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ORIGINAL ARTICLE

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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Abstract
Though Inconel 718 alloy possesses excellent material properties and has various key applications in different industries, 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 tribofilms 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

1 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

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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, sublayer work-hardened layer, tribofilm formation, and microstructural analysis of the contact surfaces.

2 Experiment setup and design

2.1 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 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. Fig. 1a 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 Fig. 1b. 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. Fig. 1c 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

Table 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

[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].

2.2 Experimental methodology

Turning tests were performed on a Boehringer VDF 180 CNC lathe. The experimental setup is shown in Fig. 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 2 s 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 Fig. 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 2):

T1: uncoated tungsten carbide; no treatment.
T2: tool treated with Al-10%Si; a very short turning pass of about 2 s was performed on the AlSi bar.

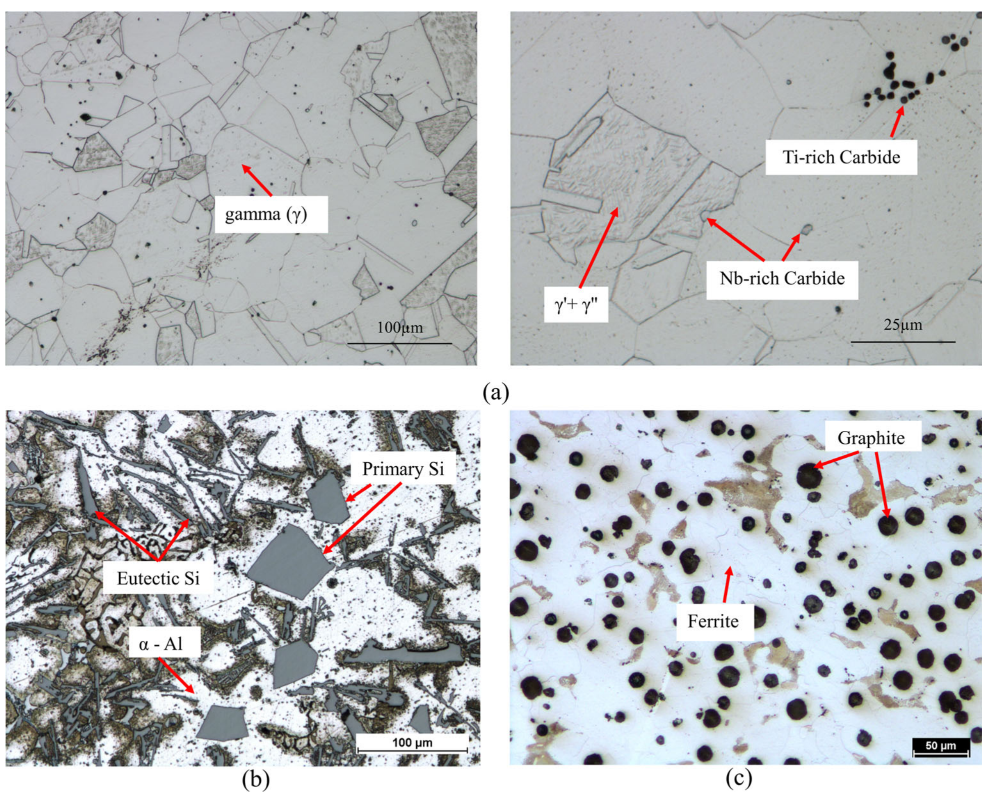


Fig. 1 Microstructure of **a** Inconel 718, **b** Al-10%Si, and **c** ductile cast iron

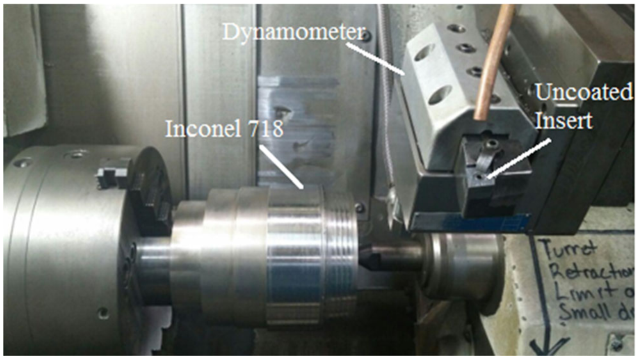


Fig. 2 Experimental setup for machining of Inconel 718

T3: tool treated with cast iron; a very short turning pass of about 2 s 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 1 or 2 s of machining with Al-10%Si, followed by the same process for the cast iron.

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, 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 2 s. 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.

Table 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

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.

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-

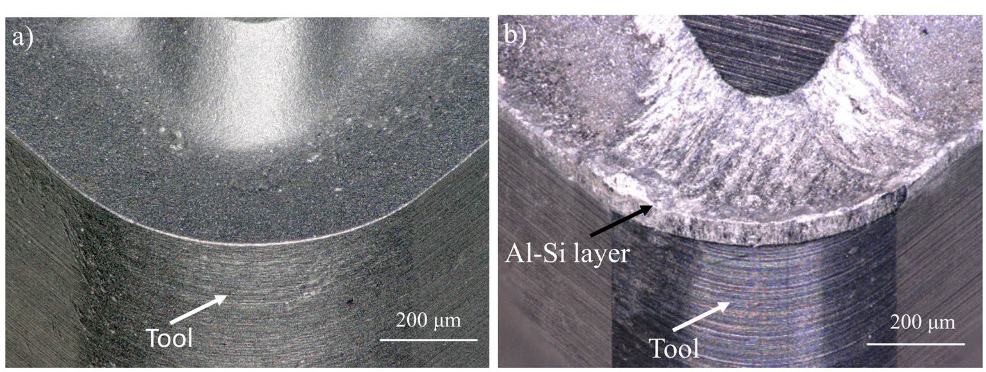


Fig. 3 The layer formed on the tool through the treatment process: **a** uncoated carbide and **b** treated tool

Table 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

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. Nano-indentation 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 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.

3 Results and discussions

3.1 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. Fig. 4a shows the average flank wear vs cutting time and Fig. 4b 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.

High temperatures and pressures at the cutting zone, combined with low cutting speeds during the machining of Inconel 718, lead 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 Fig. 4a, 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 min 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 Fig. 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 Fig. 5a. 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. Fig. 5b shows the SEM image of tool chipping occurred on the uncoated tool after 11 min of cut.

The machining temperature of Inconel reaches very high values. In dry machining conditions, our measurements with VarioCAM HD 1024 infrared camera (Fig. 6) showed temperatures exceeding 820 °C. Considering the similar works reported in open literature for machining conditions, the

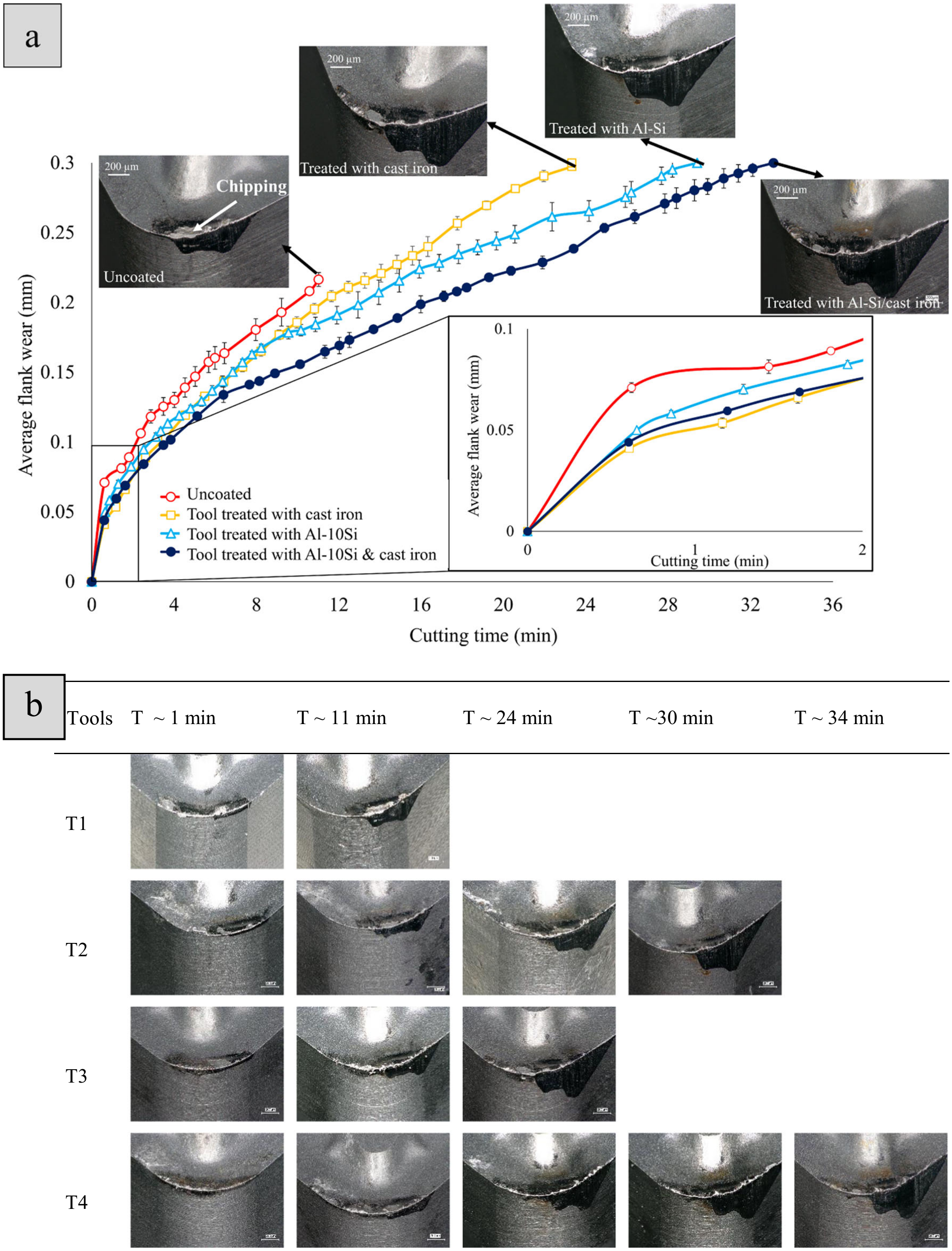
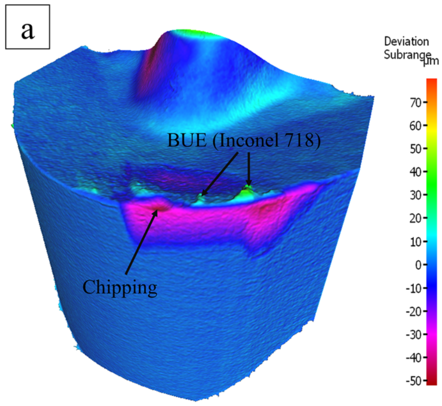


Fig. 4 **a** Flank wear vs cutting time and **b** flank wear measurement at different cutting time (*T*) for uncoated and treatment inserts during machining of Inconel 718

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. Fig. 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



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

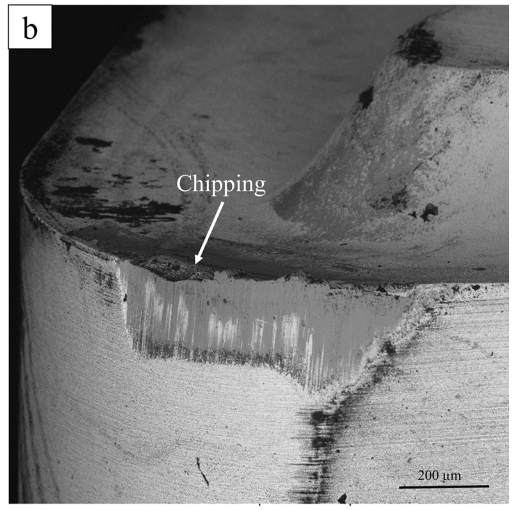


Fig. 5 Chipping of the benchmark at the 11 min of cut (end of tool life) during machining of Inconel 718. **a** Volumetric measurements with white light interferometer with focus variation technology. **b** SEM image of the chipped tool

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. Fig. 8a, b shows 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 (Fig. 8b) compared to the benchmark (Fig. 8a) 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 3.5). Furthermore, Al-Si possesses high compatibility with oxygen to form beneficial tribofilms on the tool-workpiece interface. The XPS results shown in Fig. 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 Fig. 4a, 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.

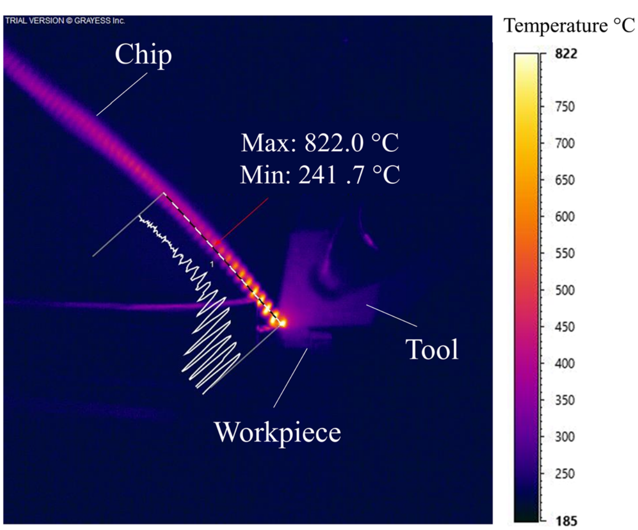


Fig. 6 Temperature distribution at the tool-chip interface during machining of Inconel 718

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 1 s, were alternatively performed on cast iron and Al-10Si (Fig. 10). As can be seen clearly in Fig. 10b, the lubricious cast iron layer leads to aluminum material flow in the direction of chip

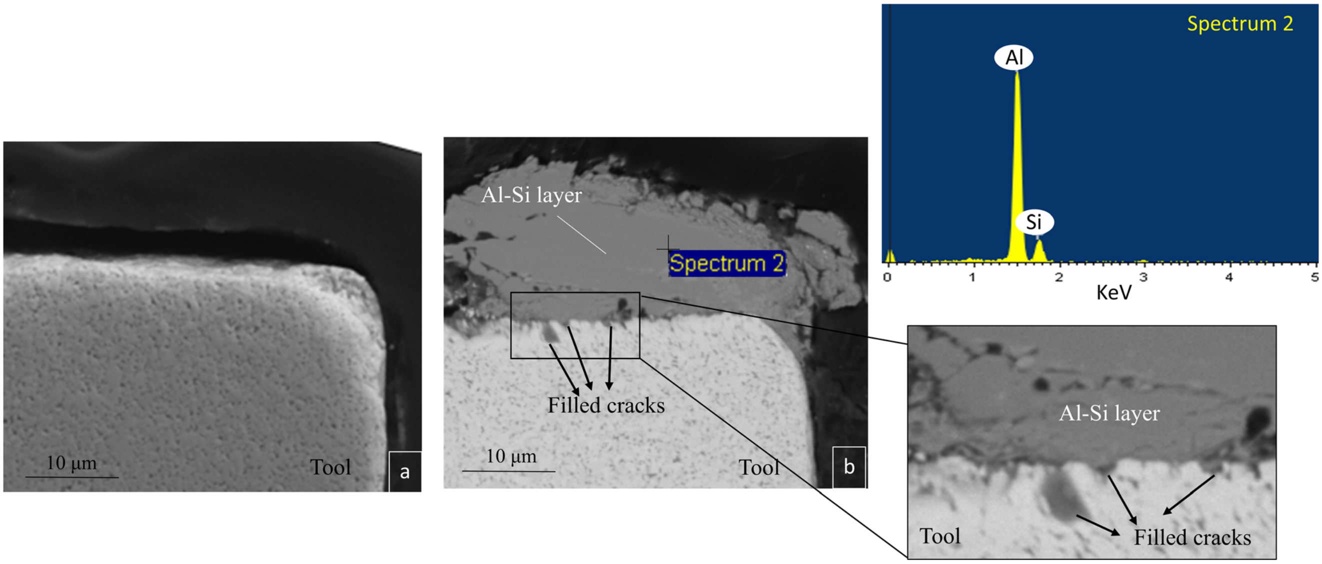
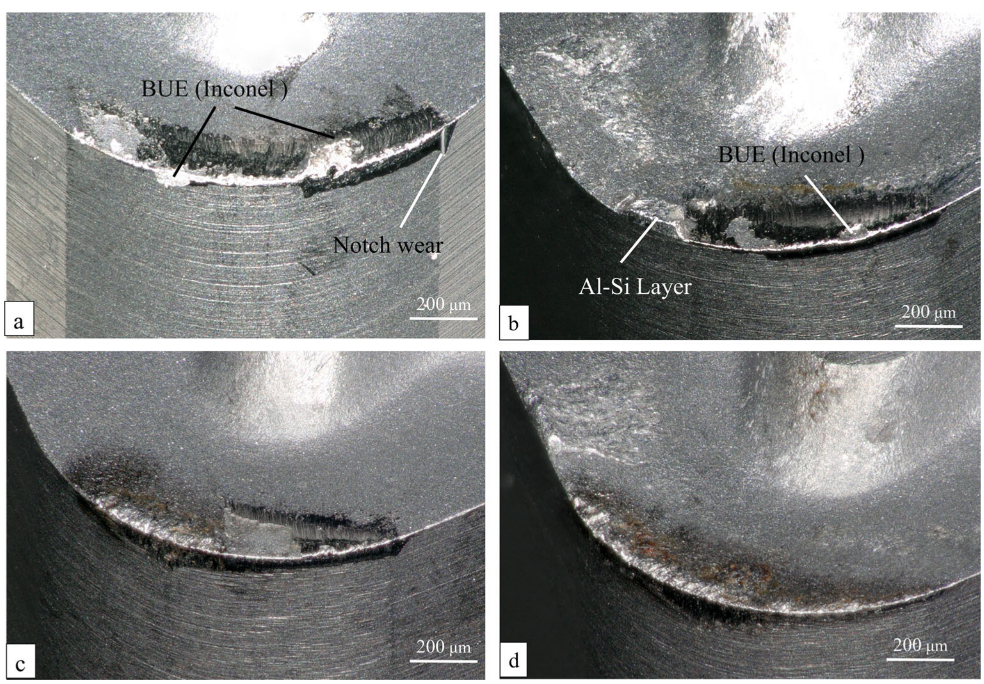


Fig. 7 Backscattered images of the cross section of **a** benchmark and **b** treated tool with Al-Si (T2)

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 Fig. 4a, 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.

Fig. 8c 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.

Fig. 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)



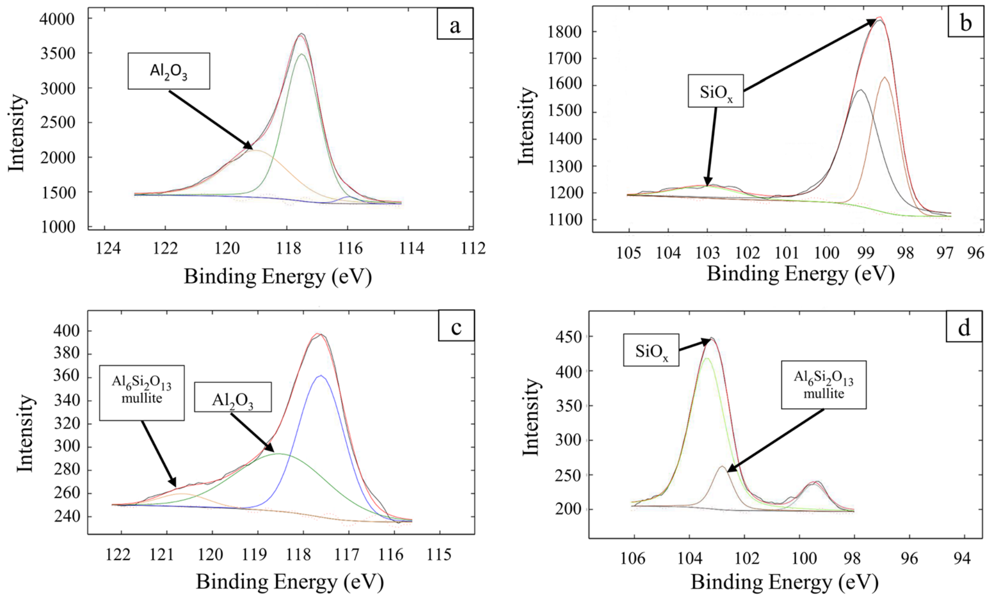


Fig. 9 HR XPS spectra of the surface of tools. **a**, **b** Treated tool with Al-Si. **c**, **d** Treated tool with Al-Si which worn during machining of Inconel 718

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 (Fig. 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 (Fig. 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 (Fig. 8d). As can be seen in Fig. 4a, the tool life of the T4-treated tool was considerably higher than that of 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.

3.2 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

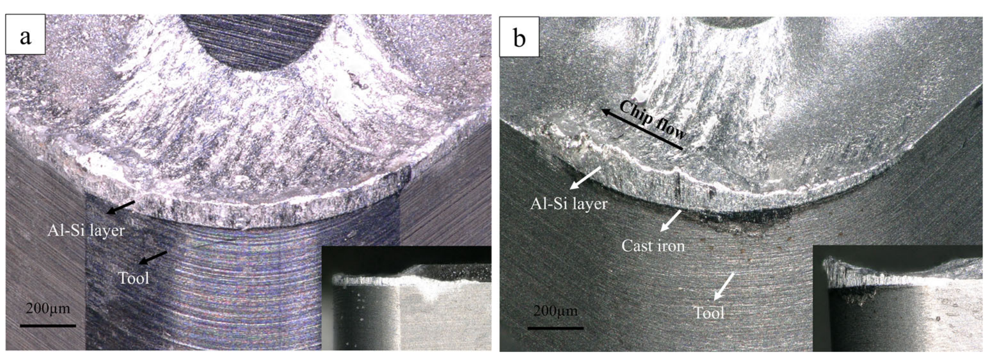


Fig. 10 Material flow of the Al-10%Si; a thin layer deposit on the tool post treatment **a** with aluminum (T2) and **b** with cast iron and then with Al-10Si

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 Fig. 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 of the investigations in this study. Fig. 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 100 N 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 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 Fig. 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 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 that of 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 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.

3.3 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 backscattered electrons (BSE) microscopy and energy dispersive electron spectroscopy (EDS) to assess the tool surface after a short cut was made on the Inconel alloy (Fig. 13).

For all the inserts, spectrum 1 in Fig. 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 Fig. 13a, 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 Fig. 13b, the thermal barrier properties of the Al-10%Si layer deposited between the tool-chip interface decreased the amount of

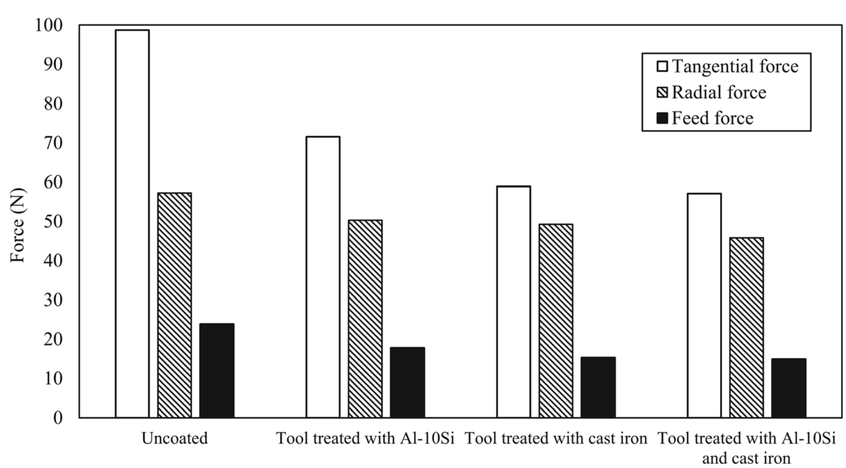
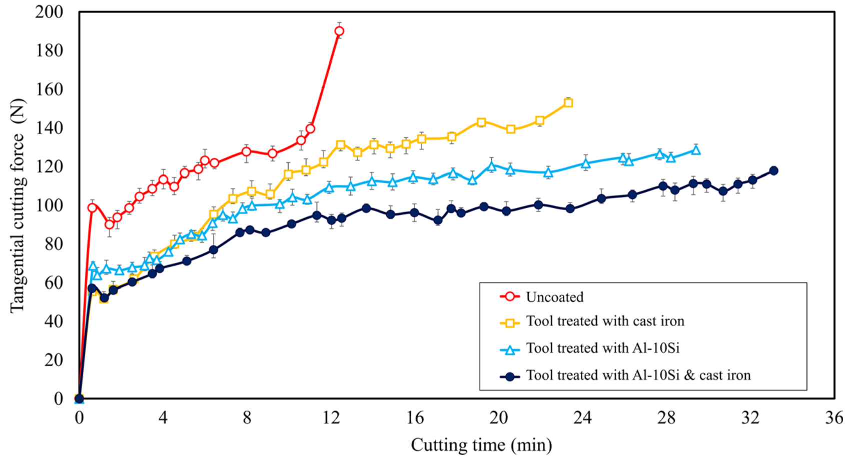


Fig. 11 Feed force, radial force, and tangential cutting force after around 1 min of cut for the benchmark (T1) and the treated tools (T2, T3, and T4)

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



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 Fig. 13c, 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 (Fig. 13d). 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.

3.4 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, 36]. Also, due to the abrasion of the work-hardened layer of the workpiece 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 (Fig. 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.

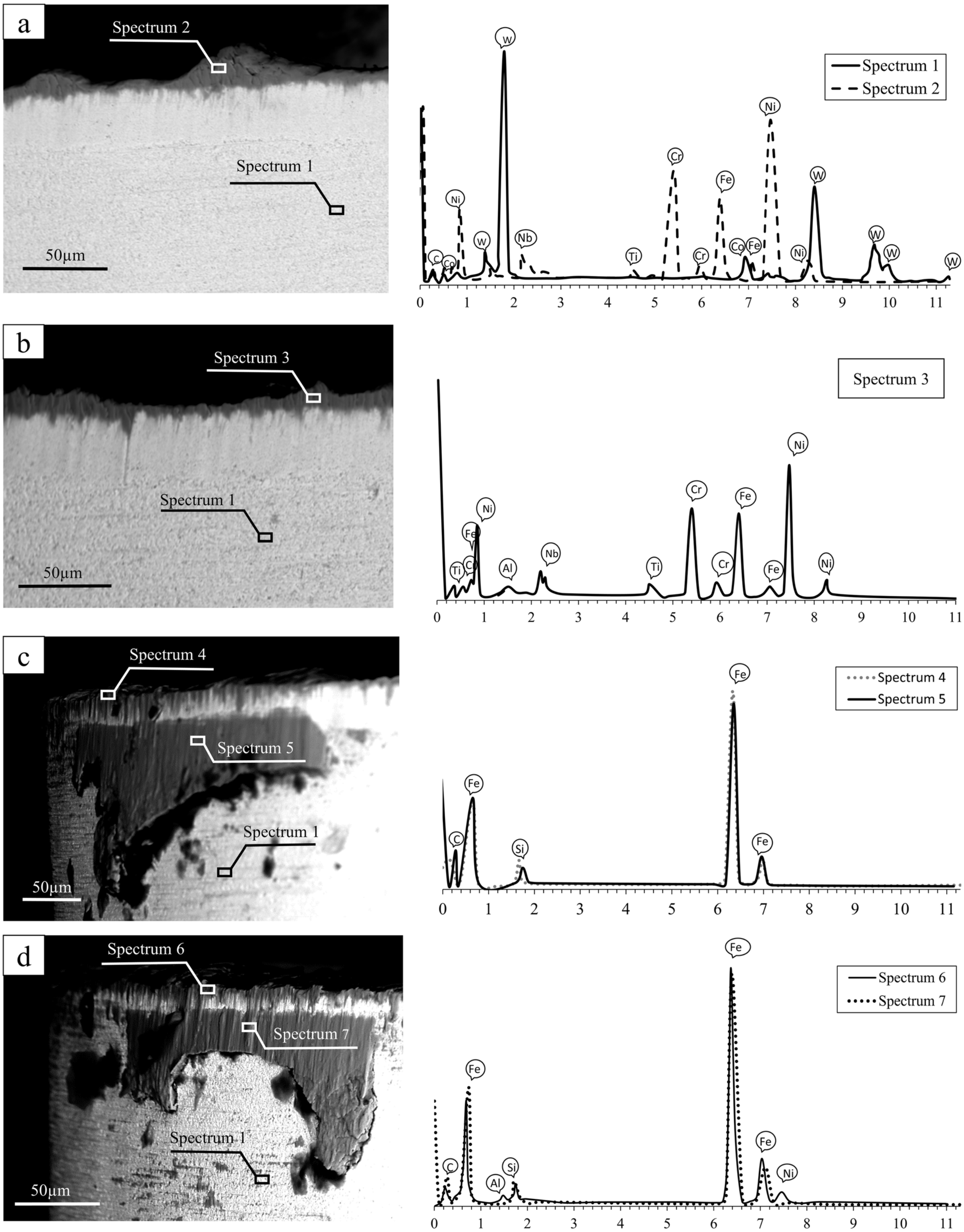


Fig. 13 Backscattered images and EDS analyses of **a** benchmark (T1) and treated tools with **b** Al-10%Si (T2), **c** cast iron (T3), and **d** Al-10%Si/Cast iron and (T4) after around 1 min of cut (36 m of cut) during machining of Inconel 718

Oxidation wear occurs at the outside of the contact zone, where it is exposed to oxygen.

Fig. 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 Fig. 14a, 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

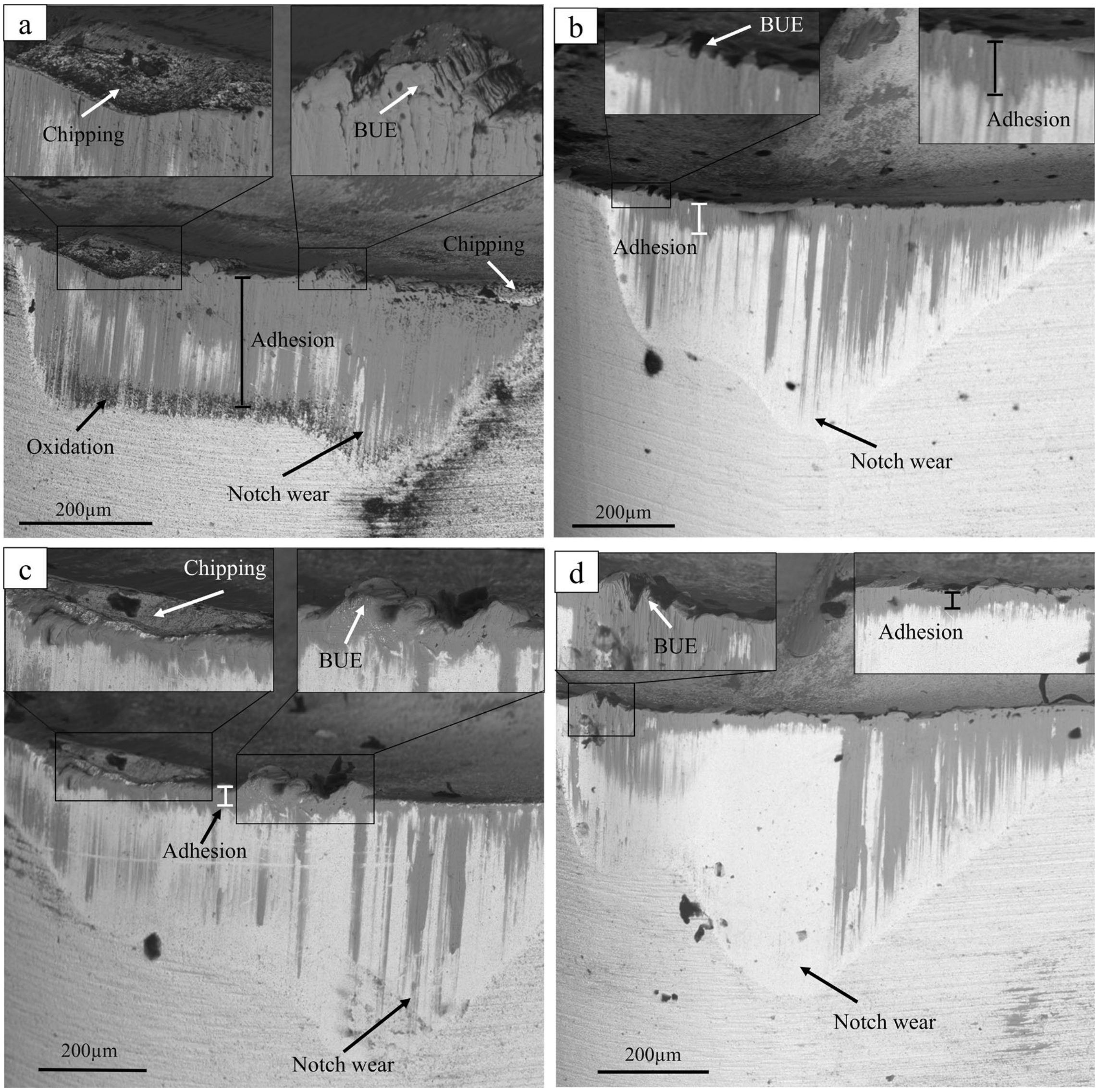


Fig. 14 SEM images of tool wear of **a** benchmark and treated tools, **b** T2, **c** T3, and **d** T4, at the end of the tool life during machining of Inconel 718

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 was observed on the treated tools because the protective layer reduced contact pressure at the tool-chip interface.

Fig. 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 Fig. 14a.

In Fig. 14b, lower BUE formed on the T2-treated tool compared to the benchmark (T1). XPS results (Fig. 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 (Fig. 14b).

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

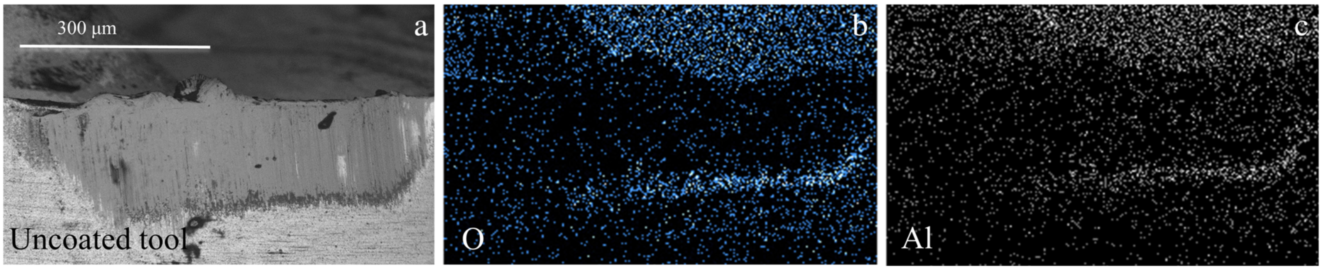


Fig. 15 **a** SEM image of the flank face of the benchmark tool after 10 min of cut. **b** Oxygen map. **c** Aluminum map

at the end of tool life for the T3 tool (Fig. 14c), 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 Fig. 14d, 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.

3.5 Machining-induced work-hardening of the workpiece

As mentioned before, high cutting 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 subsurface [18, 29]. 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).

Fig. 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 Fig. 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

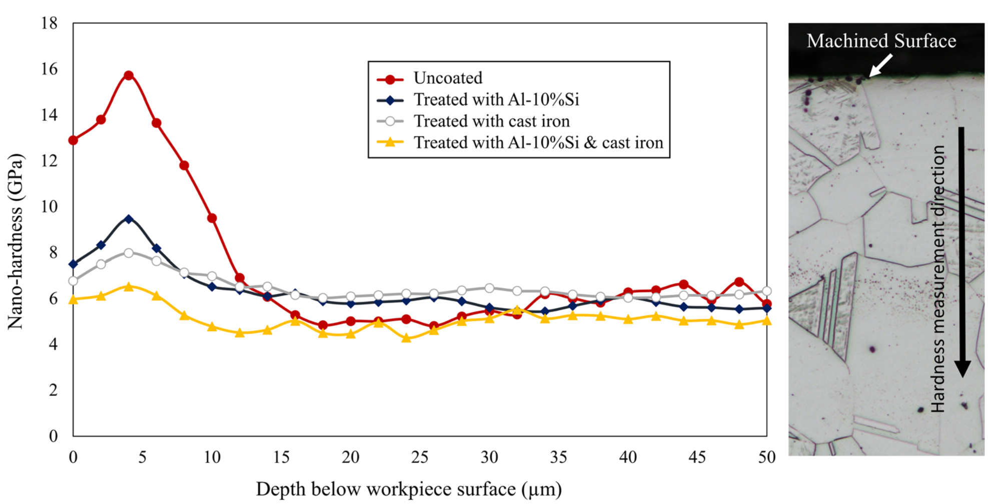


Fig. 16 Nano-hardness profiles of Inconel 718 surface after turning with T1, T2, T3, and T4 tools were observed at machining time of 3 min

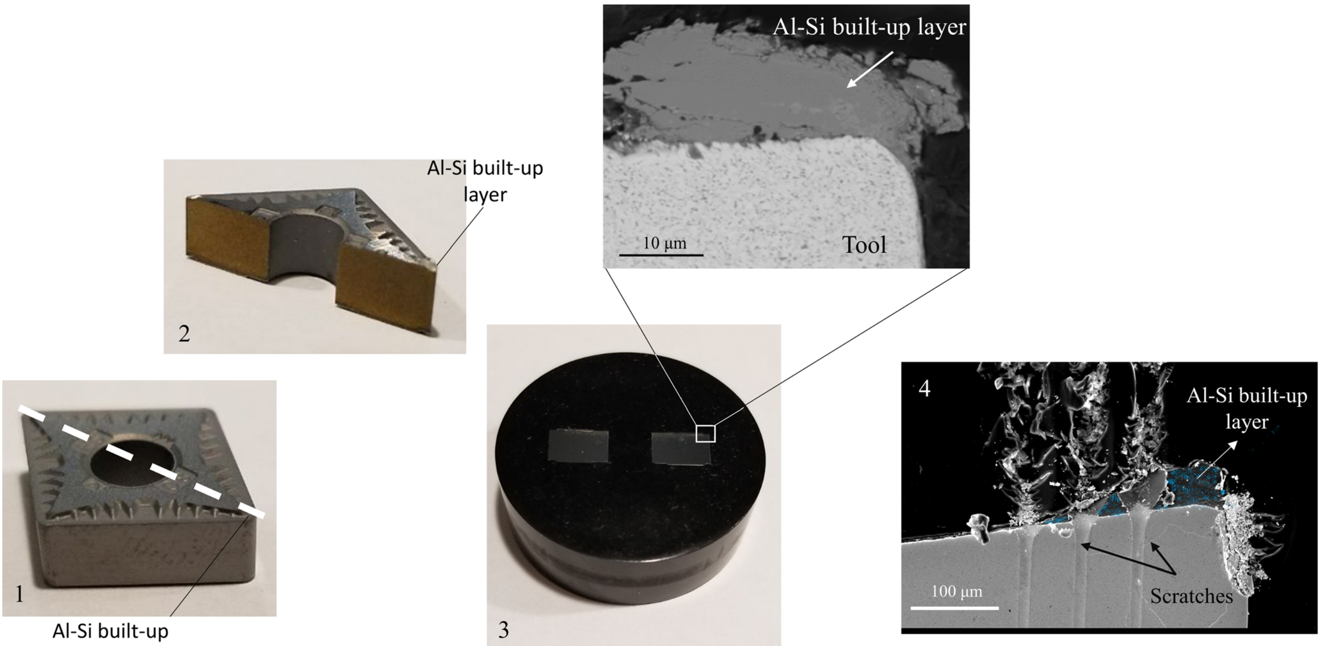


Fig. 17 Different steps for preparing the sample for the nano-wear test: steps 1 and 2) preparing the tool and cutting the tool; 3) mount the sample and then polish it; 4) the backscattered image of the tool cross section after the nano-wear test on the built-up layer and tool material

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 forms and remains 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.

3.6 Coefficient of friction

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 nano-indenter 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. Fig. 17 shows different steps for preparing the nano-wear test sample.

Table 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

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 and is shown in Table 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 4, cast iron and Al-10%Si, chosen as tool treated materials, both show very low CoFs.

3.7 Chip characteristics

Continuous chip formation was observed during the machining of Inconel 718 with both the treated and untreated tools

Table 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

Table 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

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 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.

The summary of results concerning the use of the novel method in this study is shown in Table 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.

4 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 was compared to the benchmark. For the treatment, prior to the actual machining of Inconel, a very short cut, around 2 s, 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, sublayer 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 tribofilms 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 subsurfaces 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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