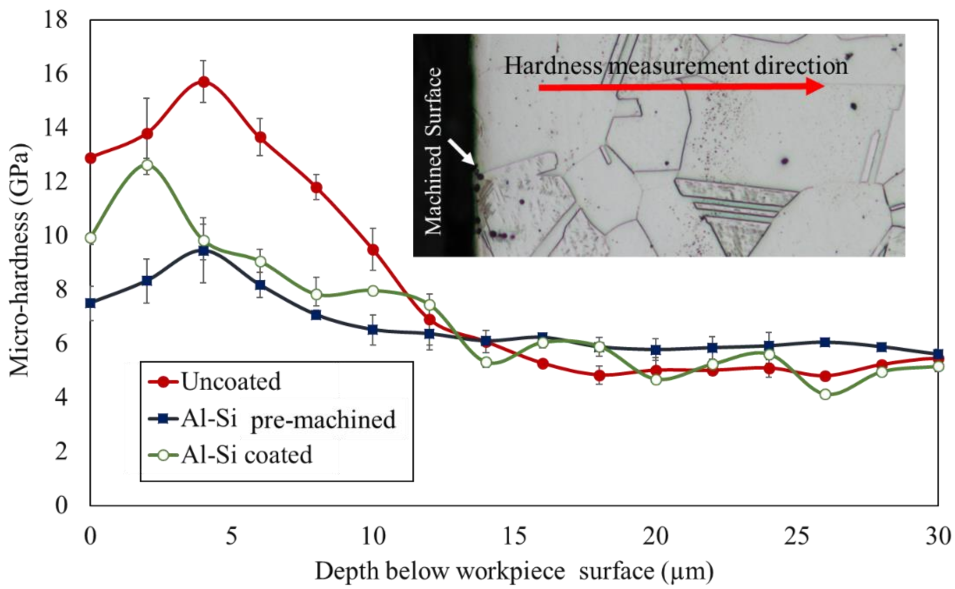


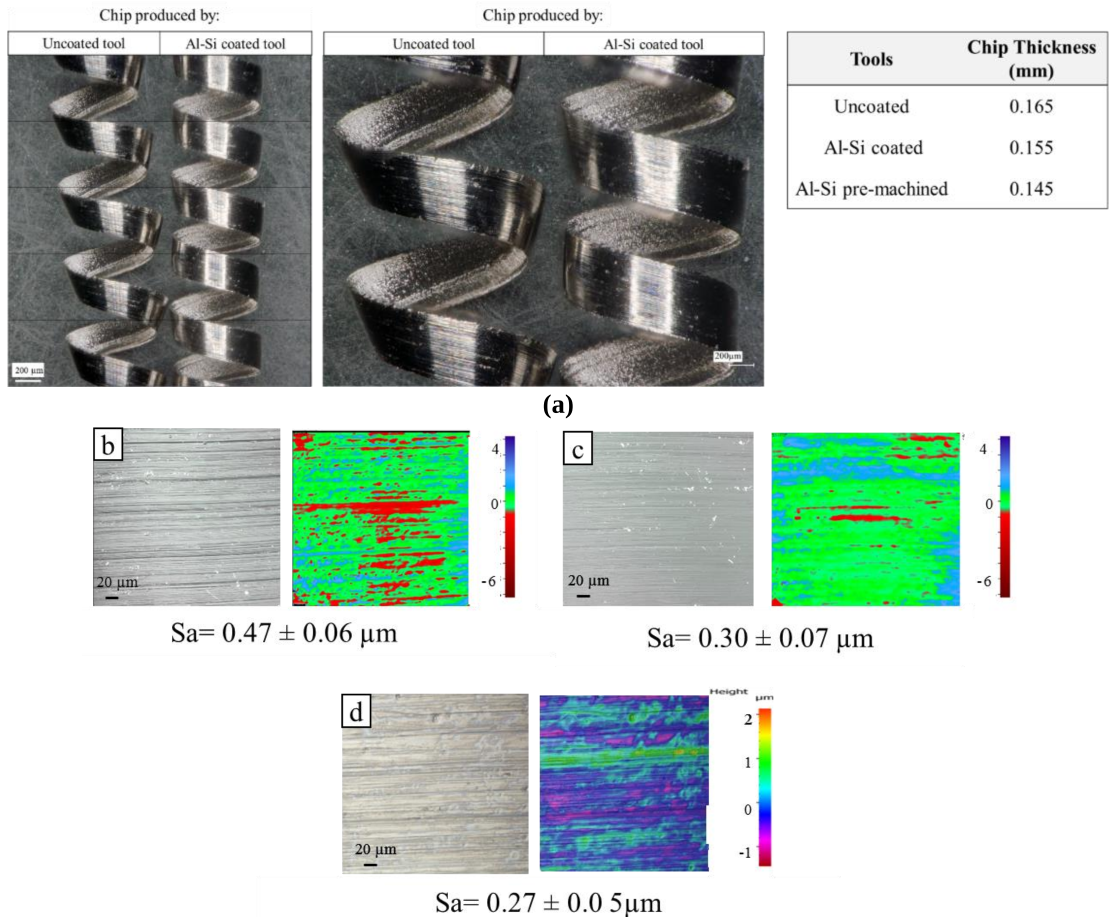
Figure 4-8. Micro-hardness measurement of the workpiece material

4.4.1.2.4 Chip morphology

Different properties of the chips generated during machining including their thickness, curliness and their back surface roughness can provide us with general beneficial information such as the friction at tool-chip contact zone and improved chip flow. As an example, a thinner, curlier and smoother chip undersurface indicates better chip flow as a result of shorter tool-chip contact length and lower friction in the cutting zone [30].

The chips produced in Inconel 718 machining with all the tools were of a continuous type. The chips produced with the Al-Si pre-machined and coated tool were curlier than the uncoated tool. An example is provided in Figure 4-9.d.

Figure 4-9.a and 4-9.c show the chip undersurface and their corresponding measured roughness for the Al-Si coated, pre-machined and uncoated tools. The undersurface roughness of the chips produced by the Al-Si coated and pre-machined tools are considerably lower than the uncoated tool. The under-surface roughness for the uncoated tool is around 0.47 µm, which shows higher friction between the tool and chip interface due to the lack of a coated layer. The undersurface roughness for the Al-Si and pre-machined tools are 0.30 and 0.27 µm, respectively. The lower value of chip undersurface roughness indicates better frictional behavior and better material flow during the machining process at the tool-chip interface. Therefore, results demonstrate superior frictional behavior of the Al-Si pre-machined and coated tools.



Tools	Chip Thickness (mm)
Uncoated	0.165
Al-Si coated	0.155
Al-Si pre-machined	0.145

Figure 4-9- a) chip produced by Al-Si coated and uncoated tools and all chip thickness, And chip undersurface surface roughness measurement produced by a) uncoated tool, b) Al-Si coated tool and d) Al-Si pre-machined tool

4.4.1.2.5 Coefficient of friction at tool-chip interface

The COF of the Al-Si deposited on the tool through the pre-machining and the PVD processes were measured. For the coated tool, the COF measurement was performed on the flat coated insert. For the pre-machined tool, the cross-section of the insert was mounted, ground and polished. The COF measurement was performed on a flat cross-section of the built-up material formed on the tool rake face (Figure 4-10). For this purpose, the scratches were performed with a constant load by the Anton Paar Revetest scratch tester. All measurements were repeated at least three times.

The results showed that the COF of the Al-Si deposited through the pre-machining process was around 0.06-0.08 and the COF of the Al-Si deposited through the PVD process was around 0.08-0.1.

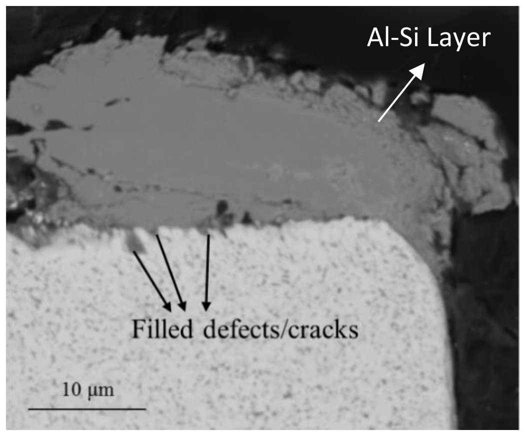


Figure 4-10. Cross-section of the pre-machined tool after mounting, grinding and polishing

4.4.1.2.6 Coating Coverage

Since the full coverage in the coated tool plays an important role in the tool performance, the cross section of the Al-Si pre-machined tool, Al-Si PVD coated tool and TiAlN as a hard benchmark tools are shown in Figure 4-11. As can be seen in Figure 4-11.a, the Al-Si deposited layer on the tool through the pre-machining process, covered the whole rake face and also the cutting edge of the tool. For the soft Al-Si PVD coated tool also all areas including the cutting edge were covered uniformly with the deposited material (Figure 4-11.b). While in the commercial hard coating as shown in Figure 4-11.c, the cutting edge is not covered with the coating material and coating layer is not uniform on the rake face. Poor coverage of the cutting edge will result in to the tool fracture. Figure 4-12 shows the damage of the cutting edge of the TiAlN PVD coated tool.

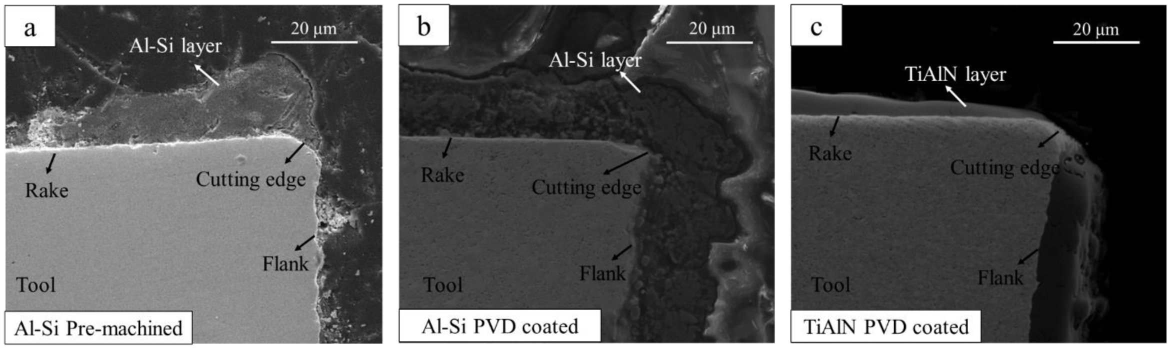


Figure 4-11. cross sections of the tool cutting edges of a) Al-Si pre-machined tool, b) Al-Si PVD coated tool and c) TiAlN PVD coated tool

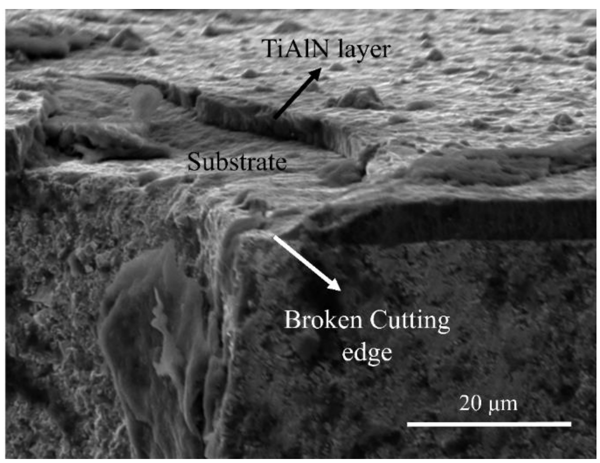


Figure 4-12. Damage of the cutting edge of the TiAlN PVD coated tool

4.4.1.3 Discussions

The results showed that the main wear mechanism for the uncoated tools during machining of Inconel was chipping, as it occurred on all the uncoated tools before 600 m of cut. Generally, there are two main reasons responsible for this severe chipping. Severe work hardening of the machined surface is one of the main reasons for the sudden tool chipping during the machining of Inconel 718. This material has a high tendency to work harden, especially under the high temperatures and pressures generated during its machining [31]. The work hardened layer of the workpiece material which has different material properties results in significant wearing of the tool especially at the notch area where it is in contact with hardened material [2]. Thus, severe notch wear in the following machining passes causes tool chipping/failure. The soft and lubricious Al-Si layer formed on the pre-machined and coated tools reduced the friction and significantly improved the lubricity at the tool-chip interface, as clearly shown in 3.1.2.4. Moreover, at the high temperatures generated during machining of Inconel, the Al-Si melts and acts as an in-situ lubricant and helps in reducing the contact pressure between the surfaces. Collectively these result in a significant reduction in cutting forces. Lower force values represent lower pressure on the tool resulting in a reduction of work hardening of the machined material. In addition, the previous study also showed a temperature reduction as a result of the Al-Si deposition which further contributes to work-hardening reduction [32]. Thus, through significant reduction of friction, temperature and pressure, work-hardening was significantly reduced by 44% for the pre-machined tool and 25 % for the coated tools.

The other main reason for tool chipping/failure during machining of Inconel 718 is the built-up edge (BUE) which tends to form on the cutting edge due to the high temperature and pressure present in the cutting zone that is prevalent when machining Inconel 718. As the BUE is constantly forming and breaking, it can also break small pieces of the tool and result in excessive chipping and finally tool breakage. The unstable behavior of the BUE is evident in Figure 4-13 for the uncoated tool at different stages of the machining process.

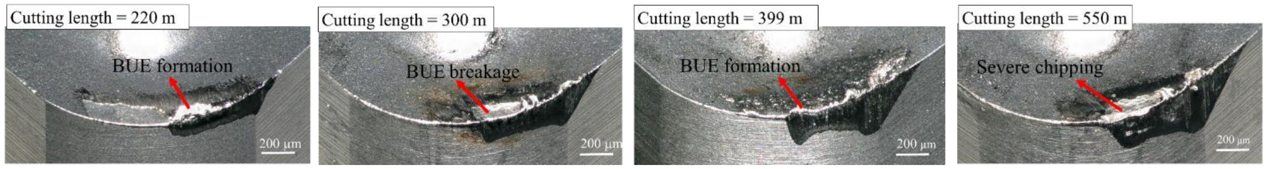


Figure 4-13. BUE formation and breakage on the cutting edge of the uncoated tool at a cutting length of a) 220 m, b) 300 m, c) 399 m, and d) 550 m

High lubricity of the coatings and further formation of lubricous layers on the tool-chip contact surfaces can significantly reduce adhesion and BUE formation.

The Al-Si deposited on the tool surface through both techniques exhibits very low coefficient of friction (COF). The COF of the Al-Si formed on the tool rake face on the pre-machined tool was measured around 0.06 to 0.08. In addition, the COF of the coating was also found to be 0.1.

Existence of this lubricious material with a very low coefficient of friction (COF) at the tool-chip contact zone resulted in less friction and easier flow of the chip and less adhesion and BUE formation.

Moreover, an XPS study performed on the rake face of the tools covered with Al-Si showed that several lubricious tribofilms including, SiO_x and thermal barrier tribofilms including sapphire (Al_2O_3) and mullite ($Al_6Si_2O_{13}$) were formed on the tool during the cutting process due to the presence of aluminum and silicon which have a high potential to react with oxygen in the cutting zone under high machining temperatures. The tribofilms formed not only protect the tool from the high temperatures associated with cutting, but they also can facilitate chip flow. Better material flow on the tool reduces the probability of adhesion and BUE formation during chip formation.

Curlier, thinner and smoother chips clearly confirmed better material flow and less friction at the tool-chip contact zone for the pre-machined and coated tools.

Reduction of work-piece work hardening in addition to the lower sticking and BUE formation resulted in a considerable reduction of chipping for both the pre-machined and coated tools. More detailed discussions on the mechanisms behind these improvements can be found in our previous studies [21], [22].

The soft Al-Si layer formed on the tool can improve other machinability aspects of Inconel 718 through a combination of different mechanisms. A significant reduction of two body and three body abrasion wear in the pre-machined and coated tools in comparison to the uncoated tool were observed which can be attributed to less contact pressure on these tools.

The results also showed that although in the pre-machined tool only the rake face and cutting edge were covered with Al-Si, it was more successful in preventing chipping than the coated tool in which all faces were coated with Al-Si. It should be mentioned that only minor chipping was observed on the cutting edge close to the end of the cut (Figure 4-6) for the coated tools. In general, severe sticking and BUE occurs at the rake face and the highest temperatures are generated in this area. Thus, results showed an improvement in the tribological properties of the rake face and cutting edge can itself significantly improve the tool chipping resistance. The higher thickness of the Al-Si for the pre-machined tool may have contributed to its better performance in reducing chipping and improving this aspect of tool life.

It should be mentioned that for the hard coatings providing full coverage especially at the cutting edge is very challenging. This is considered as the main drawback for thick coatings. The cohesive and adhesive damage of the tool is the main reason for the tool failure, especially at the cutting edge due to the high stress concentrations [33], [34]. This phenomenon was shown in Figure 4-11. As shown in Figure 4-11, the whole rake face and cutting edge covered uniformly in the Al-Si pre-machined tool which resulted on excellence tool performance. For the soft Al-Si PVD coated tool, all areas of the tool were covered uniformly with the deposited material (Figure 4-11). While in the commercial hard coating as shown in Figure 4-11.c, due to the lack of the coating adhesion, the cutting edge is not covered with the coating material. In addition, the coating thickness of the rake face is not as uniform as the flank face in the TiAlN PVD coated tools. This non-uniformity at the rake face and non-coverage at the cutting edge can be considered as one of the reasons for tool chipping and failure of hard coatings for machining of difficult-to-cut materials. Though the Al-Si in the coated and pre-machined tools will be molten and pushed outside of the contact zone, its full coverage at the beginning of the cut resulted in a considerable reduction in chipping, through damping the initial machining shock and also improving the running-in stage performance of the tool. It should also be mentioned that, although a considerable amount of Al-Si is pushed out of the contact zone due to the high pressure, the XPS result showed that a considerable amount of Al-Si still remains in the tool-chip contact zone till the end of tool life, contributing to its high performance.

It should also be mentioned that when a soft coating is removed from the cutting tool material, it is not breaking the substrate material when it is being removed. While with hard coatings, when the coating breaks away from the tool it also can break part of the substrate material easily which leads to severe tool chipping and ultimately failure over time (Figure 4-12).

It is worth mentioning that there is a limitation to increasing the thickness of the coating layer in PVD method due to the higher induced residual stress on a cutting tool. This leads to a higher susceptibility to coating delamination and tool chipping [35]. While in the soft coating having a high thickness is not a limitation.

As mentioned, the thickness of the Al-Si layer was much higher for the pre-machined tool, allowing better flow and lower contact pressure specially at the running-in stage and more damping of the initial machining shock (Inconel machining. Moreover, pre-machining can be considered as a pre-conditioning process, further improving the running-in stage performance of the tool.

In addition, since in the pre-machined tool, the Al-Si is deposited under extremely high temperature and pressure of machining, the molten metal has a higher chance of channeling through the rake face and filling small existing defects and cracks on the tool surface. Figure 4-10 shows a cross-section of the pre-machined tool. As can be seen, the small cracks on the surface are filled with Al-Si. The presence of this material in a crack can prevent the cracks from propagation which results in the prevention of large scale chipping which is especially important for machining of difficult to cut material where each minor defects can grow rapidly leading to catastrophic tool failure.

Though chipping resistance of the pre-machined tool was the best among other tools, the tool life of the Al-Si PVD coated tool was higher. Less flank wear and consequently higher tool life of the coated tool can be attributed to the protection it receives at the flank face from the presence of the Al-Si coating on this surface. Though the presence of a protective lubricious layer at the rake face is very crucial in terms of reducing the forces and improving the machinability, reducing the friction at the flank face itself can have a considerable effect on reducing the flank wear rate.

4.5 Conclusions

In the current study, for the first time, a very soft metal is used as the target material for depositing Al-Si on a cutting tool which is then used for machining of Inconel 718. Two different techniques were employed for deposition. A method proposed by the authors and named as pre-machining and PVD techniques were used with the results compared with an uncoated tool and a commercial hard TiAlN coated tool commonly used for machining of Inconel. The results showed significant improvements in tool performance with both techniques. The major findings of this study are listed below:

- Tool life studies showed that application of the Al-Si coated with 1 µm thickness, 0.7 µm thickness, Al-Si pre-machined and TiAlN coated tools for machining of Inconel 718 resulted in 321%, 231%, 201%, and 122% tool life improvements respectively, compared to an uncoated tool. The chipping was significantly reduced by the application of Al-Si deposition through both techniques.
- Around 25% and 40% improvements in cutting forces over uncoated tools were achieved by using Al-Si coated and Al-Si pre-machined tools respectively.

- The results showed that the abrasion wear was significantly reduced for the Al-Si pre-machined/coated tools compared to the uncoated tool which was attributed to the lower contact pressure at the contact zone.
- One of the major achievements of this study was reducing the work hardening of the workpiece material. The work hardened surface layer was reduced by 25% for the Al-Si coated and 40% for Al-Si pre-machined tool.

These significant improvements were attributed to several properties of Al-Si such as its high lubricity and low COF, its high compatibility and its ability to form several beneficial tribofilms within the tool-chip contact zone, its high ductility and damping properties which are especially important for absorbing the initial machining shock at the running-in stage. As the cutting temperature during machining Inconel 718 is higher than the melting point of Al-Si, it will be molten during the cutting of Inconel. Thus, it acts as an in-situ liquid lubricant and reduces friction, improves chip flow and reduces the contact pressure at the tool chip-interface. These phenomena are all consistent with the machining results obtained through the comprehensive machinability studies reported on in this paper. Furthermore, the curlier chips with less chip thickness and lower chip undersurface roughness measured for the Al-Si coated and pre-machined tools clearly showed the better friction behavior of these tools in the cutting zone as compared to the uncoated tool. This resulted in less BUE formation and in-turn less chipping as a result of the deposition of Al-Si on the tool. Considerably lower abrasion wear also further indicated lower contact pressure for the pre-machined/coated tools.

The results also showed that the Al-Si layer effectively covered the rake face and tool edge of the pre-machined tool and resulted in full coverage of both the tool edge and rake and flank faces of the coated tool. This is a significant advantage associated with applying soft coatings over hard surfaces, where maintaining a full cutting edge coverage is still a challenge especially for thick coatings. Moreover, achieving a high thickness coating is not a limitation due to the material properties of the soft layer which was especially evident for the pre-machined tool. This will result in significant tool chipping prevention especially by protecting the tool from initial shock and improving the running-in stage performance of the tool.

During the pre-machining process, since the Al-Si material is deposited on the tool under an extremely high machining temperature and pressure it has more of a chance to fill the existing cracks and prevent them from propagation than the Al-Si PVD coated tools.

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4.7 References

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5 Chapter 5

Novel Application of Ultra-Soft and Lubricious Materials for Cutting Tool Protection and Enhancement of Machining Induced Surface Integrity of Inconel 718

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Novel Application of Ultra-Soft and Lubricious Materials for Cutting Tool Protection and Enhancement of Machining Induced Surface Integrity of Inconel 718

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5.1 Abstract

Inconel 718 is widely used in different industries including aerospace where part quality concerns drive manufacturing process developments. However, despite extensive research, machining of Inconel 718 is still very challenging, often triggering severe surface quality problems. High temperatures and pressures generated at the contact zone during machining of this class of materials as well as high tool wear rates and aggressive built-up edge formation, result in severe work-hardening and the generation of high levels of unfavorable residual stress on the surface of the workpiece material. The current approach to overcome the high work-hardening of the workpiece and avoid wear and chipping is employing super hard tooling. However, the current results showed that, contrary to what is believed, depositing a very soft metallic layer on the tools can significantly reduce the severity of the dominant tool wear mechanism in this case and thereby improve surface quality. The results were attributed to alleviating the machining induced work-hardening of the workpiece material, which is the main root cause of its high tool wear rate and propensity to the tool chipping. Different soft and lubricous materials were deposited on the tools used for machining of Inconel 718, through an innovative technique and using conventional PVD coating methods. An in-depth surface integrity analysis is performed to study their effect on improving the integrity of the machined workpiece surface including reducing the work-hardening and residual stresses and enhancing the surface roughness.

Keywords: Inconel 718, Work hardening, Surface integrity, Soft metallic coatings, Al-Si coatings.

5.2 Introduction

Inconel 718 is a common nickel-chromium-iron based superalloy chiefly used in aerospace components for rocket engines, nuclear reactors, and turbine blades due to the properties such as high strength, low thermal conductivity, high resistance to thermal fatigue, corrosion and creep resistance [1]. However, these properties result in very low machinability [2]. Main machining challenges are associated with high temperatures at the contact zone due to the low thermal conductivity, high strength of the material even at high temperatures, high propensity for BUE formation during the cutting process, a high tendency for rapid work hardening, and presence of hard carbide particles in the microstructure which increase the abrasion wear and groove formation on the tool [3]. All these factors not only result in severe tool wear chipping but also affect the surface quality of the component after the machining process [4]. High surface quality is an essential requirement for aerospace components since severe failure can occur from any small crack or defect on the surface. Many studies have been carried out to improve tool performance and surface integrity during the machining of Inconel 718. All these attempts can be mainly categorized into four groups: different tool material/designs, various machining strategies, different types of coolant, and various tool material coatings [5–12]. Among all the methods tried, the most common approach to tackle these problems is to use super-hard tools or apply very hard coatings to increase the wear resistance of the tool surface. However, the harsh contact pressure at the tool-chip contact zone and the resultant high work hardening of the machined surface during machining of Inconel 718, greatly restricts the applicability of typical hard tools and coatings which may perform well in other applications. Some strategies have been employed to reduce the work-hardening by improving the tribological behavior and ease the chip-workpiece flow and thus, reduce the contact pressure. Employing lubricants is the main method to reduce the temperature, friction, contact pressure, and ease the material flow [13]. However, in the machining of difficult to cut materials like Inconel, they are not effective in reducing the friction as they cannot penetrate the chip-tool contact zone where seizure occurs. Different multilayer coatings with lubricious layers have been also tried for machining of Inconel. But they also have limited efficiency in reducing tool wear, due to the severe machining conditions experienced during machining of these classes of materials [7,10]. Therefore, improving the surface integrity remains a significant problem even when using the best-developed coatings or lubricants.

Surface integrity by itself is influenced by three parameters: mechanical properties, metallurgical behavior, and topological features [14]. All of these parameters impact residual stress, surface roughness, work hardening of the surface, and microstructure changes in machined surface thus they need to be evaluated [15].

Machining induced work-hardening of Inconel 718 is an important factor that significantly affects surface integrity and results in severe tool wear and tool chipping [16]. Numerous studies have shown that the main reason for the catastrophic notch wear of the tool during machining of Inconel 718, is work hardening [1,3,17]. So, by reducing the depth of the work-hardened layer, the notch wear of the tool can be controlled [17]. There are many parameters that can increase the hardness of the workpiece material after machining. Due to the high generated temperature realized during Inconel 718 machining, lubricant use is mandatory to reduce heat generation. However, the cycle of cooling and heating during material removal itself leads to the formation of a work-hardened layer on the machined surface [18]. Higher pressure and high cutting forces at the cutting zone are the other reasons for work hardening of the workpiece material after cutting Inconel 718. In addition to plastic deformation, the microstructure of the surface will change due to the high force, pressure, and temperature involved. Plastic deformation aggravates surface work hardening due to the growth of the dislocation density. This is a particular problem as Inconel 718 contains abrasive niobium or chromium carbide particles in the grain boundaries which interfere with the motion of the dislocations [16]. Therefore, more plastic deformation will be generated on the machined surface of this material and the dislocation density there will be excessive [19].

Residual stress is another important factor to be considered during the machining of Inconel 718. The stress-induced into the component will affect its quality and long term performance, particularly under fatigue loading conditions. In addition, residual stress can have an effect on the dimension of the finished parts impacting assembly and performance. Testing has shown that high residual stresses remain on the workpiece surface after machining of Inconel, due to high cutting forces and temperatures [20]. When studying residual stresses, it is important to distinguish between compressive and tensile residual stress. The tensile and compressive residual stress generations are influenced by thermal and mechanical properties, respectively [3]. Tensile residual stress generally leads to crack propagation, fatigue and creep failure, whereas a favorable compressive residual stress level might have a beneficial effect on the aforementioned parameters [21]. In machining of Inconel, due to the lower thermal conductivity of this class of material, the temperature on the cutting zone is high, which is the chief cause of tensile residual stress forming on the machined surface.

Poor machinability of Inconel 718 will also result in high surface roughness of the machined part. This is an issue specially for aerospace applications where surface finishes impact component life and performance.

Authors in previous studies showed that, as opposed to common current practices in using ultra-hard coatings/depositions for machining of hard materials, the deposition of ultra-soft layers on the tool material through different methods can significantly increase tool performance by reducing friction, easing the material flow, decreasing the contact pressure and consequently lower heat generation and thus the temperature in the contact zone [22–25]. All these improvements can alter the integrity of the machined surface in machining, which is of prime importance during machining of Inconel 718. In the current study, the effect of the deposition of ultra-soft and lubricious layers on a tool through a new method proposed by the authors as the “pre-machining” technique on the surface integrity of the machined surface during the cutting of Inconel 718 is investigated in detail. The assessments involve the investigation of the machined surface roughness, microstructure orientation, work hardening, and residual stresses. The results of the deposition of ultra-soft materials on the cutting tool through the pre-machining process were also compared with the conventional physical vapor deposition (PVD) coating method.

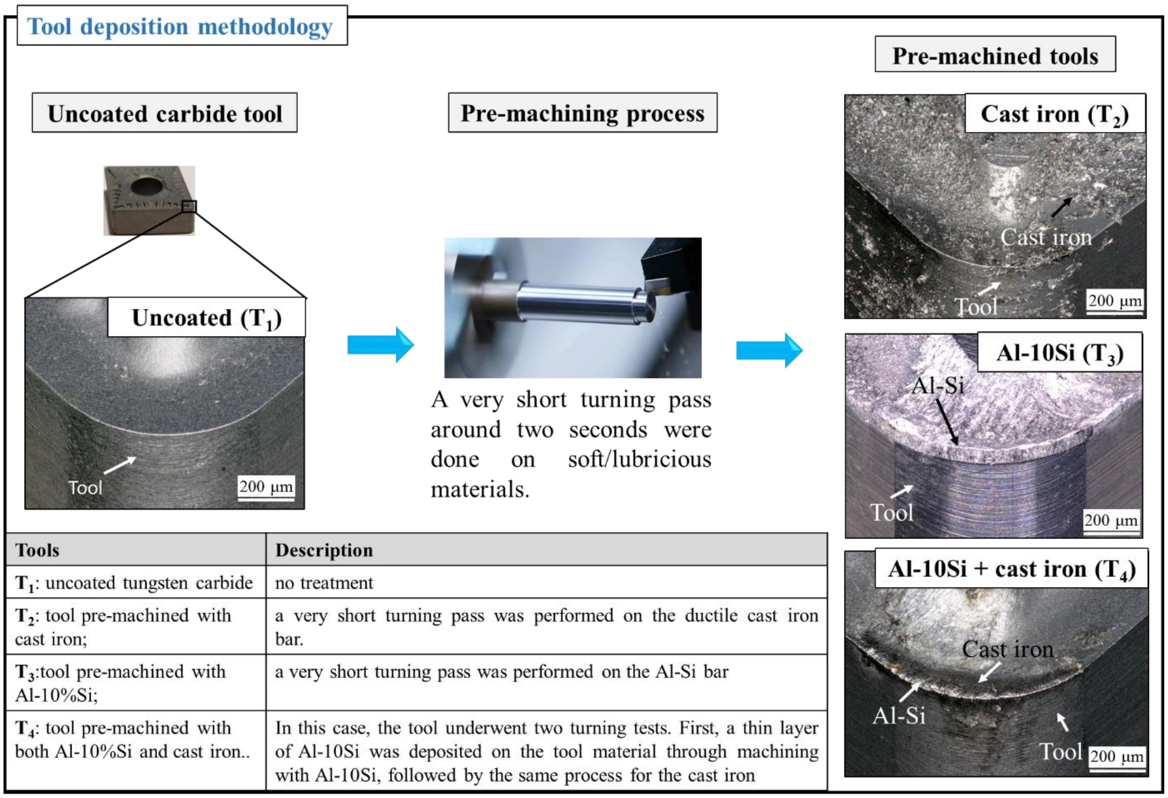
5.3 Experimental Procedure

5.3.1 Deposition process

In this study, a novel cost-effective method is used to deposit a soft and lubricious layer on the tool [23]. This novel “Pre-machining” or “Pre-treatment” method consists of a layer being deposited on a tool through a few seconds of machining of the target material. As soft and lubricious materials, Al-10Si and ductile cast iron were selected for this process. Al-Si was chosen due to its low shear strength, low melting point, good compatibility, low friction, and good ductility. Ductile cast iron was selected on account of its self-lubricating behavior. The chemical compositions of the Al-Si and cast iron are shown in, respectively. Figure 5-1 shows the method used for the deposition of these soft and lubricious materials on the tool during the machining process. To deposit a layer on the uncoated tungsten carbide cutting tool in the pre-machining process, a turning process was performed on the bar target material (Al-Si and/or cast iron) for around 1-2 seconds. During the pre-machining process, a thin built-up layer of the workpiece materials adhered on the cutting tool. The cutting conditions for the pre-machining processes were selected experimentally after lots of trials to achieve a uniform full material coverage on the top of the tool. To achieve a uniform layer, high cutting speed and low feed rate were selected. The cutting speed at which Al-Si was deposited was greater than that of cast iron due to its lower hardness. A high depth of cut was selected for the pre-machining process to obtain full coverage of the deposited layer on the tool. To avoid any tool wear on the tool as a result of the pre-machining process, a minimum time of around two seconds was selected for all the deposition processes. It should be mentioned that all the tools were examined after the pre-machining process and no tool wear was detected. The selected cutting conditions for the pre-machining processes are shown in Table 5-1. More information related to the pre-machining process can be also found in the author's previous studies [22,23].

In this study, the selected soft/lubricious materials were deposited on the tool under obtained cutting conditions in three combinations. On the first insert, only a thin single Al-10Si layer of around 40 ± 5μm was deposited by machining an Al-Si bar for 1-2 seconds. The main constituents of the Al-Si workpiece material selected for this study are around 90% Al and 10% Si. For depositing the cast iron on the second tool, the insert was machined with cast iron for a couple of seconds. The main constituents of cast iron are around 5% C (in the form of graphite) and 95 % Fe. Due to the graphite content of the cast iron, graphite residue was detected on the tool in the form of a powdered layer of a couple of microns' thickness, covering the tool edge. In the third insert, a combination of both Al-Si and cast iron was deposited on the tool surface. In this case, first, a layer of Al-Si was deposited on the tool via machining followed by a layer of cast iron likewise deposited on the top of the

Al-Si layer. A thin built-up layer of AlSi and graphite was formed on the tool as a result of this process.



Tools	Description
T_1: uncoated tungsten carbide	no treatment
T_2: tool pre-machined with cast iron;	a very short turning pass was performed on the ductile cast iron bar.
T_3:tool pre-machined with Al-10%Si;	a very short turning pass was performed on the Al-Si bar
T_4: tool pre-machined with both Al-10%Si and cast iron..	In this case, the tool underwent two turning tests. First, a thin layer of Al-10Si was deposited on the tool material through machining with Al-10Si, followed by the same process for the cast iron

Figure 5-1- Experimental steps for the preparation of the pre-machined tools

Table 5-1- Cutting conditions for tool pre-machining process

Cutting Parameters		**Cutting Speed (m/min)**	**Feed Rate (mm/rev)**	**Depth of Cut (mm)**	**Cutting fluid**
Pre-machined tools	**Al-10%Si**	450	0.06	1	dry
	Cast iron	250	0.06	1	

5.3.2 Experimental set-up

The pre-machining was performed on the uncoated carbide tool prior to the cutting of Inconel 718. In the current study, provided pre-machined tools used for the machining of

Inconel 718 had a hardness of 32-34 HRC. The turning tests were carried out on a Boehringer VDF 180 CNC lathe. The mechanical properties and main chemical composition of the Inconel 718 used are shown in Table 5-2 and Table 5-3, respectively. It should be mentioned that the chemical compositions of Inconel 718 were measured by Varian Vista Pro Inductively Coupled Plasma (ICP) instrument linked with Expert II software and the material properties of Inconel 718 were provided by the supplier.

Table 5-2- Material properties of Inconel 718

Property	Density (kg/m^3)	Young's Modulus (GPa)	Ultimate Tensile Strength (MPa)	Yield Tensile Strength (MPa)	Thermal Conductivity (w/mK)	Specific Heat Capacity (J/kg °C)	Melting Point (°C)
Value	8190	200	1375	1100	11.4	435	1260-1336

Table 5-3- Main chemical composition of Inconel 718

Material	Ni	Cr	Fe	Mo	Nb	Ti	Al
Wt %	55.6	17.2	15.65	2.9	5.24	1	0.6

The cutting conditions for machining of Inconel 718 are shown in Table 5-4. In general, low cutting speeds of around 20-30 m/min, high feed rates and high depth of cuts are recommended for carbide tools during machining of Inconel 718. The reason for selecting a low cutting speed for machining of this class of material is its poor machinability. However, high feed rates and depth of cuts are commonly recommended to minimize the chipping and notch wear that occur as the result of tool-tip contact with the work-hardened layers of the workpiece in shallow cuts. In the current study, the cutting conditions were intentionally pushed to their upper limits for this type of cutting tool. Thus, high speed

(50m/min) and relatively low feed rates and depth of cuts (0.1 mm/rev and 0.15 mm respectively) were chosen to investigate tool performance under aggressive conditions. It should be mentioned that a semi-synthetic waterbased coolant-CommCool HD^{TM} 8800 with a concentration of 7% and a pressure of 7 bar was applied during the machining process of Inconel 718.

Table 5-4- Cutting conditions for machining Inconel 718

Cutting Parameters	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	Cutting fluid
machining with Inconel 718	50	0.1	0.15	wet

To estimate the tool life during Inconel 718 machining, flank wear was measured after a defined length of cutting using a Keyence microscope. The end of tool life criteria was either flank wear of 0.3 mm based on the ISO 3687 or severe tool chipping which is considered as one of the main problems during machining of Inconel 718. Each of these criteria happened first, corresponding cutting length was considered as the tool life. The cutting forces were measured with a Kistler dynamometer. The surface roughness of the machined surface was assessed by a white light interferometric microscope. To observe the microstructure of the Inconel material after machining, samples were cut and mounted in Bakelite. The mounted samples were then grinded and polished to remove all scratches from the surface. The samples were finally etched with a Glyceregia etchant. The hardness measurement of the machined surface was carried out on a Micro Materials NanoTest system. Hardness was measured starting from the machined surface down to the core material, using a Berkovich diamond indenter in a load-controlled mode at 40 mN load. An optical Nikon microscope was used to capture the microstructure of the materials.

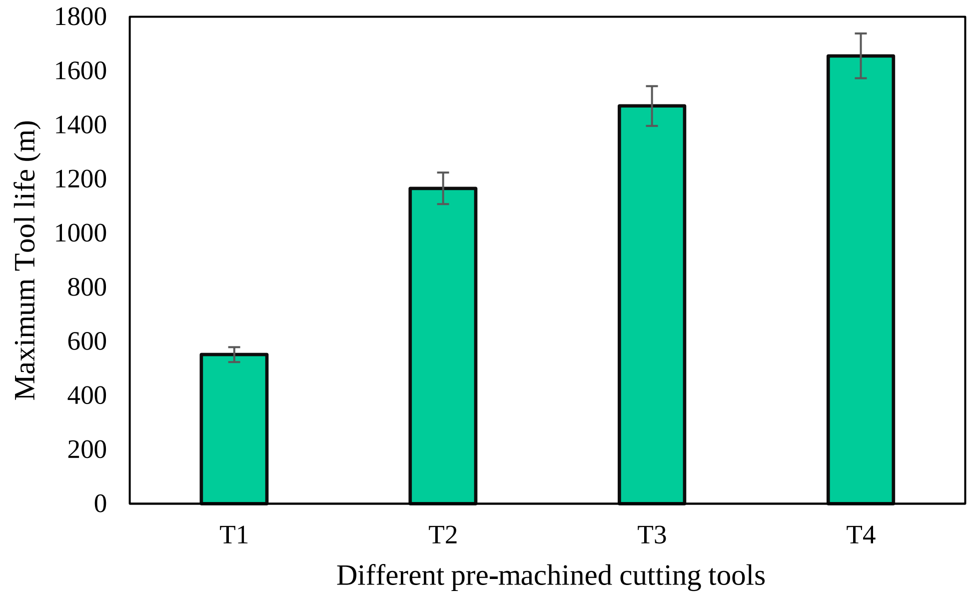
Electron backscattered diffraction (EBSD) imaging was carried out on a Schottky field emission gun-equipped SEM at high resolution to assess crystal deformations, using AZtec EDS/EBSD software. Data collection was performed at 199.35 Hz with a step size of 2 µm during the sample scans. Residual stresses on the workpiece surface were measured with X-ray diffraction (XRD) equipped using LEPTOS software. Cobalt X-ray radiation at a wavelength of 1.79 Å (Kα) was used to measure the residual stress of the machined surface.

5.4 Results and discussions

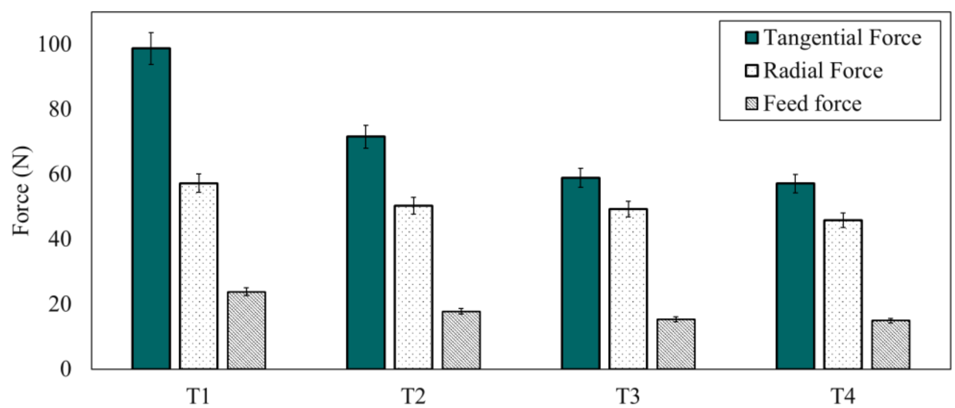
Turning tests were carried out on Inconel 718 with uncoated and different pre-machined tools to assess the effect of the deposition of different soft and lubricious materials on tool performance. The tool life and initial cutting forces of the pre-machined and uncoated tools were compared and shown in Figure 5-2. All the cutting experiments were repeated at least for three times. As can be seen in Figure 5-2-a, the deposition of the soft/lubricious materials on the tool described in the experimental section, significantly improved tool life. The tool life of the tools pre-machined with cast iron (T_2), pre-machined with Al-Si (T_3), and pre-machined with a combination of AlSi/cast iron (T_4) pre-machined tools were around 2.16, 2.41 and 2.75 times greater than the Uncoated tool, respectively.

The feed, radial, and tangential cutting forces at the running-in stage of all cases were measured and compared during the cutting process of the pre-machined and uncoated tools (Figure 5-2-b). As can be observed in Figure 5-2-b, cutting forces of all pre-machined tools were lower than the uncoated tools. As shown in Figure 5-2-b, the initial cutting force of the uncoated tool was around 100 N, which was considerably higher than that found when using the pre-machined tools. Applying a soft/lubricious layer on the cutting tools lowered the cutting force by around, 45% for T_2, 30% for T_3 and 45% for T_4, in comparison with the uncoated tool.

The tool life improvements and cutting force reductions observed in the pre-machined tools are attributed to the presence of the lubricious deposited layers on the cutting tool. In their previous studies, the authors show that the deposition of a soft/lubricious film on the tool was also successful in reducing adhesion and sticking, reducing abrasion and consequently reducing tool chipping [22], [23]. The roots of all these improvements come from lower friction, better material flow, lower contact pressure and lower level of heat generated at the tool-chip interface due to the presence of the lubricious film in the cutting zone. The authors previously showed that the enhancement of all mentioned factors resulted in better tool performance and consequently better overall machinability of Inconel 718 [22], [23]. Furthermore, an improvement in tool performance and chipping reduction resulted in surface integrity improvements and especially in reducing the work-hardening of the workpiece material during machining. This is particularly important for multi-pass machining operations where the depth of cut is limited. In the current study, due to the importance of surface integrity, an attempt is made to find the effect of the deposition of the lubricous layer on surface integrity during turning of Inconel 718.



(a)



(b)

Figure 5-2. a) Tool life and b) initial cutting force for the uncoated tool (T_1), pre-machined with cast iron (T_2), pre-machined with Al-Si (T_3), pre-machined with Al-Si and cast iron (T_4)

Mechanical, topological and metallurgical changes occur on the machined surface during the cutting of Inconel 718 due to high machining temperatures and mechanical loads. All of these changes affect surface integrity. Surface integrity can be evaluated by studying residual stress, surface roughness, work hardening of the surface and microstructure changes of the surface [26]. Various aspects of surface integrity are discussed in the following sections.

5.4.1 Work-hardening of the machined surface

Work hardening is considered as one of the main problems of machining of Inconel 718, resulting in severe wear and chipping of the tools. The hardness of the machined surface increases following the machining process. As the top surface of the workpiece gets hardened, the tool which is in contact with the hardened layer gets chipped and can fail dramatically. As shown in Figure 5-3, the work-hardened layer can cause notching and chipping on the tool at the distance from the tooltip equal to the depth of cut. In addition, the depth of the notch wear has a relation with the depth of the work-hardened layer [17]. Although the notching is far from the tooltip, by increasing the cutting time it results in catastrophic tool breakage and chipping. Figure 5-4 shows the significant tool chipping and notch wear occur on the uncoated tool after around 500 m of cut. To protect the tool-tip from chipping and fracture as a result of cutting the hardened layer, different strategies and methods are suggested, each has its own limitations or challenges. As an example, high feed rates and depth of cuts, higher than the depth of the work-hardened layer, are commonly employed in the industry to protect the tool-tip from chipping. However, this strategy not only impairs the surface quality of the machined part, but it also increases the load on the tool and can itself result in chipping and more importantly increase the depth and magnitude of the plastically deformed layer on the workpiece, in turn resulting in a high tool wear rate and the occurrence of chipping in subsequent passes.

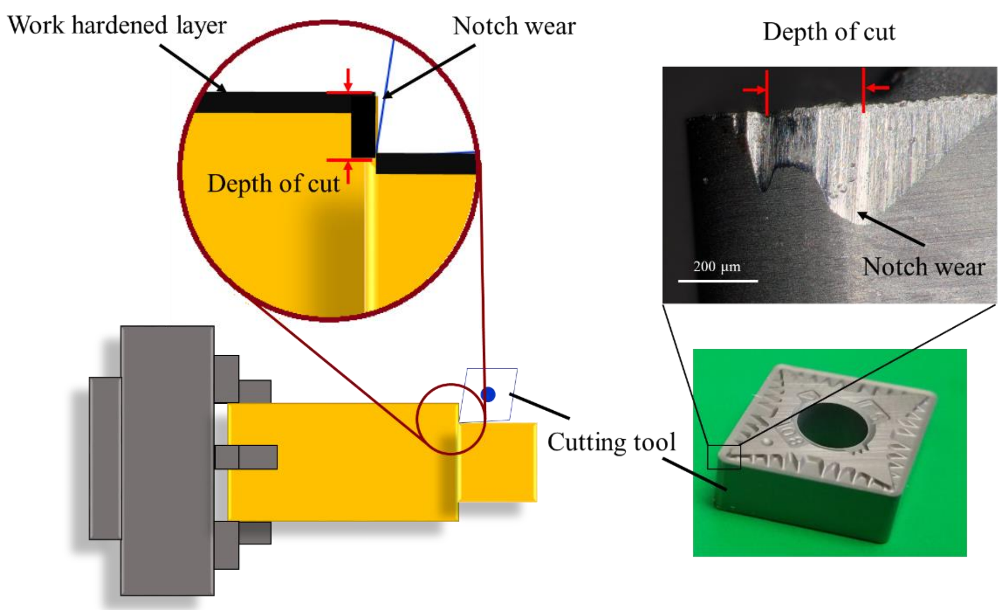


Figure 5-3. Work hardened layer and corresponding notch wear on the tool

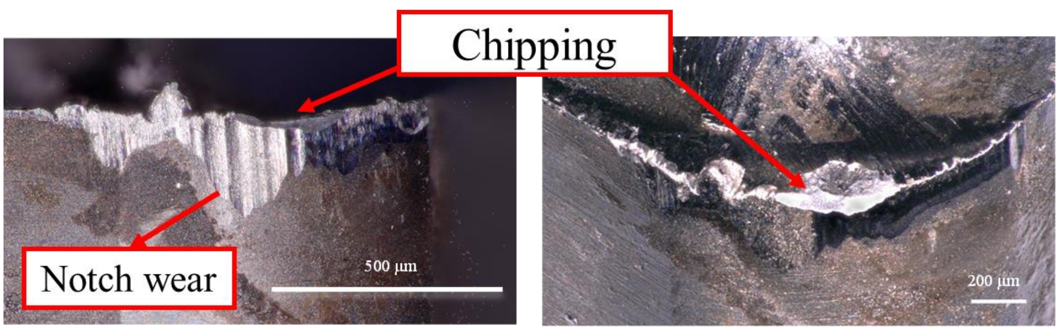


Figure 5-4. Severe tool chipping and notch wear of the uncoated tool

Another typical approach to overcome this problem in machining operations is employing super hard tooling like polycrystalline diamond or applying super hard coatings on carbide tools, which are the most commonly used tools in the industry [27]. However, as long as the root cause of the problem, which is mainly hardening of the workpiece surface, is not addressed, even the hardest tools will fail rapidly.

In this study, contrary to what is currently practiced, a very soft layer of metals was deposited on the tool. This was done to improve the lubricity and chip flow which result in a reduction to the work-hardening of the workpiece material and a corresponding improvement in tool life.

To show the amount and the depth of the top work-hardened layer, nano-indentations were performed on the workpiece surfaces after being machined with different tools for a constant length of cut. Figure 5-5 shows the hardness variation of the surface machined with uncoated and pre-machined tools. As demonstrated in Figure 5-5, the maximum hardness values of the surface machined by all the pre-machined tools were significantly lower than that of the surface machined by an uncoated tool. Work hardening was reduced by 44% in the surface machined with an Al-Si pre-machined tool, by 50% with a cast iron pre-machined tool and by 59% with a tool pre-machined by both Al-Si and cast iron.

The major work-hardening of the workpiece surface is typically assessed by the degree of work hardening factor which shows the percentage increase of the work hardening toward the bulk material. Thus, a lower value of the degree of work hardening indicates a better machinability performance. The lowest degree of work hardening obtained in this study, 8.33%, belongs to the tool pre-machined with a combination of Al-Si and cast iron. Table 5-5 indicates the degree of work hardening in other related studies performed in a similar conventional range of cutting speed for machining of Inconel. It is worth mentioning that to the best of our knowledge such an improvement in work hardening has not been reported previously.

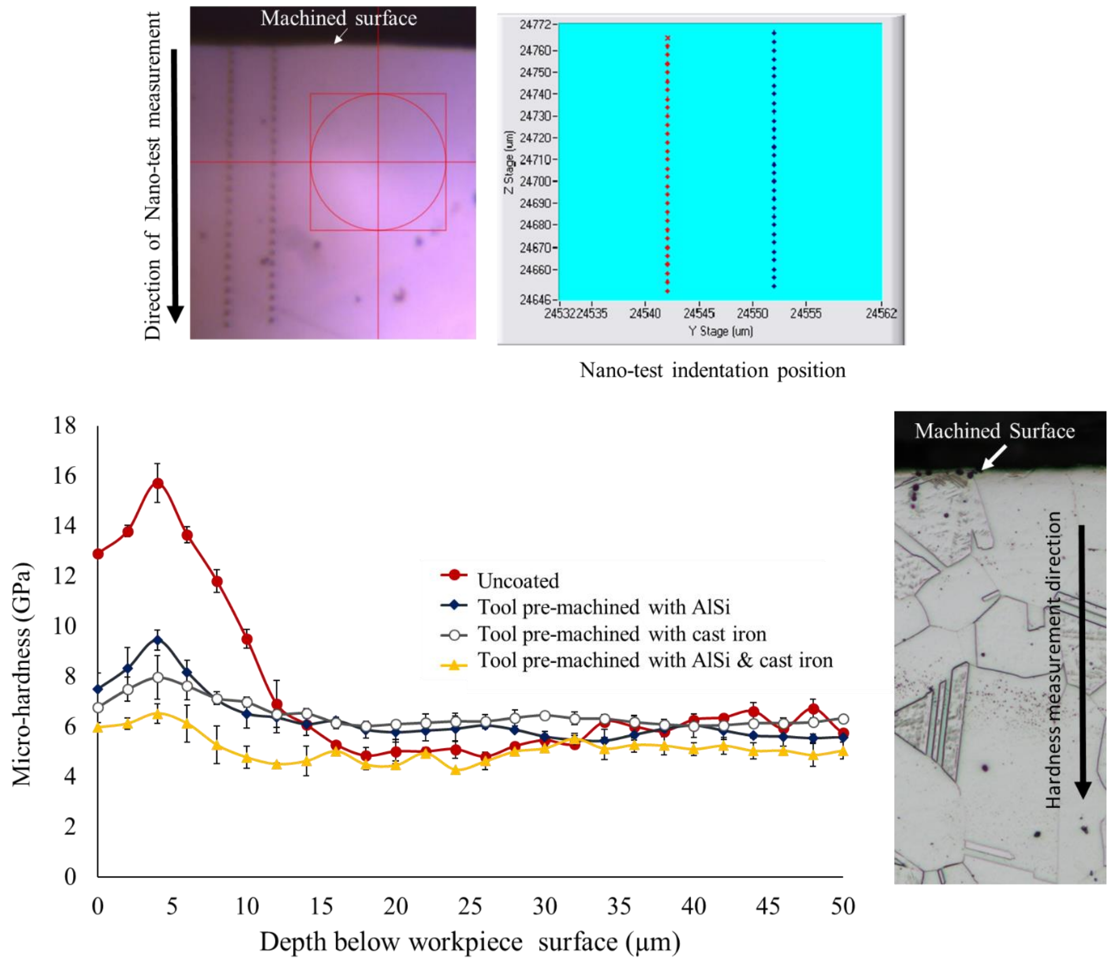


Figure 5-5. Work hardening behavior of the machined surface of Inconel 718 following turning by the uncoated tool (T_1), pre-machined with cast iron (T_2), pre-machined with Al-Si (T_3), pre-machined with Al-Si and cast iron (T_4)

In general, work hardening is a sign of plastic deformation [30]. High slip lines on the material are obvious signs of plastic deformation [31]. The density of dislocations in the material structure increases due to the variation of the stress field in the material and dislocation movement which result in plastic deformation. In general, there are three parameters that can accelerate plastic deformation; temperature, pressure, and the state of tool wear.

Table 5-5-The degree of work hardening of the machined surface in related studies

Researchers	% DWH (degree of work hardening) = (MHs*-MHb*)/MHb *100
Touazine et al [19]	20.13 14.86
Pawade et al [8]	60
Umbrella et al [28]	13.95
Sharman et al [29]	16.88
Current study	8.33

*MHs: Maximum Hardness of surface, MHb: Maximum Hardness of bulk

Hardness alteration of the workpiece material following the machining of Inconel 718 occurs due to the high temperature, and pressure during chip formation. The generated temperature can reach 1200° C and pressures can go as high as 4 GPa [29], [32]. To obtain a better chip flow, better fictional and better-cooling behaviors the use of lubricant is essential during Inconel 718 machining. Unfortunately, lubricants in the machining of difficult-to-cut materials cannot penetrate into the tool-chip interface zone where seizure occurs. Since lubricants cannot enter the contact zone where there is complete contact, they are not very productive in improving lubricity. In some cases, adding liquid lubricants/coolants can also have a negative effect on tool life especially when applied in intermittent cutting operations such as milling. In general, liquid lubricants/coolants are added to reduce or remove the heat generated in the cutting zone. However, this cyclical cooling during exposure to the liquid lubricant/coolant followed by subsequent heating during tool engagement can itself result in work hardening and be detrimental to tool life [33], [34]. In addition, as tool wear increases the geometry of the tool is less favorable so the plastic deformation experienced at the subsurface of the machined part increases due to the larger contact area between the tool and the workpiece. This means that as the tool wear increases, the contact area becomes larger, resulting in more friction and higher temperature and thereby more plastic deformation on the machined surface.

Figure 5-6 indicates the cross-section of the surface machined with uncoated and pre-machined tools after a short cutting pass. As can be seen, the slip lines are present on the material cross-section close to the machined surface. The slip lines, representing plastic deformation on the surface machined with an uncoated tool, are formed at a deeper depth within the workpiece material (Figure 5-6-a). The reason for the higher depth of plastic deformation is mainly related to the higher wear rate of the uncoated tool compared to the pre-machined tools. Therefore, the plastic deformation is higher due to the higher friction and temperature in the surface machined with the uncoated tool. As can be seen in Figure 5-6, slip lines on the surface machined with the pre-machined tools were only present in the grains close to the machined surface. However, slip lines were formed on the grains far from the surface machined with an uncoated tool. Fewer slip lines were observed on the surface machined with the tool pre-machined with a combination of both Al-Si and cast iron (Figure 5-6-d) compared to the tools separately pre-machined with Al-Si (Figure 5-6-b) and cast iron (Figure 5-6-c).

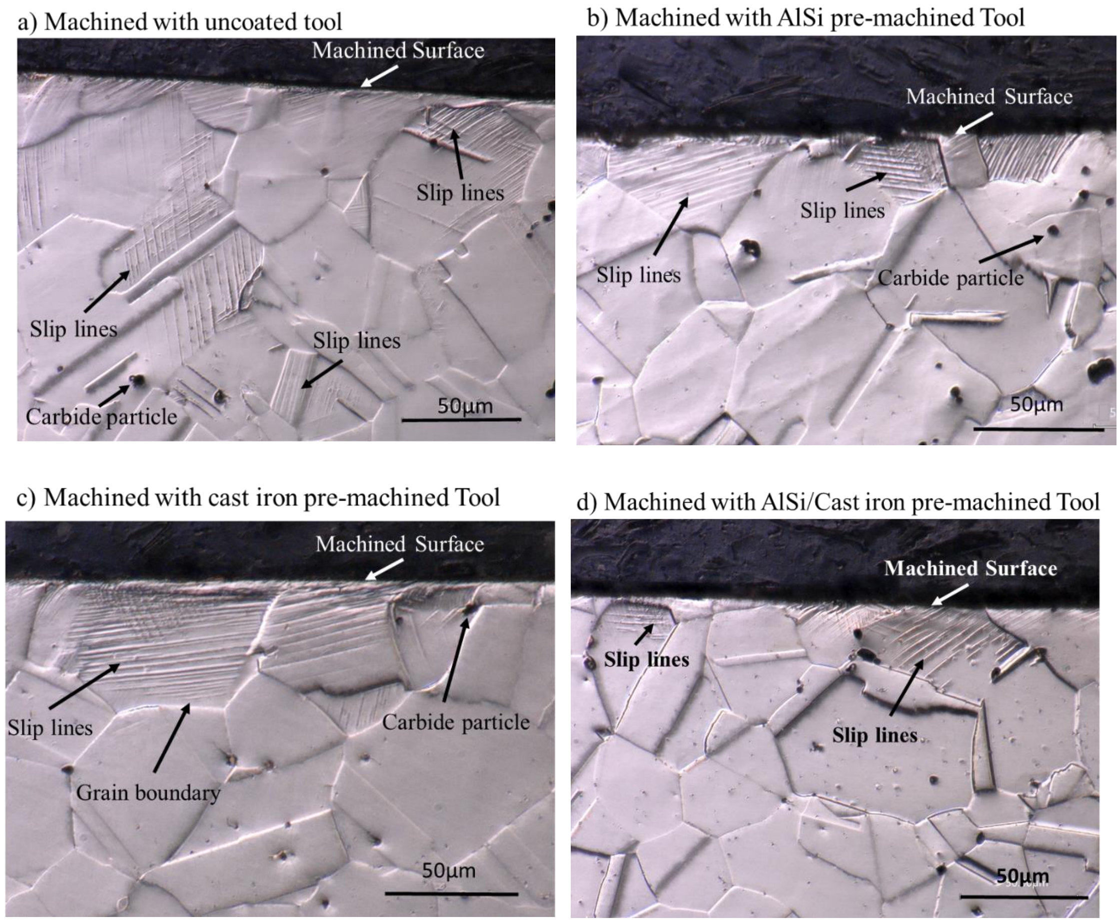


Figure 5-6- Cross-sections of the Inconel material machined with a) Uncoated carbide tool, b) Tool pre-machined with Al-Si, c) Tool pre-machined with cast iron, and d) Tool pre-machined with Al-Si and cast iron after a short cutting pass (20 m of cut)

5.4.2 **Reorientation of the grains**

As discussed before, major work hardening occurs in the vicinity of the machined surface which can be observed in Figure 5-5 for all cutting tools used in this study. However, the depth of the affected area can be much larger, which is difficult to capture with the nano-indentation line measurements. The 2-D optical images provided in Figure

5-6 clearly showed that for the uncoated tools the deformation was not limited to the surface but also spread to the grains far from the top surface. Moreover, the nano-hardness measurements only provide the hardness values and do not offer any additional information about the grain orientations, slip lines and also plastic deformation in the depth of the material. To obtain this essential information, electron backscatter diffraction (EBSD) images of the deformed areas of the machined surface are presented in Figure 5-7. The local misorientation and inverse pole figure (IPF) maps obtained from the machined surface down to the bulk material for the uncoated tool (T_1) is presented in Figure 5-7-a and the corresponding images for the tool pre-machined with Al-Si and cast iron (T_4) are presented in Figure 5-7-b.

The grain orientation on the surface of the workpiece material will change during the cutting process. The main reasons for this are localized heating, high stress and high pressure at the tool-workpiece interface during the cutting process. The changes in the grain orientation and plastic deformation are more severe during machining of materials such as Inconel 718, since extremely high forces, temperatures, and pressures are applied to the workpiece material during machining [35]. Moreover, carbide particles exist on the grain boundary of Inconel 718 which prevent the dislocation motion within the microstructure and result in further work-hardening of the material. Therefore, if the work hardening and plastic deformation are not controlled they can pile up more and deformation can penetrate deeper into the depth of the material. When the depth of the plastically deformed layer is larger, the machining of the material is almost impossible as the tool cannot be positioned below the deformed region. That is why, in the machining of hard-to-cut materials, researchers try to use one pass machining instead of multiple passes. Our approach was very successful in preventing this phenomenon, allowing multiple passes, lower feed, and smaller depth of cut.

The grain misorientation close to the machined surface is clearly more severe, strain regions are larger and accumulation of the slip lines near the grain boundaries are more pronounced and spread to the depth of the workpiece material for the uncoated tool compared to the pre-machined tools. Considerable accumulation of slip lines at the grain boundaries is linked to more shear stress and consequently to the formation of more dislocations and more plastic deformation for the surface machined with the uncoated tool.

The larger deformation regions on the surface machined with an uncoated tool can be attributed to the higher cutting forces and wear values (shown in Figure 5-2) and poor lubricity at the cutting zone. As mentioned before, forces and pressures at the cutting zone during machining with the T_4 tool are significantly lower than that of the uncoated tool (T_1).

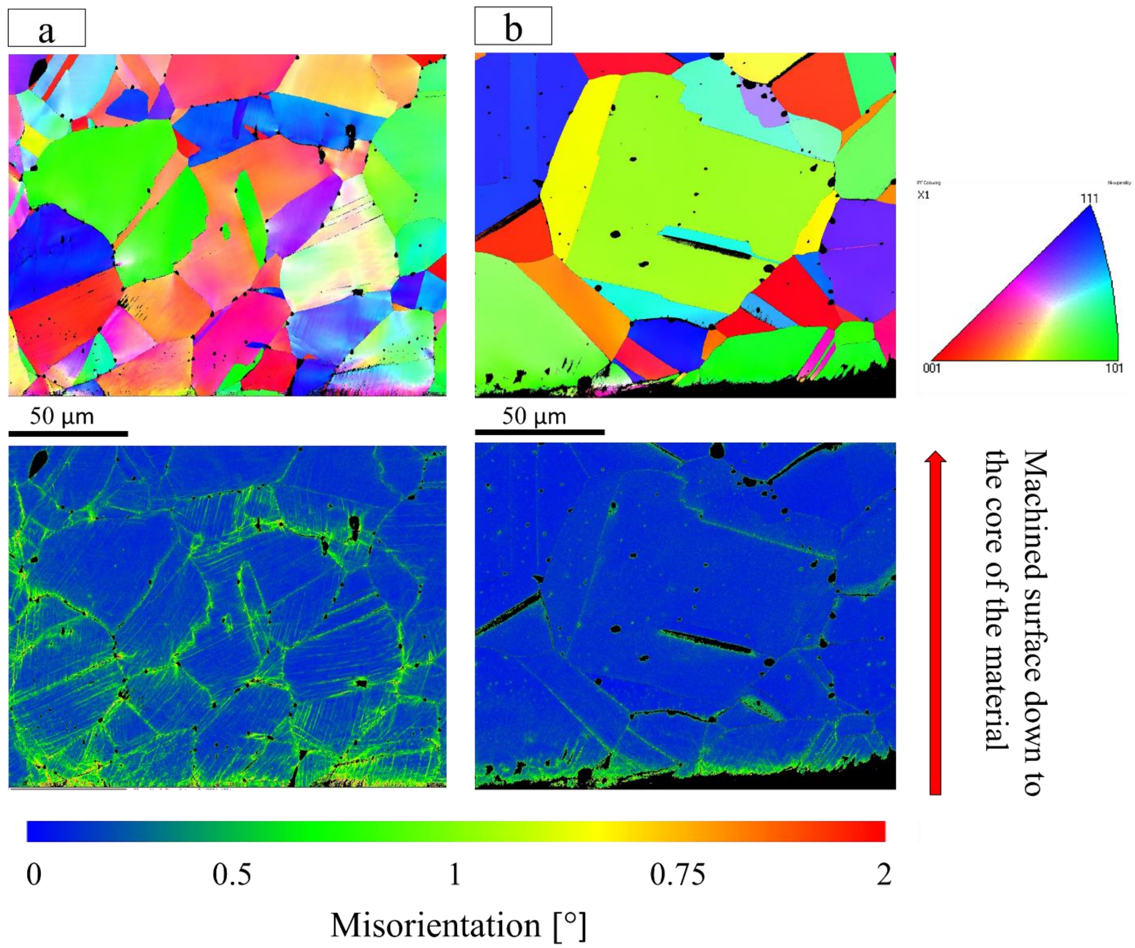


Figure 5-7- local misorientation and inverse pole figure (IPF) maps from the machined surface with a) uncoated, and b) pre-machined with Al-Si and cast-iron tools

5.4.3 Residual stress of the machined surface

Following any machining process, a certain amount of stress remains in the material, which is known as "residual stress". Residual stress can be tensile or compressive. Tensile stress occurs due to the thermal load and compressive stress occurs due to the mechanical load (plastic deformation). Generally, tensile residual stress will increase the susceptibility to crack propagation, contributing to eventual tool failure [36]. In addition, it can affect the dimensional accuracy and fatigue resistance of the workpiece material [37]. During the machining of Inconel 718, the generated heat remains on the surface due to the low thermal conductivity of Inconel 718. Thus, in most cases, the surface residual stress is tensile in nature due to the high machining temperature resulting from high friction and over time from high tool wear levels, especially when operating at high cutting speeds [15], [38].

The measured residual stresses generated on the workpiece surfaces after a brief cutting period for each tool are shown in Figure 5-7, in the feed and the cutting directions. For consistency purposes, all tests were performed with a new tool at a constant cutting length. The residual stress measurements were performed on the machined surfaces after being cut with different tools at the same spot corresponding to approximately the end of cutting length for each tool. As all the tools were relatively new and sharp, the thermal loads dominated the mechanical loads resulting from the tool wear and thus for all the samples with different tools the residual stress had a tensile nature.

As shown in Figure 5-8, the residual stresses in the cutting direction did not change considerably for the tools pre-machined with cast iron (T_2) and the tool pre-machined with Al-Si (T_3) compared to the uncoated tool (T_1). However, the residual stress significantly decreased in the cutting direction for the tool pre-machined with a combination of Al-Si and cast iron. Although no significant reduction of residual stress was observed in the cutting direction, except for the tool pre-machined with a combination of Al-Si/cast iron (T_4), residual stresses in the feed direction were found to noticeably decrease for all tools. As illustrated in Figure 5-8, residual stresses in the feed direction were lower for all the surfaces machined with different pre-machined tools. The residual stress in the feed direction of the machined surface decreased by 23% for the tool pre-machined with cast iron, 19% for the tool pre-machined with Al-Si and 29% for the tool pre-machined with both Al-Si and cast iron.

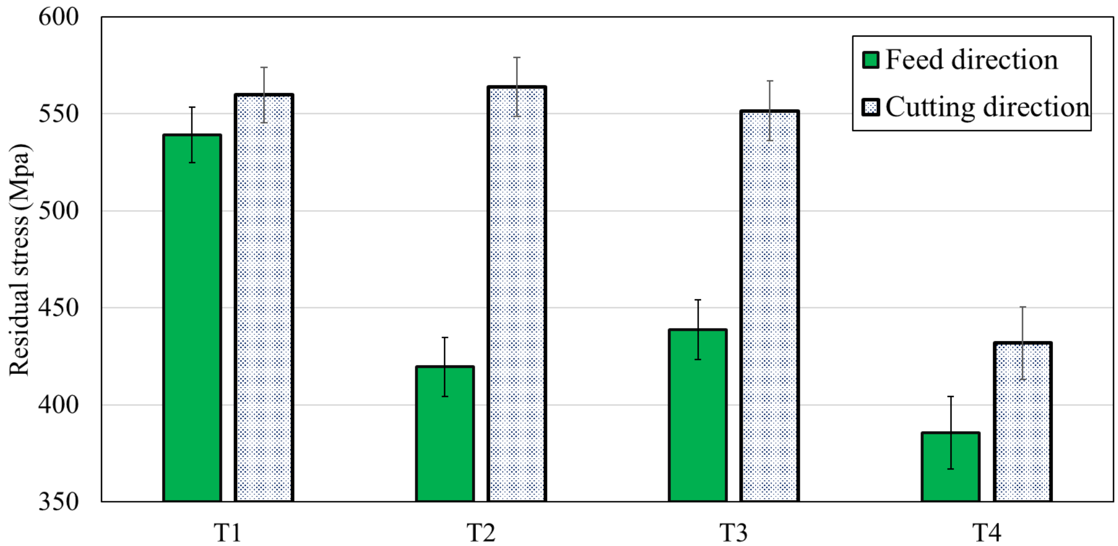


Figure 5-8. Residual stress in the feed and cutting directions of the surface machined with an uncoated tool (T_1), tool pre-machined with cast iron (T_2), tool pre-machined with Al-Si (T_3) and tool pre-machined with Al-Si/cast iron (T_4)

The residual stresses on the cutting direction are significantly influenced by the state of tool wear. Yet, since the tool wear was relatively low for all tools, no significant difference was noticed for the pre-machined tool. The low value for the T_4 tool, pre-machined with both Al-Si and cast iron, contributed to the lowest tool wear rate, lowest tangential forces and best lubricity among all the tools tested. It should be mentioned that in the present method mainly the rake face of the tool is covered with the target material as shown in Figure 5-9. However, due the slippery nature of graphite in the cast iron, it was observed to also cover the flank face of the tool as well, contributing to lower residual stress in the cutting direction.

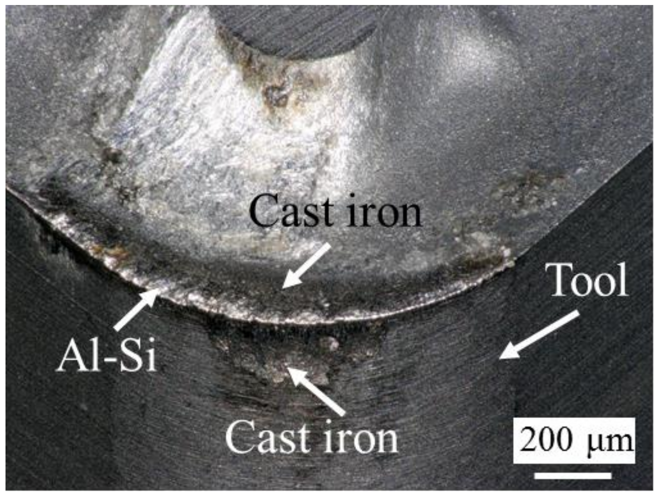


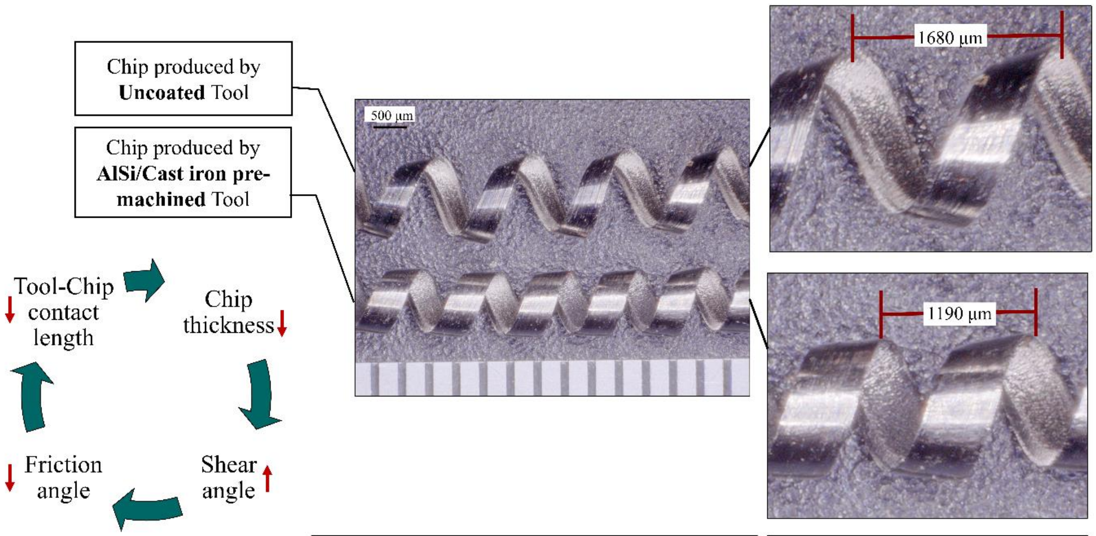
Figure 5-9. Tool Pre-machined with Al-Si and cast iron

It is worth noting that, in our previous study PVD coated tools with Al-Si, in which both faces were covered with Al-Si, were compared with the Al-Si pre-machined tools, where only the rake face was covered with Al-Si. The results showed that full coverage of the rake face especially at the tooltip with a lubricious material sufficiently improves the overall machinability, decreases the overall tool wear rate and prevents chipping [24].

The main reasons for the significant reduction in residual stresses in the feed direction are better lubrication and low friction at the tool-chip interface, resulting in easier chip flow and better chip formation.

Figure 5-10, clearly shows that thinner and curlier chips were generated for the pre-machined tools with Al-Si and cast iron compared to the uncoated tool, confirming a better chip formation for this case. Similar trends were observed for the other pre-machined tools.

Shorter contact lengths and less friction, as a result of the application of a lubricious material at the tool-chip interface, results in thinner and curlier chips. The coefficient of friction (CoF) of all deposited materials on the tool face was measured by nano-wear tests. A series of nano-wear tests with a Berkovich indenter under a constant load of 2 N were performed on each layer formed on the tool. For measuring the CoF of each material, the nanoscratch test was performed passing through the built-up edge layer formed on the pre-machined tools and the tools materials. The CoF values for each material are presented in Figure 5-10. As seen, the Al-Si and cast-iron exhibit very low coefficients of friction, contributing to their high lubrication efficiency. The deformed chip thicknesses which represent frictional behavior at the cutting zone were also measured for the Al-Si/cast iron pre-machined and uncoated tools after 20 m of cut. For this purpose, chips were collected after the first machining pass for all tests, then mounted and polished. The deformed chip thicknesses were measured by optical microscopes. The results show that the deformed chip thickness decreased by using Al-Si/cast iron pre-machined tool in comparison with the uncoated tool. These results indicated that the frictional behavior was improved by using the pre-machined tools. The corresponding shear plane angles were also calculated for each case. The formula shown in Figure 5-10 was used to calculate the shear-plane angles. As shown in Figure 5-10, the shear angle increased as a result of using the Al-Si/cast iron pre-machined tool compared to the uncoated tool. A higher value of shear angle can represent lower energy required to deform the material during a cut.



Tools	Deformed chip thickness-tc (mm)	Shear angle-Φ (°)
Uncoated	0.1645	32.49
AlSi/Cast iron Pre-machined	0.1412	36.83

Material	Coefficient of Friction
Inconel 718	1.4
Al-10%Si	0.06- 0.08
Cast iron	0.04-0.06
Carbide tool	0.2

$$\tan\varphi = \frac{r\ Cos\ \alpha}{1 - r\ Sin\ \alpha}$$

φ: Shear angle

α: rake angle = 5°

$$\text{r: Chip Compression Ratio} = \frac{\text{uncut chip thickness}}{deformed\ chip\ thickness}$$

$Uncut\ chip\ thickness = feed = 0.1\ mm$

Figure 5-10. Chip shape, chip thickness and corresponding shear angle produced by the tool pre-machined with AlSi and cast iron compared to the uncoated tool, Also, coefficient of friction of the deposited materials, tool material and workpiece material

5.4.4 Surface roughness

Generally, there are three factors that affect the surface roughness of a machined workpiece. The first is the presence of a built-up edge (BUE) which is a layer of workpiece material forming on the tool rake face. The BUE layer on the rake face of the tool can break and fragments of it can drag all over the surface during machining and deteriorate the quality of the workpiece material. Cutting parameters such as cutting speed, feed rate and depth of cut are counted as the main factors affecting surface roughness. The geometry of the tool such as insert shape, nose radius (edge preparation), rake angle also impact roughness [39]. In this study, the cutting parameters and the geometry of the tools were identical for all tools. Thus, the main factor affecting the roughness can be considered to be built-up edge formation.

Thus, surface roughness values of the workpiece increase due to micro-welding and BUE formation during the machining of Inconel 718. In addition, Inconel 718 contains hard carbide abrasive particles in its microstructure that cause the emergence of cracks and cavities on the surface of material. Previous studies by authors showed that the deposition of the mentioned materials was extremely successful in built-up-edge and adhesion wear reduction [21,23]. This improvement not only affected the tool performance, it also improved the surface quality of the machined material significantly by making the cutting edge more consistent.

The surface roughness values (R_a) of Inconel 718 workpiece for the pre-machined tools were compared with the corresponding one for the uncoated tool (Figure 5-11). The results showed that the surface roughness of the workpiece material after machining with an uncoated carbide tool (T_1) was around 1.6 µm after completing close to 50 m of linear cut. The roughness values of the surface machined by tools T_2 and T_3 after the same length of cut were more than 0.4 µm less than that of the T_1 tool. The lowest surface roughness was achieved for the surface machined with the T_4 tool, equal to 0.7 µm which was approximately half of the value achieved for the tool T_1.

The presence of a beneficial layer between the tool-chip interface can decrease the force required to remove the material, thereby improving the surface finish. The better surface finish of the materials machined with the pre-machined tools is due to the better frictional behavior at the tool-chip interface, which promotes material flow during the turning process. Low BUE formation as well as reduced initial tool wear and lower cutting force, significantly benefit the surface finish of this hard to cut workpiece material.

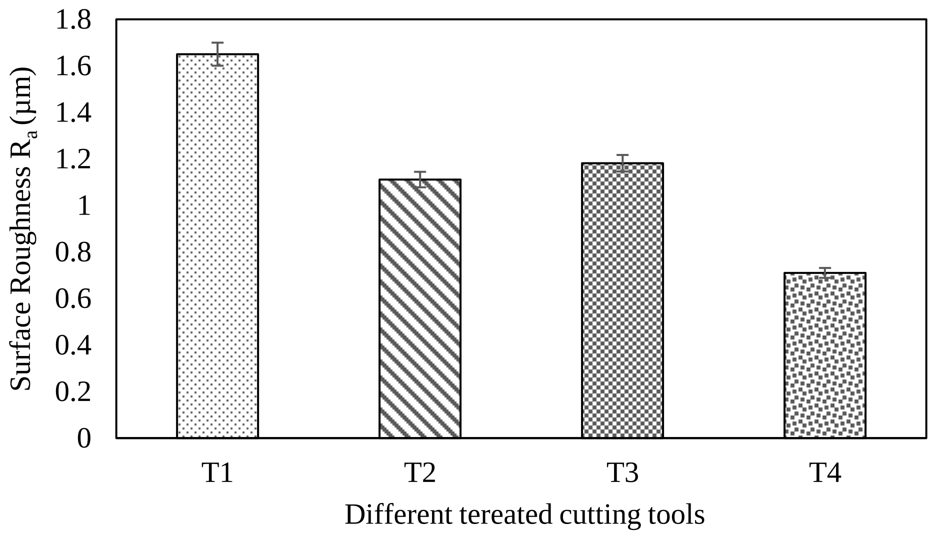


Figure 5-11. Surface roughness (R_a) of the surface machined with an uncoated tool (T_1), tool pre-machined with cast iron (T_2), tool pre-machined with Al-Si (T_3) and tool pre-machined with Al-Si/cast iron (T_4)

5.4.5 Comparison of the conventional PVD method for coatings with the current technique

In the current study, layers of soft and lubricious metallic materials were deposited on the tool through a new method proposed and referred to by the authors as the *pre-machining* technique. In the previous study, the authors showed that this simple and cost-effective method can be used as an alternative to other coating techniques such as PVD or CVD, especially for the deposition of soft metals [23].

Since the PVD method is a common tool coating process used in industry, Al-Si was deposited using the PVD process. The performances of the two processes were compared. A detailed comparison is discussed in a previous study [23]. It was shown that the performances of both tools were very similar, both resulted in significant improvements in the machinability of Inconel 718, including an increase in tool life (Figure 5-12-a), reduction in forces (Figure 5-12-b), reduction in the BUE formation and adhesion (Figure 5-12-c), reducing the friction and improving the chip formation (Figure 5-12-d) and reducing the abrasion wear.

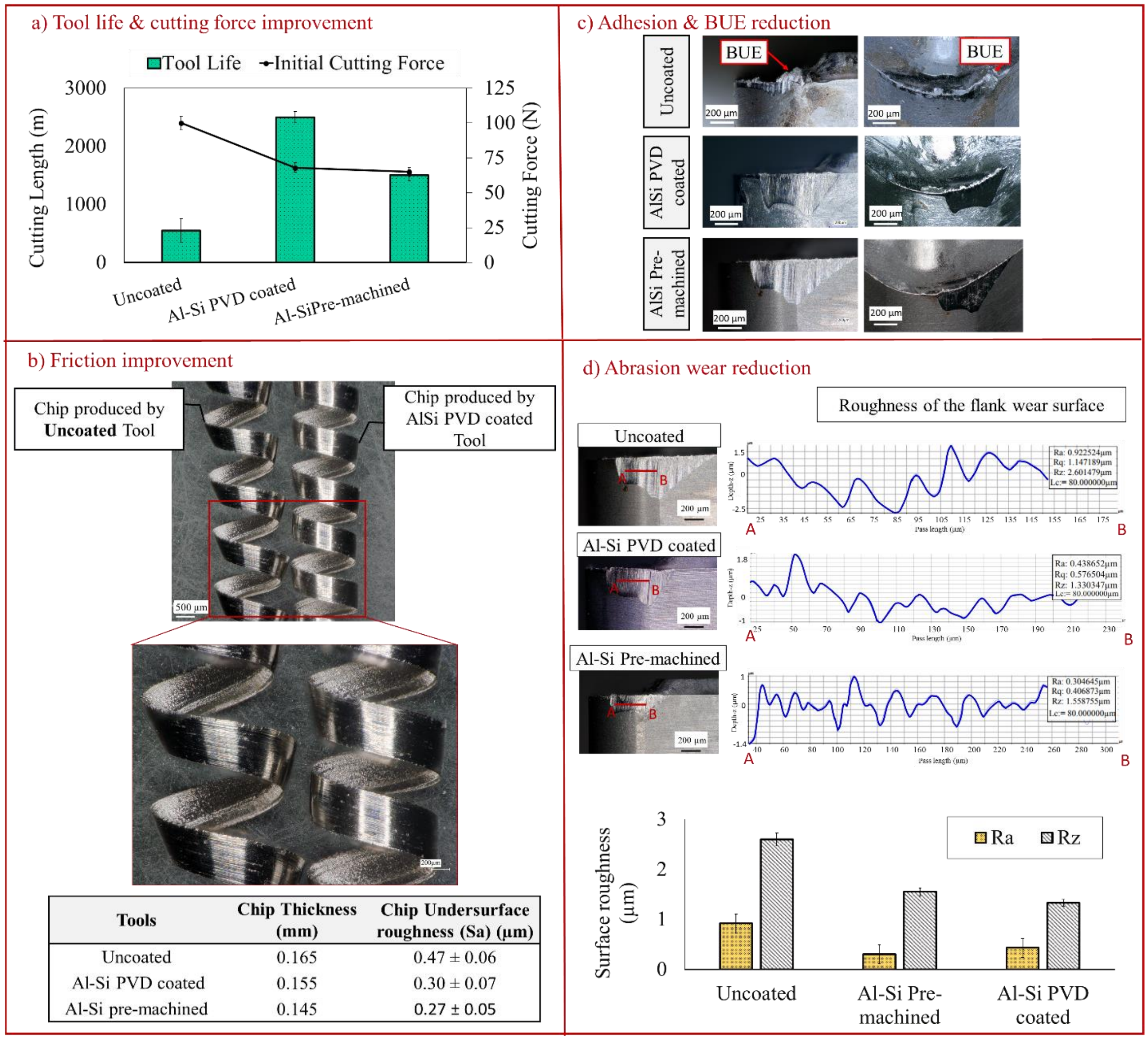


Figure 5-12. Brief overview of the comparison between the AlSi PVD tool with the AlSi pre-machined tools

The current study also showed that regardless of the mechanism of deposition, whether it is deposited through a conventional PVD coating method or through the proposed pre-machining method, deposition of Al-Si on the tool significantly improves the surface integrity of the machined workpiece. As discussed before, properties of Al-Si including its high lubricity, low coefficient of friction and high compatibility with the workpiece tribo-system are the main reasons for such improvements.

Since work-hardening is the most important factor affecting the machinability of the Inconel 718, the hardness variation in the workpiece surface after being machined with PVD coated tool with Al-Si is also compared with the uncoated tool (Figure 5-13-a). The results showed that Al-Si deposited on the tool with either method resulted in a reduction in the work-hardening of the surface. The PVD coated tools with Al-Si also showed 25% reduction in the machining induced work-hardening.

Residual stresses of the surface machined with AlSi PVD coated tool were measured and compared with surface machined with the uncoated tool. Moreover, as shown in Figure 5-13-b, residual stresses in both feed and cutting direction decreased significantly for the AlSi PVD coated tool; up to 61% in cutting and 64% in feed direction compared to the uncoated tool. Roughness values (R_a) of the surface machined with AlSi PVD coated tool were also measured and compared to the uncoated tool as shown in Figure 5-13-c. The arithmetic average value (R_a) of Inconel 718 surface machined with AlSi PVD coated tool was found around 1.1 µm, while for the uncoated tool after the same length of cut it was around 1.6 µm.

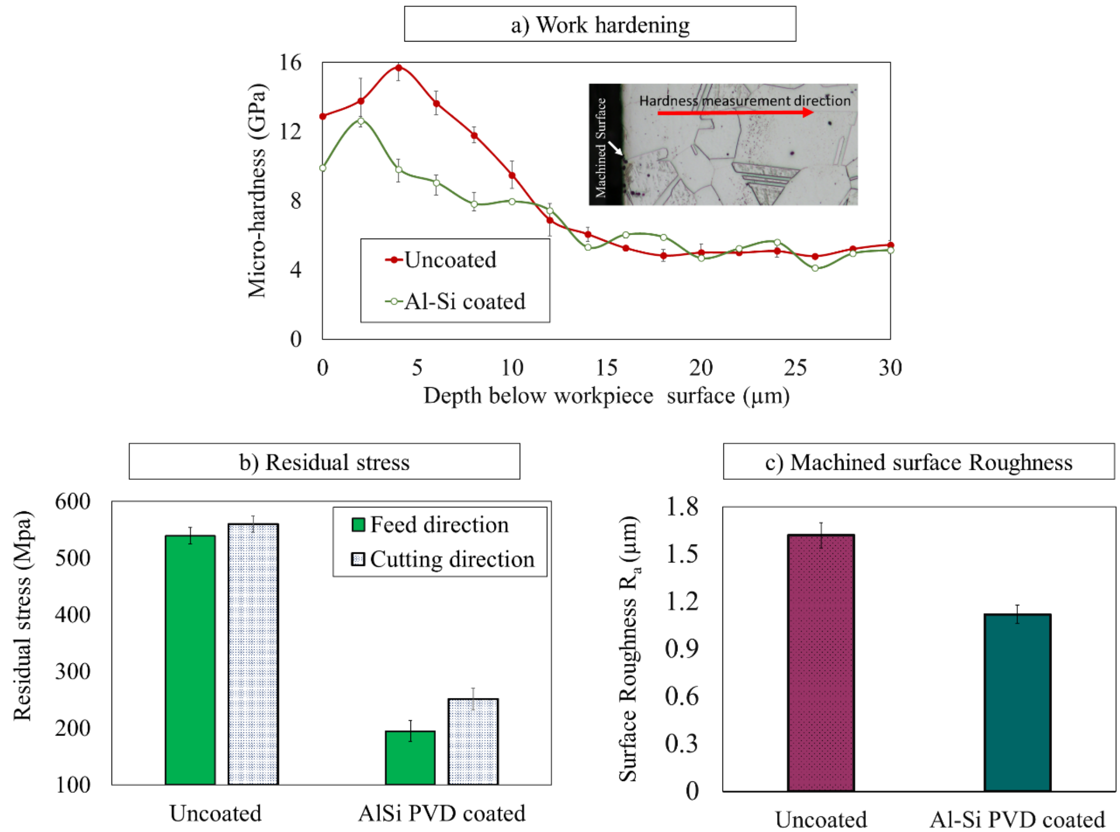


Figure 5-13. Surface integrity comparison of the AlSi PVD coated tool with the uncoated tool including: residual stresses, surface roughness and hardness variations of the cross-section of the machined surface

5.5 Conclusions

This study showed that, contrary to what is believed and practiced till now, the deposition of very soft and lubricious metals on a tool can significantly improve the machinability of Inconel 718. This achievement is accomplished by addressing the main challenges associated with machining Inconel 718 including reducing the machining induced work-hardening. The following conclusions briefly explain the main achievements of the current work:

- In this study, AlSi, cast iron and combination of both AlSi and cast iron were deposited on the tool, through the innovative method proposed by authors as the "pre-machining method". Results showed that the tool life was increased by 173%, 120%, and 204% compared to the uncoated tool after deposition of Al-Si (T_2), cast iron (T_3) and combination of both (T_4), respectively. In addition, the initial cutting force of the tools T_2, T_3 and T_4 were decreased by 30%, 45%, and 45%, respectively.
- The results showed that the work hardening of the surface was reduced significantly up to 59% by the deposition of the combination of AlSi and cast iron layers on the tool. This improvement is, to the best of our knowledge, the highest one reported till now which is attributed to the soft and lubricious nature of the deposited materials and their effectiveness in reducing the friction, contact pressure and temperature during machining of Inconel.
- EBSD results showed a significant misorientation of the workpiece surface machined with the uncoated tool. While the depth of the misorientation of the grain decreased significantly in the surface machined with the pre-machined tool with AlSi and cast iron. Optical images of the surface also showed that the depth of deformation in the surface machined with the pre-machined tool was more than uncoated tool.
- The tensile residual stress value of the surface machined with a pre-machined tool decreased up to 30% compared to the surface machined with the uncoated tool.

- The surface roughness of the part machined with the pre-machined tool improved compared to the surface machined with the uncoated tool.
- For the sake of comparison, the tools were also coated with Al-Si through the conventional PVD method and were used for machining of Inconel 718, under the same cutting conditions. The results showed that the pre-machining method had a very similar trend as the PVD method, both contributing to significant improvements in the surface integrity of the machined surface.

5.6 Acknowledgments

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6 Chapter 6

Characterization and Machining Performance of a Chipping Resistant Ultra Soft Coating Used for the Machining of Inconel 718

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Sushant Rawal:	Assisted with coating depositions.
Stephen. C. Veldhuis:	Supervisor of the paper.

Characterization and Machining Performance of a Chipping Resistant Ultra Soft Coating Used for the Machining of Inconel 718

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6.1 Abstract

Inconel 718 is widely used in the aerospace industry due to its excellent mechanical properties, such as high corrosion and heat resistance and great strength at elevated temperatures. Unfortunately, the poor machinability of this alloy still presents a major challenge for manufacturers. Developing different types of tool coatings is a common method for enhancing the machinability performance of this class of materials. Almost all of the coatings selected to improve tool productivity are super-hard coatings. Authors have shown in their previous study that the deposition of a soft monolayer Al-Si coating on a tool, which has never been used before for machining applications, significantly improves tool performance and outperforms most of the recommended hard coatings during the machining of Inconel 718. Since deposition parameters in the PVD process play a significant effect on the properties of coatings and since no data is present in the literature for this tool coating, the effect of three main deposition parameters including bias voltage, deposition time, and gas pressure were investigated around their proposed extreme ranges. The Al-Si coatings deposited under different parameters were characterized and discussed in terms of hardness, roughness, coverage, adhesion, residual stress, coating microstructure, and coating material distribution. Based on the results of thorough coating characterizations, the Al-Si coating with full coverage and uniform material distribution was selected for further machining investigations. The results showed that most defects and complications in commercial hard coatings used for the machining of Inconel, including hardness, roughness, and residual stress formation, are not of any concern for Al-Si coatings, and the limits of the parameters should be defined mainly based on the microstructure and composition uniformity of the coating. The results also showed that a soft Al-Si PVD coating improves tool life by around 500%, which is much higher than the commercially available coatings, and decreases the initial cutting force by 150% during the machining of Inconel 718. The in-depth material characterizations of the coating, including TEM/EDS and XPS analysis and machinability analyses, showed that the considerable improvements were mainly attributed to the superior lubricating properties of the Al-Si coating deposited on the cutting tool.

Keywords: Al-Si coating, Inconel 718, PVD coatings, Soft coatings.

6.2 Introduction

Inconel 718 is considered to be a difficult-to-cut material due to its great strength at high temperatures, high tendency of work hardening, low thermal conductivity, high tendency to stick to other materials and the existence of abrasive carbide particles in its microstructure [1–3]. Therefore, severe tool wear, chipping, and failure are the major issues expected when machining this class of alloy [3]. Many studies have been carried out to enhance the tool life and control of sudden tool chipping during the machining of Inconel 718 using different techniques such as various tool material coatings, various tool geometries/texturing, various coolant deliveries and different machining strategies [4–8]. However, none of these methods achieved significant success in controlling tool failures. Using different types of coatings is one of the most common methods for improving tool life and performance during the cutting process. Almost all coatings developed for the machining of difficult-to-cut materials are hard coatings used to improve the wear resistance properties of the cutting tool. As an example, TiAlN, TiAlCrN, TiCN, TiN/AlTiN, and TiAlCrSiYN/TiAlCrN are some hard coatings typically selected for the machining of Inconel 718 [9–13]. The hardness of these coatings is above 20 GPa which is considered as a super-hard coating material. Among the various types of coatings, the TiAlN coating is the most widely used to machine difficult-to-cut materials due to its high hardness, wear-resistance, and oxidation resistance properties [14]. The performance of hard coatings is chiefly affected by deposition parameters such as deposition temperature, gas pressure, bias voltage, and deposition time [15]. For example, changing the gas pressure or bias voltage during the deposition process can affect coating properties such as hardness, composition, microstructure, and adhesion [15–17]. Therefore, an inappropriate selection of deposition process parameters can cause various coating defects such as poor adhesion, microdroplet formation, poor coverage, and pitting defects. So, the selection of the appropriate deposition parameters is crucial for hard coatings.

To improve the performance of hard coatings used to machine hard-to-cut materials, researchers are seeking to develop a coating that has a good balance of high hardness and toughness, which in turn is a big challenge as both of these properties are inversely related to each other [15]. Although researchers have tried to increase the hardness of the coating to improve wear resistance, excessive hardness itself can lead to coating failure. Therefore, finding a method to increase both the hardness and toughness of the coating may be the best approach. Studies show that wear resistance can also be improved by other properties such as fatigue resistance and chemical stability, which are also compatible with toughness. As a result, ductility and lubricity are essential properties of coatings which can impact performance and should be measured and improved [18]. However, studies show that lack of lubricity is one of the problems of hard coatings during the machining of hard-to-cut materials [19,20].

Solid lubricant coatings with a low coefficient of friction (COF) and good ductility are the best solution for improving lubricity at the tool-chip interface. Solid material with excellent frictional behaviour at the tool-chip interface can easily shear, facilitating material flow during cutting [20]. Soft metals with low hardness and low shear strength can also act as solid lubricants by enhancing lubrication, thereby improving wear resistance [20] . Soft solid lubricant coatings such as MoS_2, Au, Ag, and Cu are introduced for different applications. These classes of soft coatings have limited applications and are not used to machine hard-to-cut alloys due to their poor durability under a high load [20,21]. However, researchers are trying to find a solution to increase the durability of soft/solid lubricant coatings deposited on tools used for cutting materials that are not as difficult as hard-to-cut materials. Although each of these methods offers advantages, they also have their limitations. As an example, in some studies, applying a texture on a tool filled with a solid lubricant is proposed to improve the durability of these classes of coatings used for the machining of regular workpiece materials [22,23]. However, tool texturing, in addition to being expensive, cannot be applied close to the tooltip without weakening the tool in the machining of difficult-to-cut materials such as Inconel 718. There are very few studies where an attempt is made to improve the lubricity of the coatings by adding a nano soft layer like Cu on top of the hard layer to provide a multilayer coating. However, the soft nanolayer on these hard coatings because of the low thickness value of the soft nanolayer does not show promising results for improving the lubricity of the coating and reducing the contact pressure [19].

Contrary to what is believed, authors in their previous study showed that the deposition of a monolayer soft Al-10%Si coating on the cutting tool, using different deposition techniques, can improve the tool performance during the cutting of Inconel 718 [24–28]. The aluminum component of this coating was selected due to its high ductility, low shear strength, low coefficient of friction, high reactive compatibility with oxygen creating a beneficial tribofilm, and a low melting point. Adding 10% silicon to the aluminum not only improves the fluidity of the aluminum, thereby easing the material flow, but can also react with oxygen to form lubricious tribofilms [29]. The previous results indicate that deposited Al-Si on the cutting tool acts as an in-situ liquid lubricant during the machining of Inconel 718, which resulted in reduced contact pressure and friction in the cutting zone. Tool chipping elimination, notch wear reduction, adhesion wear reduction, built-up edge reduction, easier chip flow, and work hardening reduction were achieved due to the deposition of the Al-Si through different methods on the cutting tool.

Since the deposition of a monolayer soft Al-Si coating on a cutting tool through the PVD method has never been used in machining applications including hard-to-cut materials, in the current study, a detailed analysis of this coating has been done. As mentioned, different deposition parameters affect the properties of hard coatings and limit their deposition process significantly. However, they might not affect the properties of a soft coating. Therefore, it is necessary to determine the effect of different deposition parameters on the properties of an Al-Si soft coating. To distinguish the differences between hard and soft coatings under different deposition parameters and determine the desirable properties of the soft Al-Si coating, the effect of three main deposition parameters including bias voltage, time, and pressure at their extreme range were investigated. Detailed characterizations of the soft Al-Si PVD coating deposited under the selected parameters were done to investigate its properties and performance using XRD, SEM/EDS, optical and interferometer microscopes. The performance of the introduced soft Al-Si PVD coated tool in the machining of Inconel 718 was also evaluated and compared with the uncoated and commercial hard coated tool. Furthermore, the corresponding mechanisms responsible for significant tool performance improvement are also discussed in detail using SEM/EDS, and XPS analysis.

6.3 Experiment setup and design

6.3.1 Deposition process

Al-Si coatings were deposited on an uncoated tungsten carbide tool with a cathodic arc ion plating process. For the deposition process, a Kobelco AIP-S20 deposition system equipped with two superfine cathodes (SFCs) arc evaporation sources with extended plasma ranges were used. All uncoated tungsten carbide inserts were provided by Kennametal with grade K313 and specifications of CNGG120408FS. The rake angle and nose radius of the cutting tools were 5° and 0.4 mm, respectively. The flat carbide inserts used for the characterization of the AlSi coatings were polished and cleaned with acetone before the deposition process. The target material, containing 90% Al and 10% Si made by powder metallurgy, was selected for the deposition process. In the current study, the effect of deposition parameters such as bias voltage, pressure, and deposition time on an Al-Si coating deposited in the presence of an inert Ar gas in a vacuum chamber at 10^{-3}Pa, a temperature of 500°C, a table rotation speed of 5rpm, and an arc source current of 150 A were investigated.

It should be mentioned, as will be discussed in detail in the next sections, that although a slight change in these parameters for the available hard coatings can have a significant effect on coating properties and, in turn, on their performance, these new soft coatings show very different behaviour. Changing these parameters either does not have any considerable effect on coating properties (such as hardness or elastic modulus) or, if being altered by the parameters, does not have any considerable effect on the performance of the coating (like roughness and thickness). Thus, the parameters that affect the properties on the coating were mainly chosen at their extreme levels for this coating to reflect their different behaviour, mechanisms, and defects.

Since there was no data available for this coating, the parameters for the deposition were selected in different steps, explained below, after numerous pilot experiments. For the ease of explanations, the test parameters are divided into two group tests each including two sub-group tests, as shown in Table 6-1.

Table 6-1. Coating deposition parameters and divided groups

Group test 1 including:

Subgroup test 1-a (with a dashed border): Constant V and Constant t, Ascending P
Subgroup test 1-b (with a pattern fill): Constant P and Constant t, Ascending V

Coating $C_{V\text{-}P\text{-}t}$	**Bias voltage, V** *(V)*	**Argon pressure, p** *(Pa)*	**Deposition time, t** *(min)*
$C_{40\text{-}1\text{-}30}$	-40	1	30
$C_{40\text{-}4\text{-}30}$	-40	4	30
$C_{80\text{-}4\text{-}30}$	-80	4	30
$C_{120\text{-}4\text{-}30}$	-120	4	30

Group test 2 including:

Subgroup test 2-a (with a dashed border): Constant V and Constant t, Ascending P
Subgroup test 2-b (with a pattern fill): Constant V and Constant P, Varying t

Coating $C_{V\text{-}P\text{-}t}$	**Bias voltage, V** *(V)*	**Argon pressure, p** *(Pa)*	**Deposition time, t** *(min)*
$C_{40\text{-}1\text{-}30}$	-40	1	30
$C_{40\text{-}4\text{-}30}$	-40	4	30
$C_{40\text{-}4\text{-}15}$	-40	4	15
$C_{40\text{-}4\text{-}120}$	-40	4	120

6.3.2 Experimental Procedure

The workpiece material used for the machining tests was Inconel 718 with a hardness of 32–34 HRC and main chemical composition of 55.6% Ni, 17.2% Cr, and 15.65% Nb. The mechanical properties of Inconel 718 are shown in Table 6-2. All machining experiments were carried out using a Boehringer VDF 180 CNC lathe. During the turning process of Inconel 718, a semisynthetic CommCool HD water-based coolant with a concentration of 5% and pressure of 7 bar was applied. It should be mentioned that usually a low cutting speed, high feed, and high depth of cut are used for the finishing process of Inconel 718. However, in this study, intensive cutting conditions consisting of a high cutting speed, low feed, and low depth of cut were selected to evaluate the performance of the tool. A cutting speed of 50 m/min, feed rate of 0.1 mm/rev, and depth of cut of 0.15 mm were selected for the machining of Inconel 718.

Table 6-2. Material properties of Inconel 718

Property	Density (kg/m^3)	Young's Modulus (GPa)	Ultimate Tensile Strength (MPa)	Yield Tensile Strength (MPa)	Thermal Conductivity (w/mK)	Specific Heat Capacity (J/kg °C)	Melting Point (°C)
Value	8190	200	1375	1100	11.4	435	1260-1336

During the experimental tests, tool wear was measured and captured after each cutting pass with a Keyence VHX-5000 digital Microscope. Cutting forces were measured during the machining process with a Kistler dynamometer. A Tescan Vega II LSU Scanning Electron Microscope (SEM) equipped with an Oxford X-Max 80 Energy Dispersive X-ray

Spectroscopy (EDS) detector and Inca software was used for the material characterization and elemental analysis of the coated and uncoated tools.

The thickness of the coatings was measured with a BC-2 Miba Coating Group ball crater system and a steel ball with a diameter of 25mm. The hardness and Young modulus of the coatings were evaluated by an NHT3 nanoindentation tester using a Berkovich diamond indenter at a load of 1mN. The overall hardness value was measured by performing 40 indents on each coating. The surface roughness measurement of the coating was measured by a Bruker Alicona InfiniteFocus microscope equipped with focus variation technology.

The hardness variation of the Inconel machined surfaces was performed by Micro Materials NanoTest system. The Berkovich diamond indenter with a constant load of 40 mN was used for measurements, and the hardness values were reported in GPa.

The formation of various tribofilms was validated by x-ray photoelectron spectroscopy (XPS) on the rake surface of the worn tool. For this purpose, a Physical Electronics (PHI) Quantera II spectrometer was used for XPS analysis. The source of the X-ray was from Al K-α (1486.7 eV) at 50 W–15 kV. The samples were cleaned with Ar+. A beam of 200 μm was used to collect the data, and a take-off angle of 45° was used to obtain all of the spectra. A pass energy of 224 eV was used to collect all survey spectra and 55 eV for high-resolution data.

An x-ray diffraction (XRD) system, Bruker D8 Discover instrument with cobalt radiation and a wavelength of 1.79 Å (Kα), was used on the tool surface before the machining process to evaluate various phases and residual stress values of the coatings deposited on the tool.

To evaluate and compare the frictional behaviour in the contact zone during machining, the coefficients of friction (COF) of the coating, workpiece material, and tool material were measured by an Anton Paar Revetest scratch tester. For this purpose, a Rockwell C diamond indenter with a radius of 20 μm under a constant load of 2 N and a scratch length of 2 mm was used. The COFs measurement of the coating layer and substrate were performed on the flat inserts, and the COF of the workpiece material was performed on the bulk material. All measurements were repeated at least three times.

6.4 Results and discussions

6.4.1 Coating characterization

Due to the novelty of applying Al-Si on a cutting tool via the PVD method for the machining of Inconel 718, further investigation is needed to understand the effect of deposition parameters on the soft coating's properties. For this purpose, various coating deposition parameters, including pressures, voltages, and time, were investigated under a range of extreme conditions with regards to the properties of the new Al-Si PVD coating. The deposition temperature was chosen to be 500 °C, which is close to the melting point of aluminum, to observe its effects on the coating properties. Table 6-1 shows the selected parameters of the Al-Si coating.

Generally, properties of a coating, which depend on deposition parameters, can have a significant effect on the coating performance. Coating properties consist of hardness, elastic modulus, surface roughness, adhesion to the substrate, defects, and residual stress. In hard coatings, a slight difference in each of these parameters can have a significant impact on tool behaviour. Since the effect of these parameters on the performance of the new soft coating is unknown, further investigation is required to understand the effect of them on coating properties and overall performance of the newly developed soft Al-Si coating.

Two of the most important parameters for hard coatings are hardness and elastic modulus, which are both functions of each other. Achieving the optimal balance between the hardness and toughness of the deposited coating presents a major challenge. However, for the machining of hard materials, the current trend is to increase the hardness of the coating as much as possible, and thus the toughness of the coating is compromised. Moreover, the hardness of the coating is mainly affected by increasing the bias voltage and gas pressure.

As can be seen in Table 6-3, the hardness of the Al-Si coating was very low, varying in the range of around 1.3 GPa, which is far lower than all available commercial hard coatings used for difficult-to-cut materials, in the range of 20 GPa and above [9-12]. As shown in Table 6-3, the hardness values were not significantly affected by the change of voltage (considering Group test 1, Subgroup 1-a) and pressure (Group test 1, Subgroup 1-b). Since there was no other element present in the vacuum PVD chamber except the coating target material composed of 90% aluminum and 10% silicon and inert gas, no hard phase could be formed in the coating structure during the deposition process. That is why the coating hardness was very low and not affected by the coating parameters. This was also confirmed by XRD phase analysis, as will be discussed further below.

Table 6-3. Deposition parameters of the Al-Si coating, and corresponding hardness and elastic modulus values

Group test 1 including:
Subgroup test 1-a (with a dashed border): Constant V and Constant t, Ascending P
Subgroup test 1-b (with a pattern fill): Constant P and Constant t, Ascending V

Coating $C_{V\text{-}P\text{-}t}$	Hardness (GPa)	Elastic Modulus (GPa)
$C_{40\text{-}1\text{-}30}$	1.26 ± 0.6	155 ± 77
$C_{40\text{-}4\text{-}30}$	1.36 ± 0.7	201 ± 42
$C_{80\text{-}4\text{-}30}$	1.05 ± 0.3	132 ±69
$C_{120\text{-}4\text{-}30}$	1.39 ± 0.6	242 ± 104

Group test 2 including:
Subgroup test 2-a (with a dashed border): Constant V and Constant t, Ascending P
Subgroup test 2-b (with a pattern fill): Constant V and Constant P, Varying t

Coating $C_{V\text{-}P\text{-}t}$	Hardness (GPa)	Elastic Modulus (GPa)
$C_{40\text{-}1\text{-}30}$	1.26 ± 0.6	155 ± 77
$C_{40\text{-}4\text{-}30}$	1.36 ± 0.7	201 ± 42
$C_{40\text{-}4\text{-}15}$	1.32 ± 0.5	115 ± 46
$C_{40\text{-}4\text{-}120}$	1.36 ± 0.5	115 ± 46

Another important parameter affecting coating performance is surface roughness. In general, as the surface roughness increases, contact stresses on the asperities will also grow, promoting crack initiation and propagation [30]. This is of great concern for hard and brittle coatings. The rough surface of the hard coatings can result in the coating delamination, especially during the cutting of hard-to-cut materials, when pressure is considerably high. Further post-treatment processes are typically needed after deposition to improve the surface quality of the hard coatings. This is not considered to be an issue for the proposed soft coating, due to its different characteristics. Material gently slides along the smooth surface of the soft coating during the cutting process. The top layers of the coatings themselves slide and flow between the surfaces at high cutting temperatures in the cutting zone. Therefore, a high roughness value for this soft coating surface is not an issue. As shown in Table 6-4, the surface roughness of the Al-Si coating was around 0.3 µm under almost all deposition parameters (Group tests of 1 and 2) but could increase up to 0.95 µm along with deposition time ($C_{40\text{-}4\text{-}120}$, Group 2, Subgroup 2-b). Figure 6-1 shows the roughness profiles of the three Al-Si coatings at different deposition times (Group 2, Subgroup test 2-b). As can be seen in Table 6-4, by increasing the deposition time, while keeping other parameters constant, surface roughness values increased.

Since aluminum is very soft and the coating is formed by adsorption of the Al-Si atoms, any impact of the target particles on the tool surface during the deposition process can deform the coating surface, making it rougher. As deposition time grows, multiple soft layers form on top of each other, thereby increasing the deformation caused by particle impact, and increasing its surface roughness.

Table 6-4. Deposition parameters of the Al-Si coated and corresponding thickness, surface roughness values

Group test 1 including:
Subgroup test 1-a (with a dashed border): Constant V and Constant t, Ascending P
Subgroup test 1-b (with a pattern fill): Constant P and Constant t, Ascending V

Coating $C_{V\text{-}P\text{-}t}$	Thickness (µm)	Surface roughness (Sa) (µm)	Rz (µm)
$C_{40\text{-}1\text{-}30}$	1.9 ± 0.1	0.37 ± 0.2	0.7 ± 0.16
$C_{40\text{-}4\text{-}30}$	2.1 ± 0.12	0.38 ± 0.3	1.2 ± 0.2
$C_{80\text{-}4\text{-}30}$	1.9 ± 0.1	0.4 ± 0.2	1.36 ± 0.3
$C_{120\text{-}4\text{-}30}$	2.1 ± 0.12	0.4 ± 0.3	0.74 ± 0.2

Group test 2 including:
Subgroup test 2-a (with a dashed border): Constant V and Constant t, Ascending P
Subgroup test 2-b (with a pattern fill): Constant V and Constant P, Varying t

Coating $C_{V\text{-}P\text{-}t}$	Thickness (µm)	Surface roughness (Sa) (µm)	Rz (µm)
$C_{40\text{-}1\text{-}30}$	1.9 ± 0.1	0.37 ± 0.2	0.7 ± 0.16
$C_{40\text{-}4\text{-}30}$	2.1 ± 0.12	0.38 ± 0.3	1.2 ± 0.2
$C_{40\text{-}4\text{-}15}$	0.9 ± 0.19	0.3 ± 0.2	0.5 ± 0.2
$C_{40\text{-}4\text{-}120}$	9 ± 0.17	0.95 ± 0.6	2.2 ± 0.5

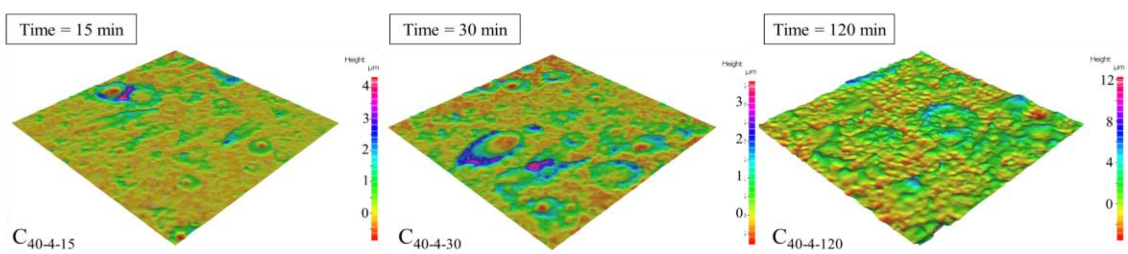


Figure 6-1. Roughness profile of Al-Si coated tools deposited under different deposition times with a bias voltage of 40 V and gas pressure of 4 Pa (Group 2, Subgroup test 2-b)

Additionally, microdroplets were observed on the coating surface which also resulted in a further increase in its roughness. These droplets typically have a spherical shape and a diameter that varies according to their melting point [15]. Since aluminum is very soft, droplets impacting more on the surface during the deposition process contribute to the deformation of the surface. Surface roughness (R_z) can represent the entire height of the surface coating layer. The microdroplets were randomly observed in all coatings in all group tests. However, the intensity of this phenomenon, represented by R_z, was more pronounced for the coated tool with the maximum deposition time (coating $C_{40\text{-}4\text{-}120}$, with deposition time of 120 minutes), which had the maximum thickness. For this coated tool, in some areas, the heights of the droplets were observed as high as 8 µm. This extensive deformation on the Al-Si coating surface due to droplet impact is shown in Figure 6-2. These droplets were caused by local heating and melting of the target material during the deposition process. Thus, they were mainly affected by the deposition temperature of the coating, which for these coatings was intentionally selected very high, close to the low melting point of aluminum. As mentioned before, since the performance of the proposed coatings was not much affected by the coating parameters, the conditions were selected at extreme levels to show these phenomena.

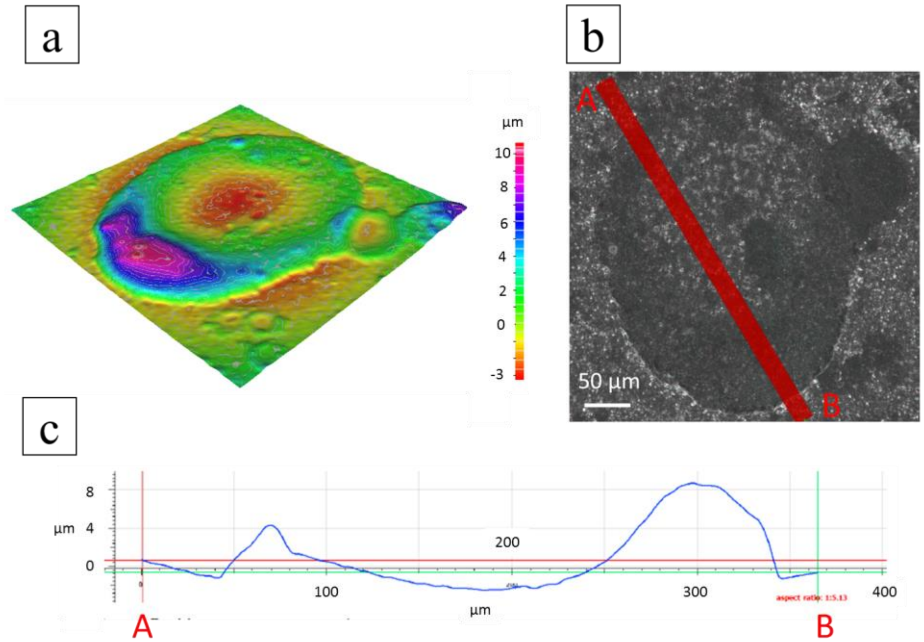


Figure 6-2. a) Profile measurement of the microdroplet formed on the surface of the Al-Si coated tool by using a Bruker Alicona infiniteFocus microscope, b) direction of the line scan measurement on the microdroplet, and c) corresponding height of the microdroplet formed on the coating surface

For example, the machining results of Al-Si coatings with different surface roughness values of 0.38 µm (corresponding to $C_{40\text{-}4\text{-}30}$) and 0.95 µm (corresponding to $C_{40\text{-}4\text{-}120}$) have shown that both tools perform similarly (Figure 6-3). These results not only demonstrate that the surface roughness variation has not affected the performance of the soft Al-Si coated tool, but it also shows that the thickness of the soft coating, at this range, also has no significant effect on its performance. The thickness of coating $C_{40\text{-}4\text{-}30}$ was around 2 µm, while the thickness of coating $C_{40\text{-}4\text{-}120}$ was around 9 µm. The reason for this is that the soft coating pushed out of the contact zone after several machining passes of Inconel 718.

However, further investigation, which will be discussed in the following sections, shows that a very thin layer of the soft coating stayed in the cutting zone until the end of the machining process.

Although the surface roughness of the coatings did not show any considerable effect on the machining performance, the high deposition time, typically corresponding to a high coating thickness and roughness value, had a significant effect on the target consumption. To give an idea, 2/3 of the target material was consumed for depositing $C_{40\text{-}4\text{-}120}$, while $C_{40\text{-}4\text{-}30}$ only consumed 1/3 of the target material. Thus, for cost reduction, the deposition time was limited to 30 minutes for further investigations. Moreover, microdroplets can also increase the target consumption and can adversely affect the uniformity and coverage of a soft coating, especially, if the coating thickness is very low. Thus, as will be shown, the deposition temperature was also reduced to 300°C for the final proposed coating investigations in order to minimize this phenomenon.

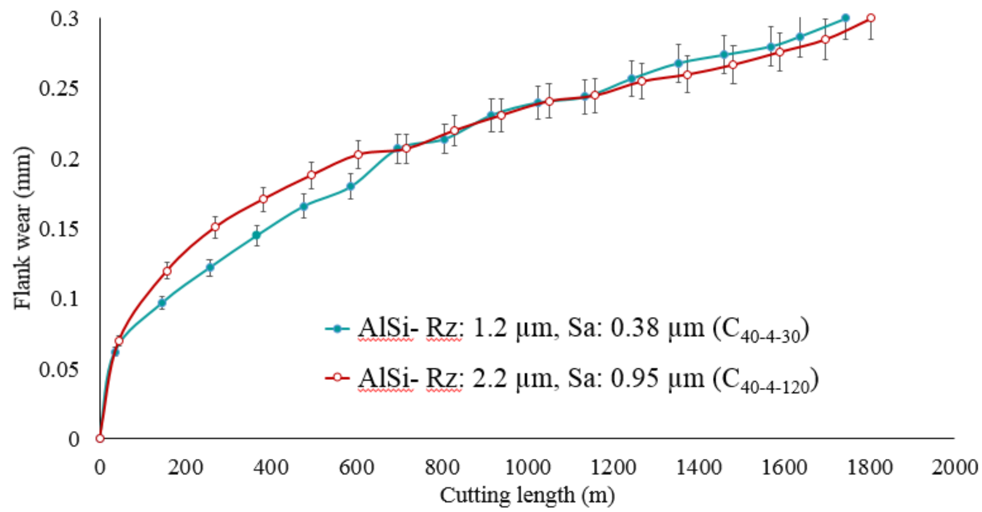
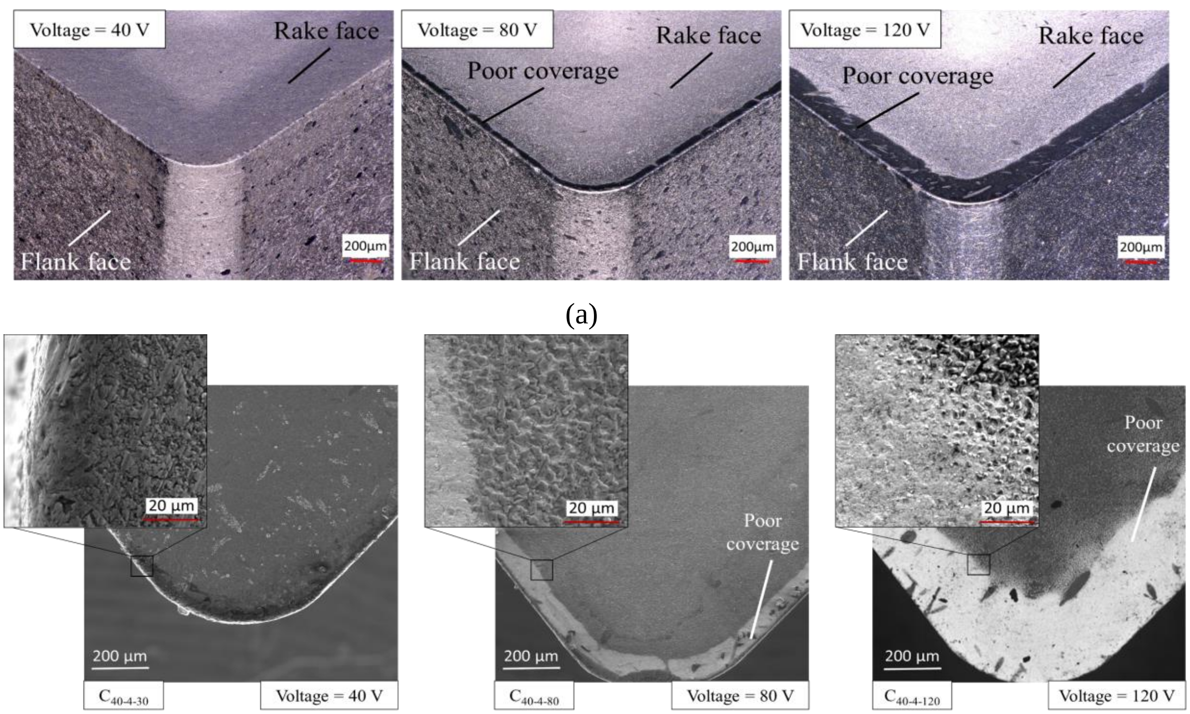


Figure 6-3. Tool life of Al-Si coated tools with different roughness values deposited under different deposition time of 30 and 120 minutes

As mentioned before, the adhesion of the coating to the substrate material is another parameter that plays an important role in the performance of hard coatings. Having a good bond between the hard coating and the substrate material is important since poor adhesion can lead to coating delamination and spallation [31]. Yet, if there is a strong bond between the coating material and the tool substrate, any coating fracture can break off a part of the tool during the cutting process. This is another factor that distinguishes this coating from the conventional hard coatings. The adhesion of the coating to the tool substrate is very low, as the metallic bond between the coating and the tool is relatively weak. Authors in their previous studies showed that tool fracture due to coating delamination is not a concern for this soft coating [26,28].

As shown above, in contrast to the commercial hard coatings, a high surface roughness, microdroplet formation on the coating surface, and poor adhesion of the coating to the substrate do not affect the performance of the proposed soft Al-Si coating considerably. Therefore, these mentioned parameters cannot be considered as restricting factors for selecting the deposition parameters of this coating. However, in this section, it will be shown that the coverage and uniform composition distribution of this coating are significantly affected by the coating parameters and play an important role in the tool performance in the machining process.

The extent to which a coating covers the cutting edge, rake face, and flank face of the tool is crucial for tool performance. Results show that coating coverage is mainly affected by the variation of the bias voltage. The effect of bias voltage on coating coverage was first investigated at different voltages of 40, 80, and 120 V, under the constant pressure of 4 Pa and deposition time of 30 min (group test 1, subgroup 1-b). As can be seen in Figure 6-4, as voltage increased from 40 V to 80 V, the cutting edge and a large area in its vicinity were completely uncovered. The uncovered area became considerably larger by further increasing the voltage up to 120 V. Two factors simultaneously contribute to this worsening coverage: the geometry of the insert, and substrate bias voltage. The shape of the insert determines the ion flux distribution. In general, the ion flux and charge concentration are higher at sharp edges than at a flat surface. Increasing the substrate bias voltage will also accelerate the ion flux, especially at sharp edges [32]. Furthermore, a higher ion flux and charge concentration at the sharp edges will intensify the re-sputtering effect, reducing the coverage of the coating deposited on the tool edges at a higher bias voltage [33]. As shown in Figure 6-4, the tool was extensively covered by Al-Si at a bias voltage of 40 V since the re-sputtering effect was insignificant. As the voltage was increased to 80 V, the re-sputtering effect overcame the coating growth at the cutting edge, leaving a distance of around 100 µm from the cutting edge uncovered by the coating. At the bias voltage of 120 V, this uncoated distance grew to 300 µm due to the high re-sputtering rate. In addition to poor coverage close to the cutting edge, re-sputtering also reduced coating thickness more near the edge compared to the flat area of the tool. Moreover, the results showed that under constant bias voltage the pressure did not have a considerable effect on the coating coverage (Group test 1, Subgroup1-b).



(a)

(b)

Figure 6-4. a) Optical images of the coating coverage on the tool at different bias voltages (Group test 1, Subgroup 1-b) and the SEM images of tools showing the microstructure of the coatings on the tool rake faces

Uniform composition distribution of coating materials on the tool substrate is another important factor affecting the performance of the Al-Si coating. For this coating, aluminum with 10% silicon was selected as the target material, since the inclusion of silicon to the aluminum increases the fluidity of the alloy and helps the material flow better [29]. It should be mentioned that although the right amount of silicon in the coating can have a favorable effect on coating performance, an excess of it can lead to machinability issues.

To assess the uniformity of the coating, the composition distribution of the coating on the cutting edge was investigated using EDS under different parameters. Figure 6-5 shows the backscattered and EDS images of aluminum and silicon distribution at the edge region for the Al-Si coating ($C_{40-1-30}$). As illustrated in Figure 6-5, the silicon distribution is nonuniform: it does not cover the edge and its adjacent areas, gradually increasing as it moves away from the tool edge toward the tool center.

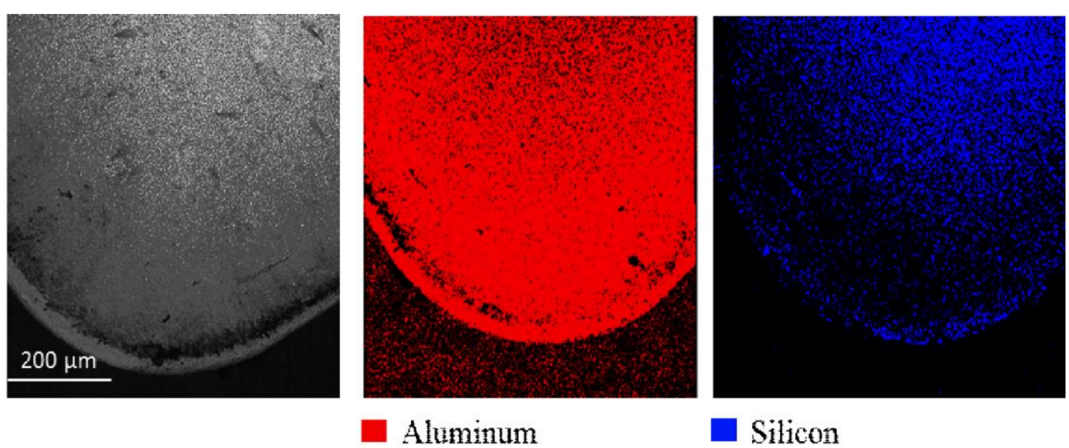


Figure 6-5. Backscattered images and EDS map of the Al-Si coating ($C_{40-1-30}$) shows the composition distribution of the coating materials

Nonuniformity of the silicon particle distributions was observed on the Al-Si coatings that were deposited under either low pressures or high bias voltages (Group test 1). Figure 6-6 shows BSE images of the silicon distribution in the Al-Si coatings at different deposition pressures and bias voltages.

The most uniform distribution was observed at the highest pressure of 4 Pa and lowest voltage of 40 V. At a constant voltage at its lowest level (40 V), this phenomenon was observed by decreasing the pressure from 4 Pa to 1 Pa. Similarly, the nonuniform distribution of Si was observed when increasing the voltage to high values of above 80 V, at a constant pressure at the highest level of 4 Pa. The results suggest that this phenomenon happens at high voltages and low gas pressure, corresponding to the highest bombardment energy and, consequently, the highest sputtering effect. As this phenomenon coincides with the edge effect phenomenon at high voltages, the silicon particles show more pronounced distancing from the edges.

Furthermore, it is known that, generally, at high temperatures close to the melting point of aluminum, the hard silicon particles do not have good bonding to the soft aluminum matrix and during the cooling, debonding of silicon can happen, as aluminum prefers to form its structure with itself and eject other elements like silicon [34].

When the silicon particles become debonded from the aluminum matrix at the cutting edge, a pure aluminum structure might form on the tool surface. Therefore, due to the very low wettability of aluminum to WC tool material, the balling effect of aluminum might occur on the coating, which is observed in Figure 6-7 [35].

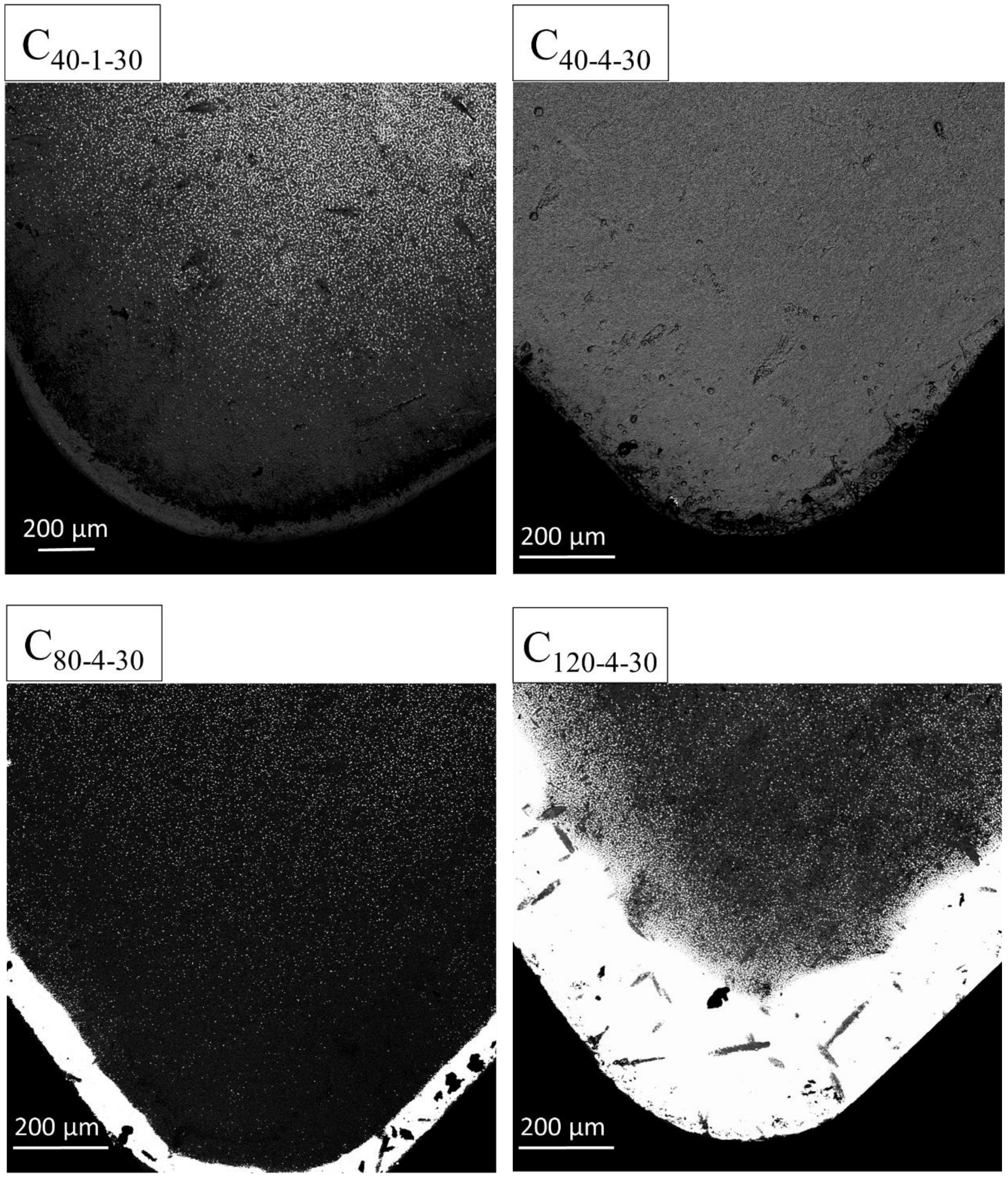


Figure 6-6. Backscattered images of the silicon distributions in the Al-Si coatings at different pressures and voltages with 30 min deposition time (Group test 1)

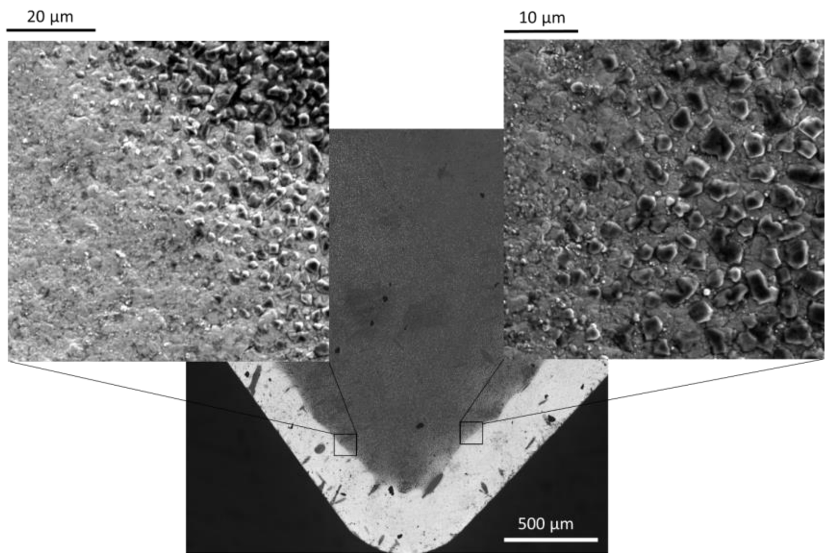


Figure 6-7. SEM images of the microstructure of the Al-Si coating deposited at120V, 4Pa and 30 min under 500°C

6.4.2 Selected coating parameters

The results discussed above suggested that most complications faced during coating were linked to the high deposition temperature. As stated previously, a high deposition temperature not only causes microdroplet formation (Figure 6-2) and increases the exhaustion of the target material, but also can result in nonuniformity of the coating structure and composition. Therefore, a lower temperature around 300°C was suggested for the soft coating deposition process.

Moreover, considering other coating defects happening at high voltages and low pressures, such as poor edge coverage and nonuniformity of the coating, lower voltages around 40 V and relatively high pressures around 4 Pa were proposed for obtaining the desired coating.

For cost reduction purposes mainly corresponding to the cost of target material consumption, the deposition time was limited to 30 minutes.

6.4.2.1 Characterization of the selected coating

Finally, in order to investigate the performance of the coating under the proposed conditions, the different properties of the selected coating ($C_{40\text{-}4\text{-}30}$) were investigated through a comprehensive coating characterization. Then, further machining performance investigations were carried out on the Al-Si coating deposited under the selected parameters, as displayed in Table 6-5.

Table 6-5. Selected parameters and the properties of the Al-Si coating deposited on the cutting tool

Coating material	**Deposition parameters**				**Thickness (μm)**	**Hardness (GPa)**	**Elastic Modulus (GPa)**	**Surface roughness (Sa) (μm)**	**R_z (μm)**
Al10Si	t (min)	V (V)	P (Pa)	T (°C)					
	30	40	4	300	1.97 ± 0.2	1.3 ± 0.16	142 ± 58	0.3 ± 0.2	0.5 ± 0.14

6.4.2.2 Coverage, uniformity, and microstructure of the coating

Figure 6-8 shows different properties of the soft Al-Si coated tool deposited at P=4 Pa, V=40V, t=30 min, and T=300°C. Figure 6-8-a shows the wire electrical discharge machining (WEDM) cross-section of the Al-Si coated tool. The sample was then mounted, grinded, and polished. The optical image of the tool in Figure 6-8-a shows the extensive coverage of the Al-Si layer deposited on the tool. The 3D images of the Al-Si coating surface show that microdroplet formation significantly reduced when the coating was exposed to a lower deposition temperature (Figure 6-8-b). Moreover, as shown in Table 6-5, the average value of Rz, which represents the microdroplet formation, was very low (around 0.5 µm). Furthermore, the microstructure of the deposited Al-Si layer was found to be very uniform (Figure 6-8-c). As EDS results in Figure 6-8-d show, aluminum and silicon were also uniformly distributed on the cutting tool.

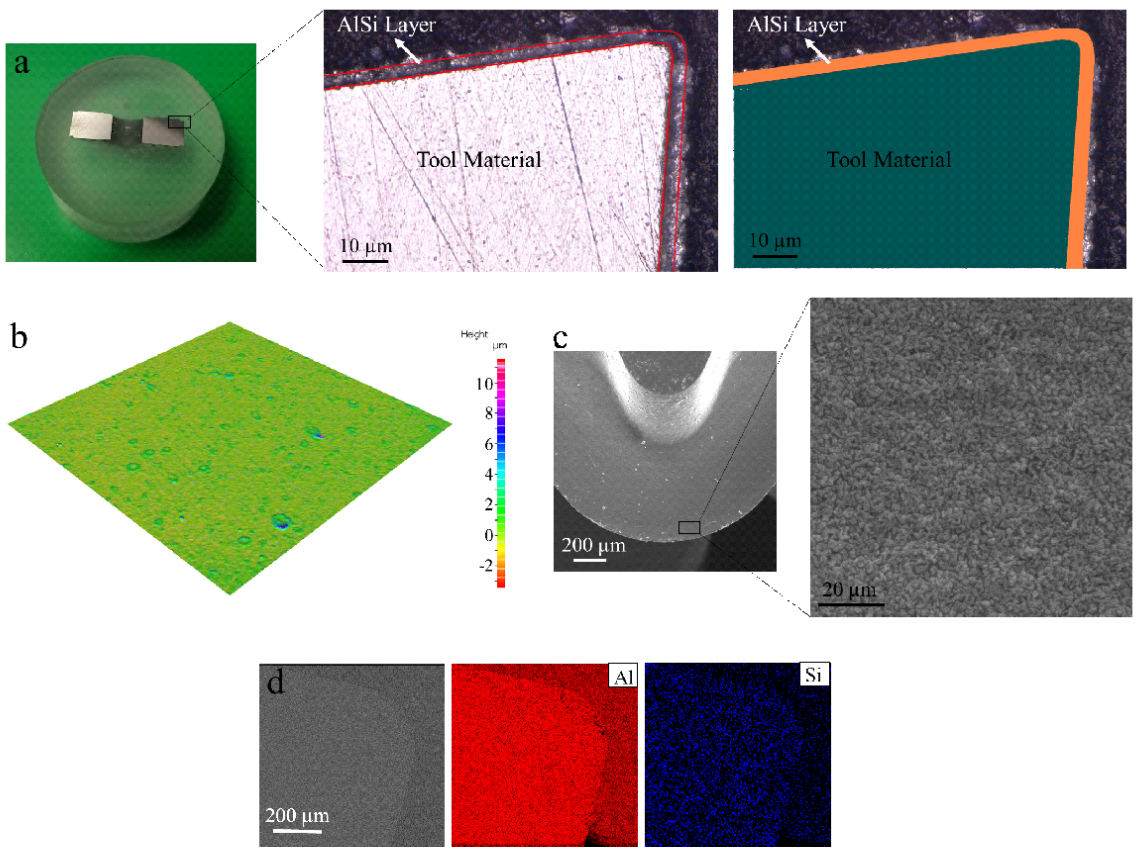


Figure 6-8. a) Cross-section of the tool and optical image of the Al-Si tool-tip, b) 3D image of the surface of the Al-Si coated tool, c) SEM image of the tool and the topography of the Al-Si layer coated on the tool, and d) EDS analysis of the rake face of the tool and distribution of aluminum and silicon on the Al-Si deposited layer.

6.4.2.3 Phase analysis of the Al-Si coating

Since the Al-Si coating is a new type of soft coating used for machining applications, x-ray diffraction analysis (XRD) was carried out on the Al-Si coated flat insert to identify different phases formed on the coating during the deposition process. The phase analysis was repeated two times, and the results show significant matches between both XRD patterns with known structures (Figure 6-9). Although Si and Al have the potential to react with carbon in the substrate material and form various phases, the results show that no reaction occurred between the substrate and the coating materials. The only phases observed on the XRD patterns were tungsten carbide (WC), which is the substrate material, and Al0.9Si0.1, which is the coating material. The results indicate that the coating only contains an Al-Si phase with a cubic structure.

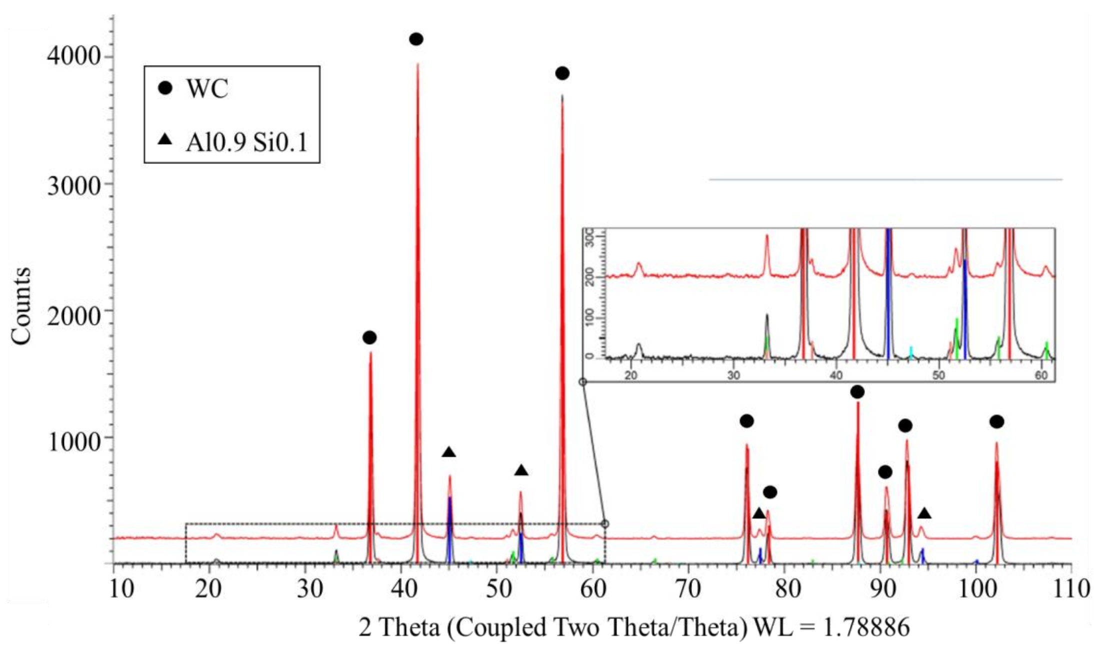


Figure 6-9. XRD pattern for the Al-Si coated tool

6.4.2.4 Residual stress of the Al-Si coated tool

The other parameter that needed to be investigated was the residual stress of the coating. The residual stress of the Al-Si coating was measured and compared with the residual stress of a commercial hard coating (TiAlN). As shown in Table 6-6, both coatings have compressive residual stresses. However, the Al-Si coating was under very low residual stress that was almost negligible compared to that of the hard commercial TiAlN coating. The high value of either compressive or tensile residual stresses in the coating can result in cohesive and adhesive failure of the coating, which consequently weakens the tool. Coating failure due to high residual stress values is considered as one of the main problems of commercial hard coated tools. As illustrated, using a soft Al-Si coating will eliminate residual stress on the coating material, thereby improving tool performance during the machining of Inconel 718.

Table 6-6. Residual stress of commercial hard and proposed soft coatings

Coating	Compressive Residual stress (GPa)
TiAlN (Commercial hard coating)	2.5 ± 0.4
Al-Si (soft coating)	0.174 ± 0.06

6.4.3 Machining performance of the selected coating

Most of the coatings used for machining hard-to-cut materials are hard coatings. There are very few studies that have investigated the application of a soft coating nano-layer on top of a hard coating to simultaneously improve the frictional and abrasive behaviours [14]. Since nanoscale soft coatings are very thin, they are not very effective on their own.

Therefore, several successive layers of hard and soft coatings are deposited on top of one another to create a multilayer coating [19]. Although these multilayer coatings can be useful in some applications, these ultra thin soft layers cannot be very effective in improving the frictional behaviour of the tools during the machining of difficult-to-cut materials such as Inconel 718. Also, any delamination or spallation occurring on a hard coating will cause the ultra-thin soft coating layers to become detached as well. If the thickness of the soft coating layers increases too much in the multilayer coating, the coating will fail due to the eggshell effect, meaning that the hard layer located at the top of the soft layer slips easily during the cutting process.

On the other hand, previous studies by the current authors have shown that a single layer of soft material on top of the tool can improve tool performance on its own even more than a hard coating [25,26]. The machining performance of the selected PVD Al-Si coating during the turning of Inconel 718 was thoroughly investigated in this study.

6.4.3.1 Tool life

To evaluate the performance of the selected Al-Si coated tool, its tool life was compared with an uncoated tool and one with a commercial hard coating (TiAlN). Figure 6-10 shows the flank wear plotted versus the cutting length for uncoated and coated tools. Flank wear of either 0.3 mm (based on the ISO 14577-4.) or severe tool chipping were selected as criteria for the end of tool life. It should be mentioned that all experimental results were repeated at least three times to achieve consistent and reliable results. The tool life of the uncoated tool was only between 400-600 m of cut. The tools mainly failed as a result of severe tool chipping and fracture after short cutting passes. Figure 6-11 shows a severe tool chipping on the uncoated tool at 500 m of cut. In contrast, the tool life of the Al-Si coated tool was between 3000-3300 m of cut, which is around 170% higher than that of the commercial hard coating and around 540% higher than an uncoated tool. As shown in Figure 6-10, the tool wear curves for the commercial hard coating and uncoated tool increase rapidly, whereas the tool wear curve for the Al-Si soft coated tool increases gradually until it reaches the maximum tool wear of 0.3 mm.

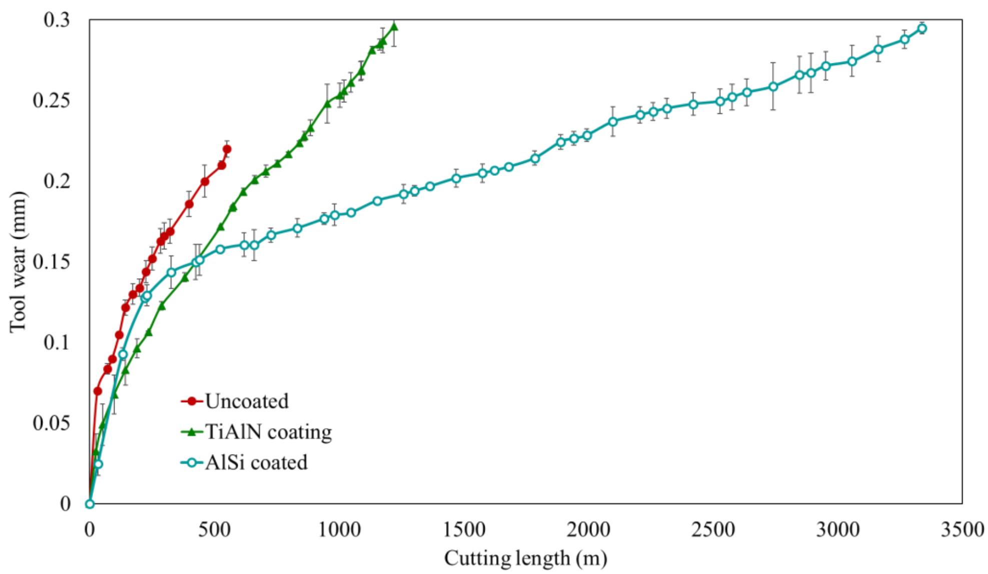


Figure 6-10. Tool life of the uncoated and Al-Si coated tools

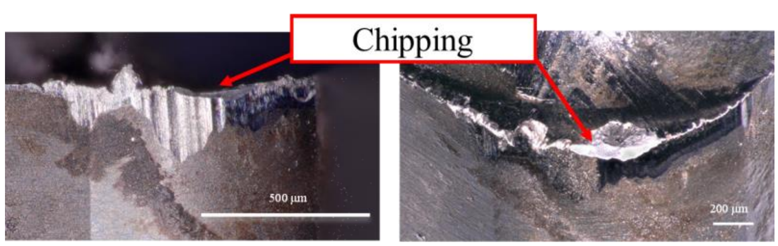


Figure 6-11. Severe tool chipping of the uncoated tool after around 500 m of cut

6.4.3.2 Cutting force

Cutting force was also measured during the cutting of Inconel 718. As illustrated in Figure 6-12, the cutting force generated with the uncoated tool was much higher than that of the Al-Si coated tool. A higher cutting force indicates higher contact pressure at the cutting zone, which can accelerate tool wear. The cutting force of the uncoated tool, as shown in Figure 6-12, gradually increased until it reached a sharp spike at the end of the cutting process due to tool chipping/fracture. However, the cutting force on the soft Al-Si coated tool was much lower than on the uncoated tool. This noticeable reduction of cutting force demonstrates that the soft coating is capable of reducing the contact pressure and easing the material flow.

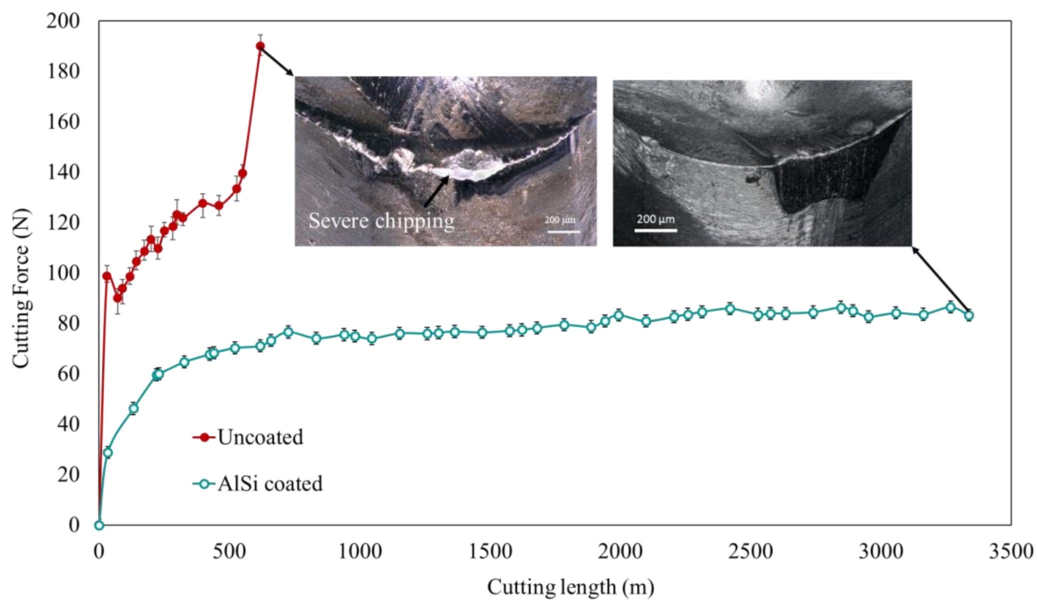


Figure 6-12. Cutting forces of the uncoated and Al-Si coated tools during machining of Inconel 718

6.4.3.3 Work hardening

Severe work hardening of the surface is one of the major challenges that occur during the machining of Inconel 718. Reducing the work hardening of the machined surface, which is responsible for catastrophic tool chipping/fractures, is one of the main goals of the current study. To measure the hardness of the machined surface, a sample of Inconel was cut using WEDM from the bulk workpiece material and then mounted, grinded, and polished (Figure 6-13). A microhardness measurement was done on the prepared sample from the top of the machined surface down to the core of the material with nanoindentation. Figure 6-13 shows the hardness variation of the Inconel surface machined with soft Al-Si PVD coated and uncoated tools. As can be seen in Figure 6-13, the trends of the hardness variation of both surfaces were the same; the hardness close to the surface increased to the maximum value and then decreased gradually as it moved further away from the machined surface. As indicated in Figure 6-13, the hardness of the surface machined with the Al-Si soft coated tool decreased significantly compared to the surface machined with the uncoated tool. Since rapid work hardening is one of the main concerns of machining Inconel, the reduction of work hardening is one of the most important achievements of using the proposed soft coating during the machining of Inconel 718.

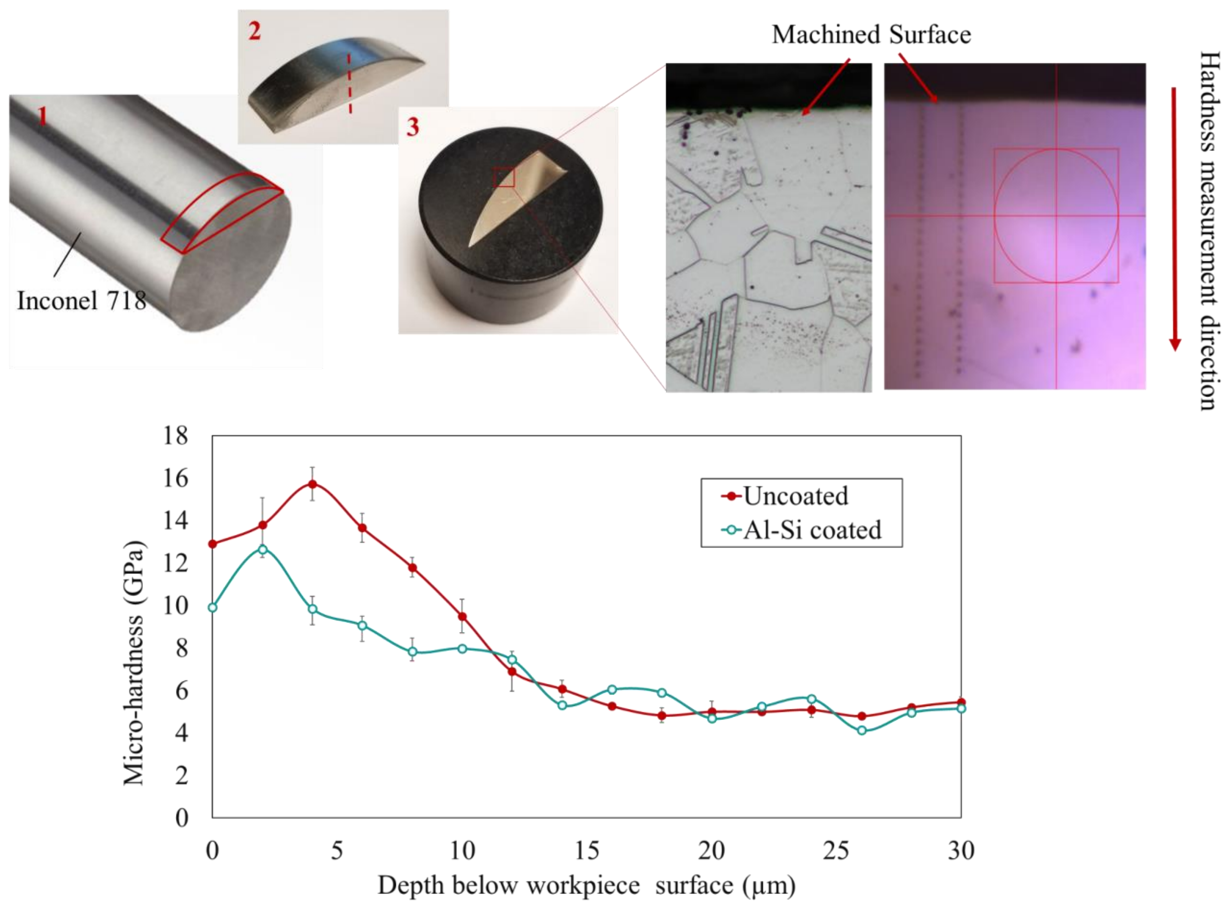


Figure 6-13. Sample preparation for the microhardness measurements; 1) Inconel bar, 2) sample cut with WEDM, 3) sample prepared after mounting, grinding and polishing, and hardness variation of the surface machined with Al-Si coated tool and uncoated tool

6.4.4 Mechanisms resulting in the tool performance improvement of the Al-Si soft coating

The new proposed Al-Si PVD soft coating with a uniform coating composition and structure and full coverage was extremely successful in achieving tool life improvement, cutting force reduction, and work hardening reduction. In this section, a detailed characterization has been done to better explain the reasons behind these significant improvements.

6.4.4.1 Coefficient of friction

One of the main reasons for the improved performance of the Al-Si coated tool in comparison with hard coatings is its better lubricity and low coefficient of friction (COF) in the contact zone. Better frictional behaviour eases the material flow and decreases the contact pressures as well as heat generated in the cutting zone.

To gain a better understanding of the frictional behaviour in the cutting zone, for the purpose of comparison, the COFs of the Al-Si PVD coating, tungsten carbide (WC), and Inconel 718 were measured and are shown in Table 6-6. The COF of the soft Al-Si layer was significantly lower than that of the tool and the workpiece materials. When the low COF Al-Si layer was located between the tool and the workpiece during the machining process, the workpiece material could slide better on the tool surface, resulting in lower forces and lower cutting energy. The common method to improve lubricity and frictional behaviour during the cutting process is to apply lubricants. Yet, conventional lubricants have difficulty reaching the area in the tool chip interface where seizure tends to occur. However, an Al-Si coating layer present in the tool-chip interface can be very successful in reducing friction in the contact zone under the temperatures and pressures present in the cutting zone. One of the main outcomes of the improved frictional behaviour was a lower cutting force, which was shown in Figure 6-13.

Table 6. COF of the tool material, workpiece material, and Al-Si PVD coating

Material	COF
Al-Si coating	0.08-0.1
Inconel 718 (workpiece)	1.4
Tungsten carbide (tool)	0.2

6.4.4.2 Tribofilm formation

Results have shown that a lubricious Al-Si layer on the tool-chip interface improves the overall machinability of Inconel 718 by reducing friction and consequently cutting forces. Although the bulk of the soft Al-Si layer was pushed out of the contact zone after several machining passes under high pressures and temperatures in the tool-chip interface during the machining of Inconel 718, XPS analysis showed that thin films of beneficial tribofilms remained in the cutting zone even till the end of the tool life. To find the chemical composition of the protective tribofilm formed on the tool surface during the machining process, an X-ray Photoelectron Spectroscopy (XPS) analysis also was done on the tool rake face.

Figure 6-14 shows the tribofilm spectra. Figure 6-14-a and 6-14-b depict the worn tool spectra after only 20 m of cut, and Figure 6-14-c and 6-14-d show the worn tool spectra after around 3000 m of cut.

Since both aluminum and silicon have a high tendency to react with oxygen to form various beneficial tribofilms, they were selected as the coating material to improve the frictional and thermal properties in the cutting zone. Studies have shown that the SiO_X

tribo-phase is very lubricious and can improve the frictional behaviour. In addition, both Al_2O_3 (sapphire) and $Al_6Si_2O_{13}$ (mullite) have low thermal conductivity, therefore they can act as a thermal barrier and protect the tool from the heat generated in the cutting zone [24]. XPS results showed that following one machining pass, layers of thermally conductive sapphire and mullite and lubricious SiOx had formed on the rake face of the tool (Figure 6-14-a and 6-14-b). XPS analysis on the rake surface of the tool at the end of its tool life demonstrated that these tribo-layers remained at the cutting zone until the end of the tool life (Figure 6-14-c and 6-14-d). The obtained results show that the Al-Si deposited on the tool not only can improve the running-in stage of the cutting process and protect the tool at the beginning of the cut, but the effect remains active till the end of tool life.

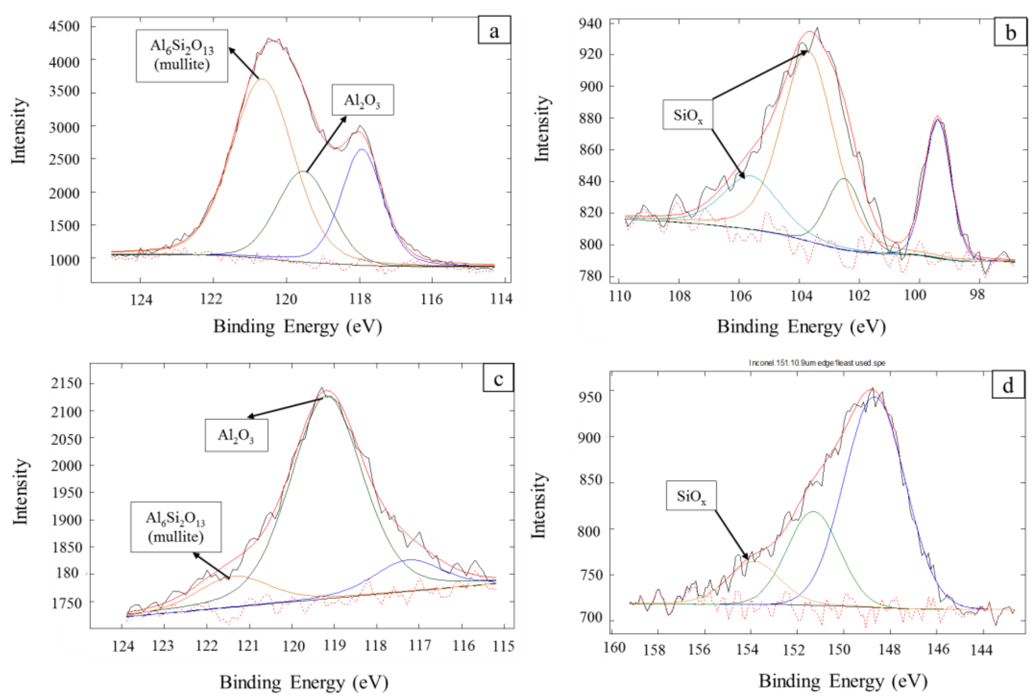


Figure 6-14. High-resolution XPS spectra of the surface of Al-Si PVD coated. a–b) after 20 m of cut; c–d) after 3300 m of cut. a, c: Al2s spectra; b: Si2p spectra; d: Si2s spectra

6.4.4.3 Reducing the adhesion wear

Better frictional behaviour reduces adhesion during machining. One of the main causes of tool fracture during the Inconel 718 machining process is the adhesion of workpiece material to the tool. When sticking increases, it can lead to the formation of a built-up edge (BUE). High temperature and friction can accelerate BUE formation [24,36]. Improving the frictional behaviour in the tool-chip interface will result in more sliding instead of sticking. Consequently, a lower amount of BUE forms on the tool surface. Figure 6-15 shows the uncoated tool after around 100 m of cut and the Al-Si coated tool after around 3000 m of cut. As can be seen, a large amount of the BUE formed on the rake face of the uncoated tool, whereas only a minor amount of Inconel material stuck to the cutting edge of the Al-Si coated tool. The significant reduction of BUE formation can be attributed to the superior lubricity and low COF of the Al-Si layer on the tool.

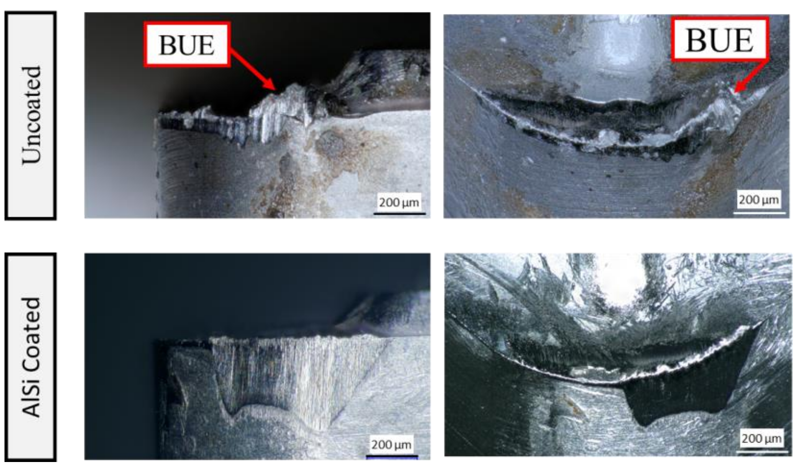


Figure 6-15. BUE formation on the uncoated tool after around 100 m of cut and on the Al-Si coated tool after around 3000 m of cut

6.5 Conclusions

In this study, an in-depth characterization was performed on a soft Al-Si coating, introduced by the authors for deposition on a carbide tool via the PVD method for the machining of Inconel 718. The Al-Si coating is a soft coating never before used for machining applications. Since this is the first time that this coating has been used for the machining of Inconel 718, the parameters that affect the properties of the proposed soft Al-Si coating were thoroughly investigated to identify the main differences they make on the performance and properties of the soft Al-Si coating in contrast with commercial hard TiAlN coatings. For this purpose, Al-Si was deposited on the tool material under extreme ranges of voltage, pressure, and time.

- The results showed that, unlike hard coatings, the hardness of the Al-Si coating was not affected by the deposition pressures and bias voltages and stayed in the range of 1-2 GPa for all coatings deposited at varying voltages and pressures.
- As opposed to the hard coatings, the roughness of the coating and its thickness up to 10 μm did not have any considerable effect on the performance of the coating.
- Since parameters such as coating hardness, thickness, and roughness have only a minor effect on the performance of soft coatings, many of the associated difficulties typically experienced during their deposition process can be avoided. This itself can be considered as an important advantage over other more difficult to deposit commercial hard coatings.

- The results showed that the uniform coverage and distribution of the soft Al-Si coating, which is mainly affected by the deposition bias voltage and gas pressure, plays the dominant role in determining the properties of this soft coating and, consequently, on the overall tool performance.
- Unlike hard coatings, an Al-Si soft coating produces almost negligible residual stress on the coating, which is a big advantage of this coating in the overall improvement of coating performance and, consequently, tool life.
- The machining results showed that the proposed soft Al-Si coating can provide a solution to the outlined machining challenges of Inconel 718. The tool life of the Al-Si coating was more than six times higher than that of the uncoated tool and around three times higher than the commercial hard coating, and the cutting force of the soft Al-Si coating was around half that of the uncoated tool. These considerable improvements can be attributed to better lubricity and frictional behaviour in the tool-chip interface. The superior lubricity of the Al-Si coating resulted in lower adhesion and BUE formation, less contact pressure at the cutting zone and lower friction.
- Although the majority of the Al-Si material was pushed out of the contact zone after a few machining passes, TEM/EDS results showed that a very thin layer stayed in the chip-tool contact zone till the end of tool life, providing lubrication, reducing seizure, and protecting the tool from fracture and wear. The XPS results also showed that a beneficial thermal barrier and lubricious tribofilms had

formed on the rake face of the tool and persisted until the end of the machining process.

6.6 Acknowledgments

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7 Chapter 7. Conclusions and Future Work

7.1 General Conclusions

Inconel 718 is mainly used in aerospace applications due to its low thermal conductivity, high strength at high temperatures, high thermal stability, and corrosion and creep resistance. However, machining Inconel 718 is very challenging. The reason for this poor machinability is due to the high strength of this alloy at elevated temperatures, high temperature generation at the cutting zone, high sensitivity to strain rate, and rapid work hardening of the machine surface which results in severe notch wear on the cutting tool, severe abrasion wear on the tool because of the existence of hard carbide particles in the microstructure of this alloy, the tendency of Inconel 718 to adhere to other materials, and BUE formation, high force generation during the cutting process because of the high strength of this alloy at high temperatures which also result in the poor surface quality of finished components. All of these challenges result in cutting tool failure or tool chipping after a short cutting length and also result in poor machined surface quality.

In the current study, two different techniques were employed to deposit soft, lubricious layers on the tool to tackle and minimize most of the machining challenges to improve the tool performance and, consequently, improve the overall machinability of Inconel 718. The two techniques are pre-machining and PVD. In both techniques, a single layer of soft material is deposited on the cutting tools. In the novel pre-machining method, the soft layer was deposited on the tool through a short machining process. In the PVD method, the soft layer was deposited on the tool by using a PVD coater. In this study, a comprehensive inquiry has been done on machinability performance and surface integrity by using both of these mentioned techniques. For each technique, all mechanisms are investigated in detail to see what effect they have on tool performance and which are responsible for tool life improvement. For this purpose, different aspects of a machinability study such as tool life studies, cutting forces, wear mechanisms, tribology studies, and the surface integrity of the machined surfaces were investigated.

The main goal of this study is to improve tool performance in machining of Inconel 718. The major findings that contribute to achieving the main aim of the current study are as follows:

1. The results showed that significant chipping reduction was achieved by using both PVD coated and pre-machined tools. Tool wear results showed up to 300% ± 10% and 500% ± 10% tool life improvement of the pre-machined and PVD coated tools compared to the uncoated tool, respectively. To the best of our knowledge these are the highest improvements achieved with different coatings ever reported for machining of this class of material.
2. Cutting force measurements showed around 45% ± 10% reduction by using the pre-machined tool and around 150% ± 10% by using the PVD coated tool compared to the uncoated tool.
3. The significant improvements were attributed to the low COF, high lubricity, excellent compatibility to form several beneficial tribofilms, and high ductility of the soft Al-Si layer deposited on the cutting tool.

4. The tool wear study showed a significant reduction in two-body and three-body abrasion wear, oxidation wear, and adhesion wear. Adhesion and BUE reduction resulted in less tool failure during the machining of Inconel 718. All of this tool wear reduced chipping leading to an overall tool performance improvement.
5. The nano-hardness measurement showed a significant reduction in work-hardening of the machined surface using pre-machined and Al-Si PVD coated tools. The results showed that up to a 59% ± 10% reduction in work-hardening was achieved. Reduction in work-hardening results in less notch wear on the tool which is one of the main machining challenges of Inconel 718. This is also the highest reduction ever reported for machining-induced work-hardening, achieved by applying different coatings.
6. Chip analysis represented better frictional behaviour at the tool-chip interface, which results in better material flow during the cutting process, a lower chip thickness, lower chip undersurface roughness, curlier chips, and lower cutting force.
7. The tribology study showed the formation of beneficial lubricious and thermal barrier tribofilms at the tool-chip interface of the Al-Si pre-machined and Al-Si PVD coated tools, which resulted in better material flow and tool protection from seizure and BUE formation during the machining of Inconel 718 when the temperature and pressure are very high. The formation of lubricious tribofilm further contributed to a significant reduction in BUE formation and therefore in tool chipping and failure reduction.

8. The results also showed a significant improvement of the machined surface integrity with both pre-machined and Al-Si PVD coated tools. The sub-surface work-hardening value and depth of deformation decreased significantly, which was attributed to the high lubricity of the coating which resulted in better chip flow.
9. The tensile residual stress value of the surface machined with the pre-machined tool declined by up to 30% ± 5% and the corresponding value for the surface machined with the PVD coated tool decreased by almost 64% ± 5% compared to the surface machined with the uncoated tool.
10. The obtained results showed that, unlike the common available hard coatings generally recommended for the machining of Inconel 718, the performance of the soft Al-Si coating was not largely affected by the deposition parameters such as deposition voltage, deposition pressure, and deposition time. Therefore, the resulting coating variables including roughness of the coating, macro droplet formation, residual stress of the coating, and hardness of the coating, have a minor effect on the coating performance in the machining process. Nonetheless, among all different coating parameters, uniform coverage and distribution of the soft Al-Si coating play a dominant role in the performance of the Al-Si PVD coating.

7.2 Research Contributions

The main Ph.D. contributions of the current study are listed below:

1. In the current study, a novel, simple, and cost-effective deposition technique was developed to improve the tool performance and eliminate tool chipping during the

machining of IN718. An in-depth study was performed to explain in scientific terms how the new method impacts the performance of the tool and the quality of the workpiece material. Machinability investigations were also done to represent a better understanding of the effect this novel approach had on the machinability of IN718. This significant improvement in the machinability of a difficult-to-cut material can have a considerable impact on reducing the machining costs of this class of alloy.

2. Different deposition techniques for applying the lubricious layer on the tool were compared. Layers deposited using PVD coating techniques were compared with a soft layer deposited through pre-machining (a novel developed method) for better industrial acceptance. The material that was deposited as a coating on the tool through both techniques is new in machining applications. Comprehensive studies have been done to find the major differences between both techniques and understand the performance of the deposited layer on the tool. To the best of our knowledge, the considerable improvement achieved in the current study was never achieved in previous studies.
3. The study provides a detailed investigation of the surface integrity of the surface machined with the new pre-machined and PVD coated tools. In the current study, the quality of the machined surface was evaluated for various aspects such as surface roughness, residual stress, microstructure orientation, and work hardening and showed significant contributions to surface integrity improvements, much

higher than the values reported for any coating ever used for machining of this class of material.

4. Since this type of coating has never been used before for machining of Inconel 718, an in-depth characterization was performed to understand the mechanisms of the proposed soft PVD coating for improving the machinability of Inconel 718 and to establish a better way to apply it in industrial settings. For this purpose, the parameters that affect the properties of the proposed soft PVD coating were thoroughly investigated to identify the main deposition parameters that affect the performance and properties of the coating.

7.3 Recommendations for Future Research

The suggestions for future studies are as follow:

1. In the current study, Al-Si and cast iron are the soft layers that were deposited on the cutting tool to improve the tool performance during the machining of difficult-to-cut materials such as Inconel 718. For a future study, the other soft materials also can be considered as a coating target material that can be deposited on the tool to improve the machinability of difficult-to-cut materials.
2. Although the focus of this study was on Inconel 718, the deposition of a soft coating, either by the novel deposition process recommended in the current study or PVD method, can be used for a variety of difficult-to-cut materials.

8 Appendix I: Tribofilm Formation

Results have shown that a lubricious Al-Si layer at the tool-chip interface improves the overall machinability of Inconel 718 by reducing friction and, consequently, cutting forces. Although the bulk of the soft Al-Si layer was pushed out of the contact zone after several machining passes under high pressures and temperatures at the tool-chip interface during the machining of Inconel 718, TEM and XPS analysis showed that thin films of beneficial tribofilms remained in the cutting zone even till the end of the tool life. Figure 8-1 shows the TEM/EDS analysis of the focus ion beam (FIB) cross-section of the worn Al-Si coated tool. Elements of tungsten (W), aluminum (Al), and nickel (Ni) as main constituents of the tool (W), workpiece (Ni), and coating (Al) were selected for EDS analysis of the FIB cross-section of the Al-Si coated tool. It should be mentioned that Al was also present in both the tool and workpiece material in low amounts. An oxygen (O) line scan was also performed to check for traces of oxide rich layers.

In all TEM images with very high magnifications, like Figure 8-1-a, a uniform layer, seen in black, covered the tool in the tool-chip cross-section. An EDS line scan analysis performed along this black layer shows that Al and O have a very good matching pattern. This is clearly visible in the line scan presented in Figure 8-1-b and 8-1-c. In the zones marked as I and III, corresponding to areas passing from the tool and workpiece material, the intensities of Al and O tended to decrease, whereas, in zone II, located in the black area, the intensities were relatively higher. The results suggest the formation of tribofilms in the black area, which was also confirmed by the XPS studies.

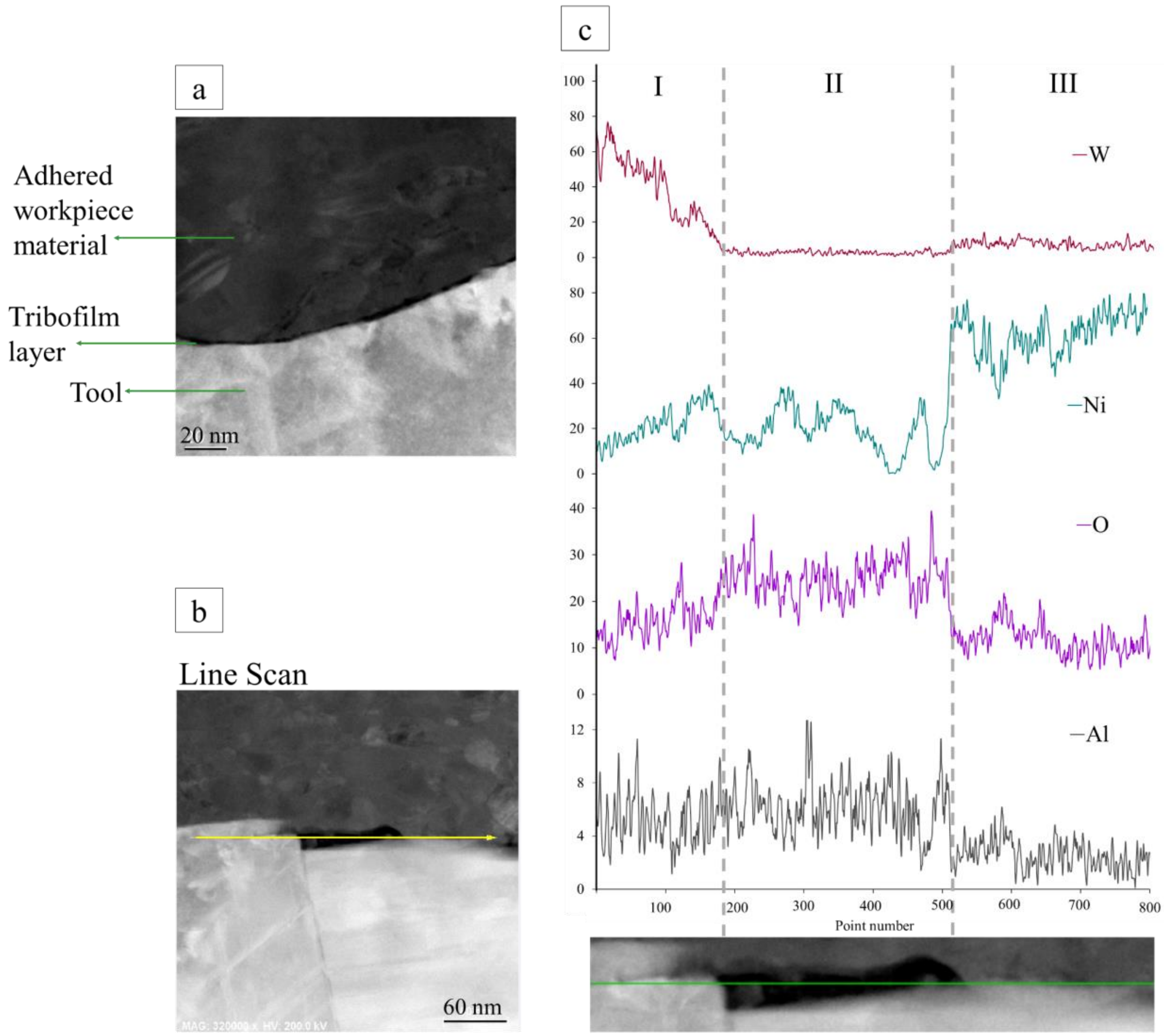


Figure 8-1. a) TEM images (FIB cross-sectional view), b) the direction of line scan at the tool cross-section, and c) corresponding EDS line scan of a cross-section of the monolayer Al-Si coated tool after using more than 3000 m of cut

To gain more in-depth information on the chemical structure of the tribofilm, selective area electron diffraction (SAED) was performed using a 200 kV electron beam in a TEM. The diffraction patterns were acquired from two different regions: at a certain distance from the interface (blue square, Figure 8-2-a) and exactly at the interface (red square Figure 8-2-a). The corresponding diffractions patterns are shown in Figure 8-2-b for the blue area and Figure 8-2-c for the red area. Since the tribofilm size (20 nm) is approximately 50 times smaller than the SAED aperture (10 microns), the same multiple diffraction ring patterns in both areas were observed. These rings correspond to the polycrystalline grains of the adhered workpiece material that are easily distinguishable on Figure 8-2-a. However, the diffraction pattern acquired at the interface shows very bright individual spots, suggesting a single-crystal structure at the interface. Some of these spots overlap with the diffraction ring patterns. To identify the nature of the single-crystal, these single crystal diffraction spots were compared to over 15 different aluminum-based and silicon-based crystals such as corundum, mullite, quartz, cristobalite, as well as different elements that compose Inconel 718. This analysis indicates that these spots likely correspond to the diffraction pattern of Al_2O_3 (in the [001] projection), which is in agreement with the aforementioned EDS and XPS results. Indeed, the two closest spots are at d= 0.391 $Å^{-1}$ from the center and seem to correspond to the (104) and $(\bar{1}0\bar{4})$ spots of Al_2O_3[010] which have an interplanar distance d= 0.392 $Å^{-1}$. Interestingly, if we only consider the interplanar distances, these spots could also correspond to the $(\bar{1}\bar{1}1)$ and $(11\bar{1})$ (d= 0.393 $Å^{-1}$) spots of mullite, $Al_6Si_2O_{13}$ [101]. The diffraction pattern of Al_2O_3 in the [010] projection is shown in the insert of Figure 8-2-d, and its overlap with the experimental diffraction pattern is shown by the red spots. As other bright spots are also noticeable in the diffraction pattern, it is important to note that due to the limited experimental equipment and the lack of a model corresponding to the crystal structure of Inconel 718, a deeper diffraction study that includes a smaller SAED aperture and an Inconel 718 model would allow the analysis to get rid of any unwanted diffraction spots coming out of the interface, to confirm our assessment, and to gain a more complete understanding of the crystal structure of the tribofilms.

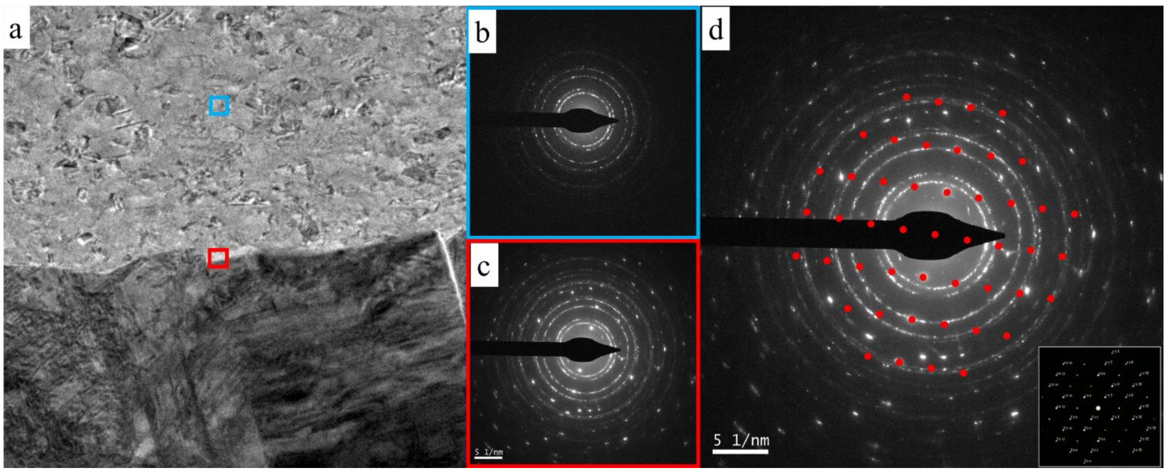
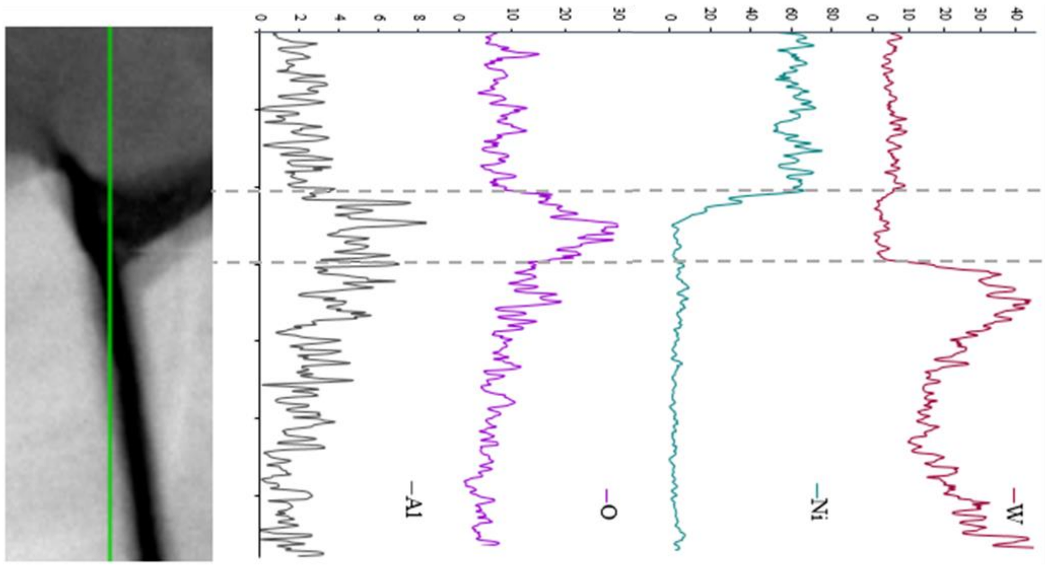


Figure 8-2. a) TEM image of the adhered workpiece/tool interface where the bright contrast at the interface corresponds to the Al-Si coating tribofilm. Blue and red squares: area where diffraction patterns were acquired. b) Diffraction pattern of the blue area, far from the interface. c) Diffraction pattern acquired at the interface. d) Diffraction pattern acquired at the interface overlapped with red spots corresponding to the diffraction pattern of Al2O3 in the [010] zone axis.

TEM/EDS results also showed that tribofilms formed on the tool can easily fill any pre-existing microcracks and defects on the tool surface (Figure8-3). Not only can filling the cracks/defects with Al-O material prevent more crack propagation and initiation, but it can also act as storage for tribofilm formation on the cutting tool surface. As can be seen in Figure8-3, the Al-O based material filled a crack that existed on the cutting tool.



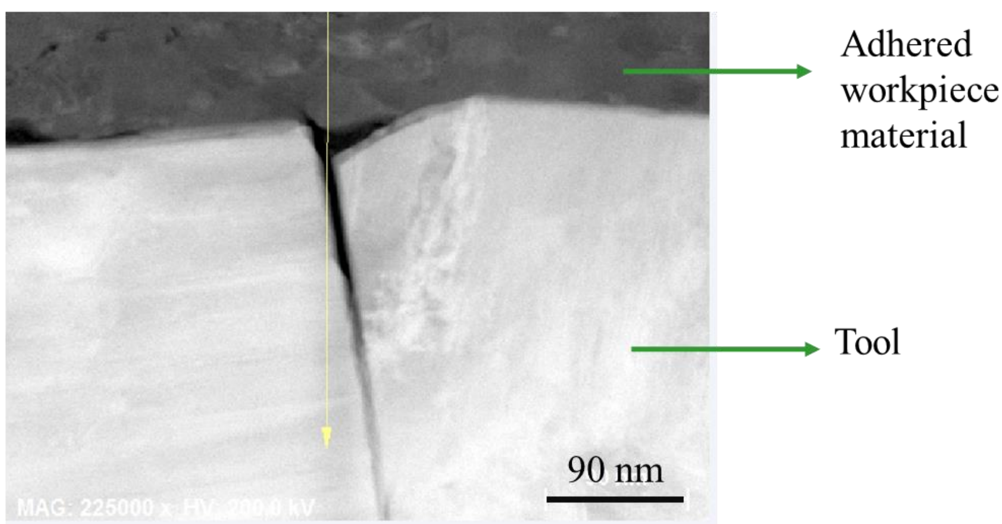


Figure8-3. TEM/EDS of the filled crack of the Al-Si coated tool

9 Appendix II: List of Publications

9.1 Journal Papers:

1. Aramesh M, Montazeri S, Veldhuis SC. A novel treatment for cutting tools for reducing the chipping and improving tool life during machining of Inconel 718. Wear 2018;414–415:79–88. https://doi.org/10.1016/J.WEAR.2018.08.002.
2. Saharnaz Montazeri, Maryam Aramesh, and Stephen C. Veldhuis. An investigation of the effect of a new tool treatment technique on the machinability of Inconel 718 during the turning process. Int J Adv Manuf Technol 2019; 100:37–54. https://doi.org/10.1007/s00170- 018-2669-3.
3. Saharnaz Montazeri, Maryam Aramesh, and AFM Arif, Stephen C. Veldhuis, "Tribological behavior of differently deposited Al-Si layer in the improvement of Inconel 718 machinability. Int J Adv Manuf Technol 2019:1–14. https://doi.org/10.1007/s00170-019-04281-1.
4. Saharnaz Montazeri, Maryam Aramesh, and Stephen C. Veldhuis, "Novel Application of Ultra-Soft and Lubricious Materials for Cutting Tool Protection and Enhancement of Machining Induced Surface Integrity of Inconel 718", Journal of Manufacturing Processes, vol. 57, pp. 431–443, Sep. 2020. https://doi.org/10.1016/j.jmapro.2020.07.002
5. Saharnaz Montazeri, Maryam Aramesh, Sushant Rawal, and Stephen C. Veldhuis, "Characterization and Machining Performance of a Chipping Resistant Ultra Soft Coating Used for the Machining of Inconel 718", Submitted to Wear.

9.2 Patent:

Aramesh M, Montazeri SC, Velduis S. Ultra soft cutting tool coatings and coating method. 2019, Ref number; US20190314900A1.