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ORIGINAL ARTICLE

An assessment of tool life in drilling of Inconel 718 using cathodic arc PVD coated carbide bits

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Abstract
The study investigates the performance of TiN and TiAlN coated carbide tools to improve the tool life in the limited explored drilling operation of difficult-to-cut Inconel 718 (IN 718). We deposited these coatings over tungsten carbide (WC) drill bits through the cathodic arc PVD route and evaluated their tool life at optimized machining parameters. Tool wear initiated with chipping at the corner of the margin and cutting edge (periphery wear), followed by coating abrasion and flank wear. In the case of TiAlN coated drill bit, we observed a notable built-up edge (BUE), indicating adhesive wear, which is not distinctly noticeable in the case of TiN coated drill bits. The comparison of the associated machining challenges between IN 718 and relatively softer EN 24 revealed no chipping but a significant built-up edge in the case of EN 24. At optimized machining parameters of 800 rpm spindle speed and 30 mm/min feed rate, TiAlN and TiN coated drill bits performed 2 and 1.6 times, respectively, better than uncoated drill bits in terms of the number of holes drilled. In addition, the performance of commercially available TiAlN coated drill bits was also compared with that of TiAlN coated drill bits produced in the present study by employing identical machining conditions. The in-house TiAlN coated drill bits yielded 50% additional life than the commercially available TiAlN coated drill bits. Additionally, the machined surface of drilled holes with TiAlN coated drill bits resulted in lower roughness (Ra) than the uncoated drill bits at the end of the respective tool life. The underlying reasons were analyzed and discussed.

Keywords Inconel · Carbide tool · Wear mechanism · Cathodic Arc PVD · Drilling · Roughness

Highlights
- Effect of CAPVD wear-resistant coatings on tool performance in drilling IN 718 is highlighted.
- TiAlN coated drill bit offered 2 times the life of uncoated drill bit and 1.5 times the life of commercially available coated drill bit.
- Unlike conventional steels, IN 718 drilling exhibited chipping as predominant failure mode.
- Abrasive and adhesive wear were dominant wear mechanisms observed while drilling IN 718.
- TiAlN coated drill bit resulted in better surface roughness as compared with uncoated drill bit.

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1 Introduction

Nickel (Ni) based superalloys possess high strength, superior resistance to oxidation and corrosion, and the ability to retain hardness at elevated temperatures (hot hardness). Hence, these alloys are preferred when severe working conditions prevail in specific applications of aerospace, petrochemical, and nuclear power sectors. [1–5]. However, the poor machinability of these difficult-to-cut materials poses challenges in the manufacturing of components. The material characteristics responsible for the associated poor machinability are as follows [2, 6, 7]:

1. Rapid work hardening during machining due to their high strain sensitivity and ability to retain hardness at high temperature (hot hardness).
2. The presence of hard carbide precipitates in microstructure, causing accelerated tool wear.
3. Low thermal conductivity (~11 W/m–K for IN 718) limits the heat dissipation from the cutting zone, steeply

raising the localized temperatures to the tune of 1200 °C (at higher cutting speeds).

4. The high affinity of alloying elements present in Ni-based superalloys towards the tool material (especially carbide tools), leading to an excessive chemical and diffusion wear at higher cutting speeds.
5. Adhesion/welding of workpiece material onto the tool surface and subsequent removal resulting in chipping of tool material.

The poor machinability of superalloys affects the economics of the manufacturing process. It increases overhead (non-value addition) costs besides resulting in production time loss. Therefore, several researchers have attempted to improve the machinability of these alloys, particularly in terms of extending the tool life and reducing the extent of surface abuse [6, 8]. The tool life is one of the most significant factors influencing overall machining cost. Every time a tool requires replacement (due to failure), businesses incur two types of costs: (1) the cost for the new cutting tool and (2) the cost related to idle machine time [9]. Therefore, an optimum tool life associated with high productivity is desirable. For a given workpiece material, mechanical (hardness, toughness) and physical (such as geometry) properties of the cutting tool significantly influence the overall tool life. The higher temperature at the tool-workpiece interface leads to accelerated wear of the tool material. Because of this, other factors, namely, the machining parameters and cooling strategies at the cutting zone, also play a significant role in adjudging the net tool life. Conventionally, harder tool materials such as ceramics (Al_2O_3, silicon nitride, SiAlON), cubic boron nitride (CBN), and polycrystalline cubic boron nitride (PCBN – though limited to roughing operations) are employed at higher cutting speed to moderate the tool life [9–13]. However, carbide tools are preferred for cutting IN 718 at relatively lower cutting speeds as a trade-off between the tool life and cost-effectiveness of overall manufacturing [9]. As the reachability of cutting fluid in the cutting zone is a prime concern in drilling operation, researchers have explored innovative cooling techniques to address this issue. Some of these techniques are minimum quantity lubrication (MQL), cryogenic cooling, hybrid cooling, etc. [14]. Minimum quantity lubrication (near-dry machining condition) provides sufficient lubrication but is not as effective in providing adequate cooling to the cutting zone [5]. In cryogenic cooling, the use of liquid nitrogen (boiling point: −196 °C) as a cooling medium results in longer tool life and improved surface finish. A combination of MQL and cryogenic cooling (hybrid cooling: MQL + cryo) reduces the feed force and enhances the tool life compared with other cooling techniques.

Though employing advanced tool materials and innovative cooling strategies lead to longer tool life, the economic consideration limits their use in practice. Consequently, the most cost-effective way to enhance the life of various tool materials is surface engineering, specifically the application of hard coatings [11, 13, 15–17]. From the cost perspective, coated tools are costlier than uncoated tools. But given the life improvement achieved in the case of coated tools, their potential to provide significant tangible savings per unit of material volume removed is indisputable. In the case of dry machining with coated tools, an amount equivalent to the overall coolant cost (coolant price, handling, and disposal charges) gets added up in this saving. Therefore, researchers have investigated the performance of numerous wear-resistant coatings such as TiN, TiAlN (Ti–rich and Al-rich), TiCrN, AlCrN, TiCN, TiAlSiN, Al_2O_3, and TiB_2 in conventional and high-speed machining [15, 16, 18–20]. The primary reasons behind the improved wear resistance of coated tools are high surface hardness and oxidation resistance of the coatings [21, 22]. Multilayer/multifunctional layers further enhance the coating performance, especially under aggressive machining conditions [23, 24]. Low thermal conductivity and better chip formation are also responsible for the demonstrated performance improvement of the coatings.

The coated tools have improved the machining performance of hard steels, but superalloys such as IN 718 possess stretching challenges due to their outstanding mechanical properties. The previous studies have demonstrated the tool life improvement while cutting the Inconel grade of superalloys by deploying coated tools (TiN, TiAlN, etc.) in turning and milling operations. However, the drilling operation was not focused much in this direction, as implied by the limited literature available [3, 4, 6]. Drilling, mostly being the last machining operation performed, needs more attention to maintain the product quality and overall cost within the anticipated window [4]. To achieve such goals, quite often, understanding the wear mechanisms involved at various cutting conditions becomes vital to establish the optimum machining parameters resulting in improved tool life.

Given the above, the present study investigates the wear behavior and failure modes associated with coated (TiN, TiAlN) and uncoated carbide drill bits in the drilling operation (wet condition) of IN 718. Furthermore, the work discusses the surface finish obtained with and without coating the drill bits and rationalizes the results obtained with scientific observations.

2 Experimental details

In the present study, tungsten carbide (WC) twist drill bits (135° point angle) of 5 mm diameter (M/s Miranda Tools Pvt. Ltd., Ankleshwar, India) and flat coupons (dimensions $25 \times 25 \times 4$ mm^3) were used as substrates for coating deposition. Figure 1 shows the functional face of the drill bit

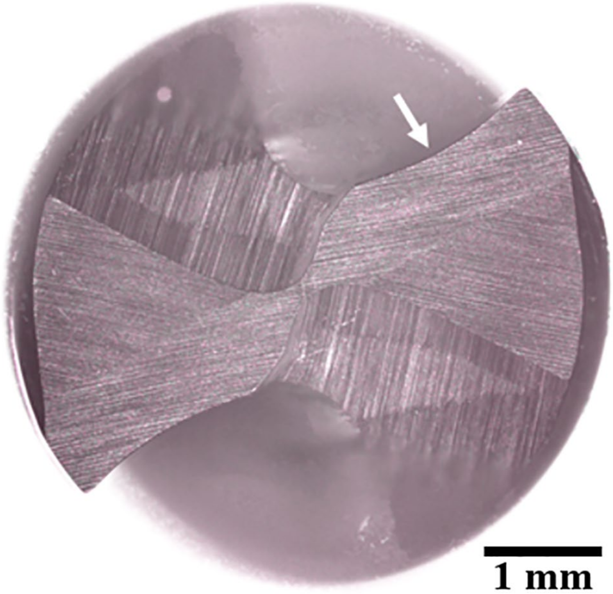

Fig. 1 Typical geometry of drill bit with curved cutting edge (indicated with an arrow)

around its transverse axis. The drill bits that were coated in the present study were subjected to a pre-treatment process to improve the edge stability and finish of the surface [25].

The pre-treatment process was accomplished in three steps, namely, the micro-blasting, edge rounding, and cleaning. Accordingly, the drill bits were micro-blasted with 15 µm Al_2O_3 powder for 4–5 s using a microblasting unit (Guyson Euroblast 2SF system, Guyson International Limited, UK). This was followed by edge-rounding in a drag-finishing machine (DF-4, OTEC Prazisions finish GmbH, Germany) for 10 min. Finally, we cleaned the drill bits and flat coupons (for the characterization of coatings) in an industrial-scale cleaning unit (TermoVide V300, Eurocold Srl, Italy) equipped with an in situ ultrasonic cleaning, rinsing, and vacuum-drying facilities. After the pre-treatment, all substrates (drill bits and flat coupons) were coated through the cathodic arc PVD system (PLATIT π^{300}, PLATIT, Grenchen, Switzerland) equipped with Ti and AlTi rotating cylindrical cathodes. The process parameters employed for coating deposition are listed in Table 1.

The coating thickness was measured using a ball crater abrasion tester (PLATIT CT 50, PLATIT Advanced Coating Systems, Switzerland). The hardness was determined using a Berkovich nanoindenter (Nano-Indentation Tester, CSM Instruments, USA) at a load of 50 mN. The hardness values were averaged over a minimum of 10 indents to obtain statistically reliable results. The adhesion strength of the coatings was measured using a scratch tester (Revetest Scratch Tester, CSM Instruments, USA) by employing a Rockwell C indenter with a progressive load of 1–180 N at a 60 N/min loading rate over a total scratch length of 6 mm. The scratch test results reported herein are mean values taken over four scratch tracks on different coupons drawn from the same batch. A scanning electron microscope (Hitachi S-3400 N, Hitachi, Japan) equipped with energy-dispersive spectroscopy was used to determine the elemental composition of the coatings. The phases formed were identified using grazing incidence x-ray diffraction (Panalytic X'Pert PRO diffractometer, Netherlands) technique. The coefficient of friction was determined by a pin-on-disc sliding wear test rig (TR-20LE-PHM400-CHM60, Ducom Instruments, Ducom Asia) under dry conditions (without any lubricant) at a normal load of 20 N for a sliding time of 5 min. The pins were made of IN 718, while the counter-face materials employed were TiN, TiAlN coated, and uncoated (WC) discs.

Table 1 Process parameters employed for TiN and TiAlN coating deposition

Process characteristics	Coating type	
	TiN	TiAlN
Cathode type	Ti	Ti, AlTi
Substrate	WC drill bits	
Substrate preparation	Ultrasonic cleaning, Ar etching, metal ion etching	
Base vacuum (mbar)	3×10^{-6}	4×10^{-6}
Coating temperature (°C)	420	450
Substrate bias (V)	−50	−50
N_2 pressure (mbar)	5×10^{-2}	5×10^{-2}
Current (A)	173	Ti: 174; AlTi: 275
Deposition rate (µm/hour)	0.7	1.8

The 30 mm thick, 120 mm diameter IN 718 (nominal composition in wt% – Ni, 50.46; Fe, 19.31; Cr, 18.13; Nb, 4.70; Mo, 4.24; Al, 1.31; Ti, 1.06; Si, 0.79) blocks were used as workpiece material for conducting the machining studies. The performance of drill bits was assessed using a 5-axis CNC (DMG HSC 55 linear, Deckel Maho, Germany) machine by drilling (under wet condition) 10 mm blind holes in IN 718 workpiece. The criteria to determine tool life were the number of holes (machining time) a drill bit could drill until the worn-out margin length reached 67% of its initial value.

To accurately determine the margin wear, 3D images of both the margins of the drill bit were captured using a focus variation microscope (alicona InfiniteFocus G5, Alicona Imaging GmbH, Austria). We measured the initial lengths of both the margins (of the unused drill bit) using MeasureSuite software and calculated an average value. After drilling five holes, we captured 3D images of margins again. The leftover margin length was then measured using MeasureSuite

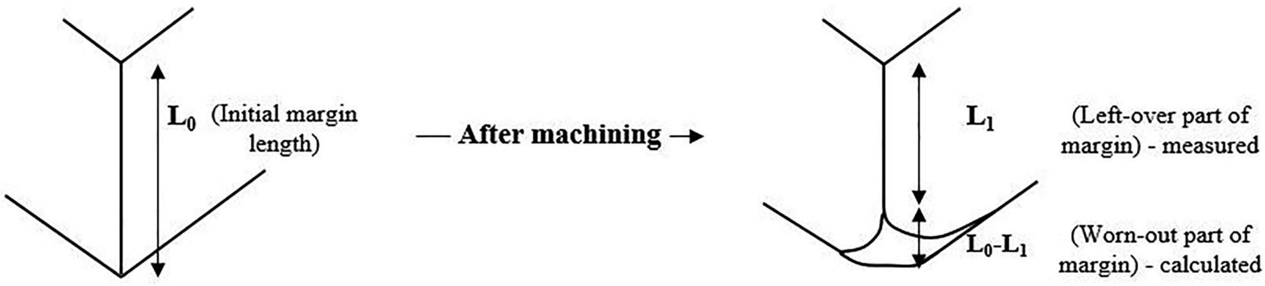

Fig. 2 A schematic of procedure followed to determine worn-out margin length

and subtracted from the initial value to calculate the worn-out margin length. We repeated this procedure after drilling every five holes until the worn-out margin length reached 67% of its initial value. A simple schematic of the procedure followed to determine worn-out margin length is shown in Fig. 2.

To improve the statistical reliability of results, we performed machining trials at least three times. The machining parameters were selected based on a separate study conducted by varying spindle speed and feed rate. A comparative study was also conducted to understand the failure modes involved in relatively softer EN 24 against those observed in IN 718. EN 24 was machined at optimized parameters of 3500 rpm and 175 mm/min feed rate [25].

After completing the machining trials, the last holes (at the end of respective tool life) drilled with uncoated, TiN coated, and TiAlN coated drill bits were sectioned and observed under the 3D microscope. The surface roughness (Ra) of the machined surface (inside the holes) was measured using MeasureSuite software of alicona following ISO 4287. The cut-off wavelength selected was 0.8 mm. The surface roughness measurements were made at three different locations of a drilled hole covering the top (entry point of the drill bit), middle, and bottom regions. An average value corresponding to each location was separately reported.

For a qualitative comparison of the tool chipping, a 3D image of the worn-out tool (at the end of life) was aligned with the corresponding image of the unused tool. Then, we comparatively assessed the magnitude of chipping using MeasureSuite software of alicona. The comparison of two datasets obtained from measured (worn-out tool) and reference (unused tool) are presented in terms of dataset deviation with color mapping. The sequence of this post-processing is illustrated in Fig. 3. Subsequently, the extent of chipping was correlated with the surface roughness of the machined surface (drilled holes). For establishing such a correlation, an area equivalent diameter of a sphere was considered as the chipping dimension. The projected area of the chipped-off region was measured using MeasureSuite software of alicona.

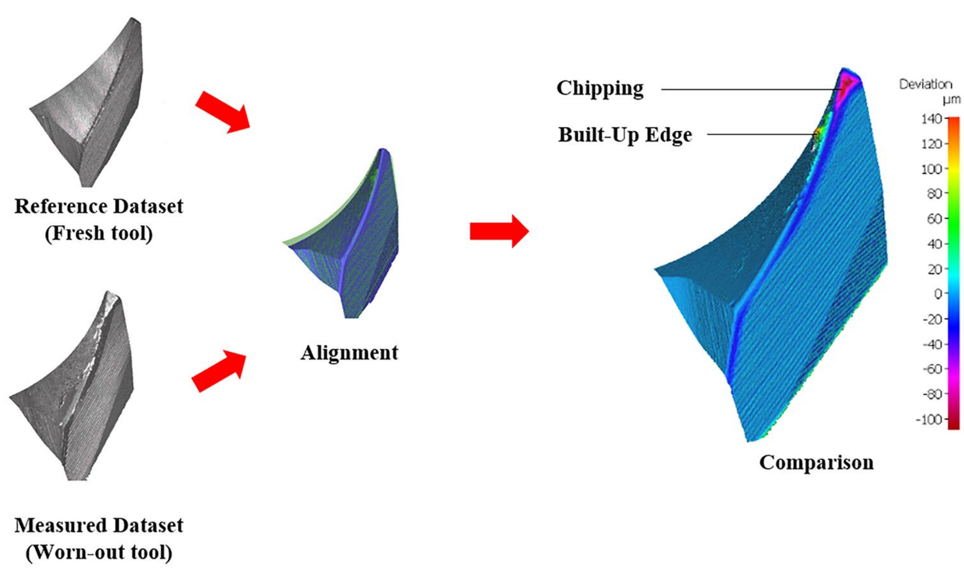

Fig. 3 Post-processing sequence for dataset comparison

Table 2 Adhesion strength, hardness, and composition of TiN and TiAlN coatings deposited through CAPVD

Coating type	Adhesion strength (N)	Hardness (GPa)	Composition excluding N (at%)	
			Ti	Al
TiN	150.15 ± 1.30	26.52 ± 0.33	100.00	-
TiAlN	102.35 ± 0.87	34.50 ± 0.97	52.64	47.36

Table 3 Preliminary phase observations for the selection of the best machining parameters

Spindle speed (rpm)	Feed (mm/rev)	Corresponding feed rate (mm/min)	Observations (After drilling 5 holes)
800	0.0875	70	Chipping at corner
800	0.0375	30	Chipping at corner (< 800–70 combination)
1200	0.0375	45	Drill bit failed abnormally
1200	0.0875	105	Excessive chipping

3 Results and discussion

3.1 Characterization of coatings

In the present study, we chose the coating deposition conditions that resulted in almost identical eventual thickness of TiN and TiAlN coatings between 3.5 and 4 µm. Table 2 presents the composition, hardness, and adhesion strength of the individual coating. The XRD analysis indicates the formation of an FCC structure commonly among TiN (ICDD PDF no.: 00–038-1420) and TiAlN (ICDD PDF no.: 04–005-5251) coatings (Fig. 4). In the case of TiAlN coating, Al:Ti ratio was selected to be approximately 50:50 as a higher ratio of Al:Ti causes a change in crystal structure from cubic to hexagonal, leading to the deterioration in mechanical properties [26, 27]. We assessed the performance of coatings using optimized machining parameters as detailed in the following section.

3.2 Optimization of machining parameters

In the case of uncoated drill bits, we observed excessive chipping at the corner (intersection of margin and cutting edge) and cutting edge while machining IN 718. Chipping being a random process brings unavoidable uncertainty in tool performance and may lead to abnormal (premature) tool failure. In contrast, while machining EN 24, there is no sign of chipping at optimized parameters (3500 rpm, 175 mm/min feed rate). Furthermore, we observed the formation of excessive BUE (Fig. 9b), which is attributed to its relatively softer and more ductile nature. In this case, the absence of chipping and the relatively softer nature of the workpiece result in a much longer tool life. This observation is also evident in previous work [25]. As tool chipping abnormally affects the tool life, the drilling operation was optimized by varying spindle speed and feed rate to minimize the chipping while machining IN 718.

Two levels of spindle speed (rev/min) (800, 1200) and feed (mm/rev) (0.0375, 0.0875) were employed to study the magnitude of chipping. Table 3 shows the summary of experimental observations. We noticed catastrophic failure (breakage) of drill bits at higher spindle speeds (1200 rev/min). Such behavior is attributed to the unstable chattering of the machining tool at higher cutting speeds [23]. Therefore, we selected a relatively lower cutting speed (800 rev/

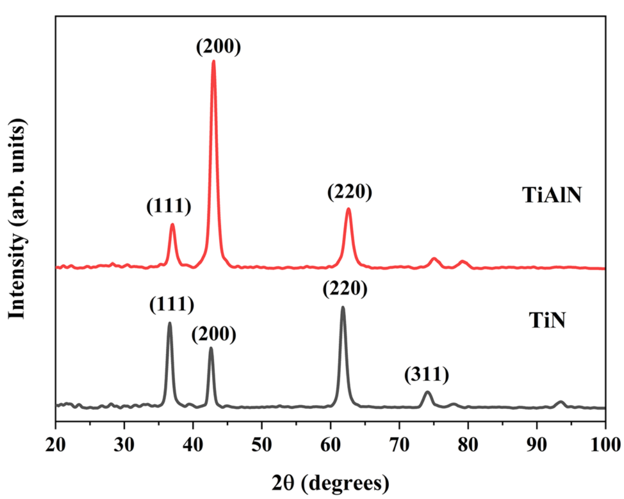

Fig. 4 GIXRD spectra of TiN (below) and TiAlN (above) coatings deposited through CAPVD

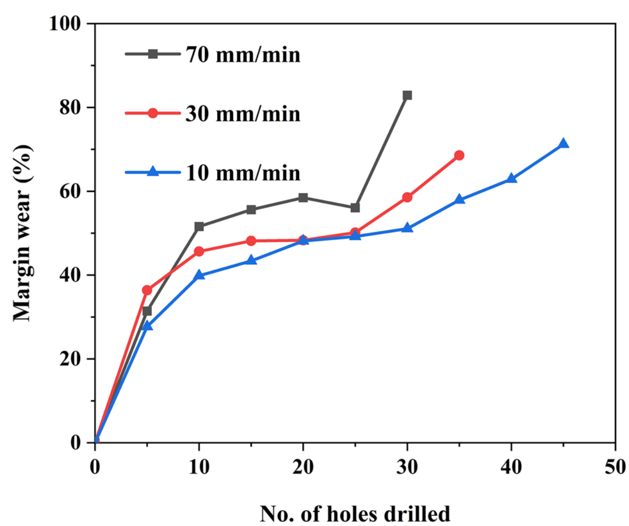

Fig. 5 Influence of feed rate on margin wear of uncoated WC drill bit at a spindle speed of 800 rpm

min) for further experiments. To investigate the effect of varying feed with constant spindle speed, a relatively lower feed of 0.0125 mm/rev in combination with 800 rev/min spindle speed was also tested. Figure 5 illustrates the effect of feed rate on tool life at 800 rpm spindle speed. Figure 6a shows the corresponding corner chipping at the initial stage of machining. A feed rate of 30 mm/min and 10 mm/min improved the tool life by 40% and 80%, respectively, over tool life measured at 70 mm/min. Such an improvement in tool life is attributed to lesser chipping at the parameters employed. It is worth noting here that the extent of chipping at 30 mm/min is lesser than that at 70 mm/min. Although 10 mm/min feed rate resulted in minimum chipping at the corner, it took a relatively long time for drilling 10 mm hole (1 min to drill one hole). Thus, a compromise between the drilling time (productivity) and the chipping phenomenon (associated with tool life) of the drill bit was essential. Therefore, we selected a feed rate of 30 mm/min and 800 rpm spindle speed as preferred drilling parameters for further experiments. Figure 6b presents the progression of chipping with machining time (at initial, intermediate, and the final stage of machining) at selected parameters, i.e., 800 rpm and 30 mm/min. The figure shows that the chipping at these parameters (800 rpm, 30 mm/min feed rate) is minimized. Although the chipping progressively increased with increasing machining time, the drill bit ultimately failed by flank wear criterion. Hence, the selected parameters reduced the chance of a premature tool failure. Figure 6b presents the corner of margin and cutting edge as it is a highly stressed zone [4]. Therefore, chipping at this region was the maximum as compared with other region such as cutting edge.

3.3 Tool life and wear mechanism

Figure 7 shows the influence of TiN and TiAlN coatings on tool life evaluated in the present study. The TiAlN coated drill bit outperformed both TiN coated and uncoated drill bits in terms of the number of holes drilled before arriving at the failure criterion. While TiN coated drill bit performed 1.6 times better than the uncoated counterpart, TiAlN coated drill bit outperformed all others and gave more than 2 times the life of the uncoated drill bit. The performance of the TiAlN coated drill bit, as shown in Fig. 8, was also compared with the commercially available TiAlN coated drill bit

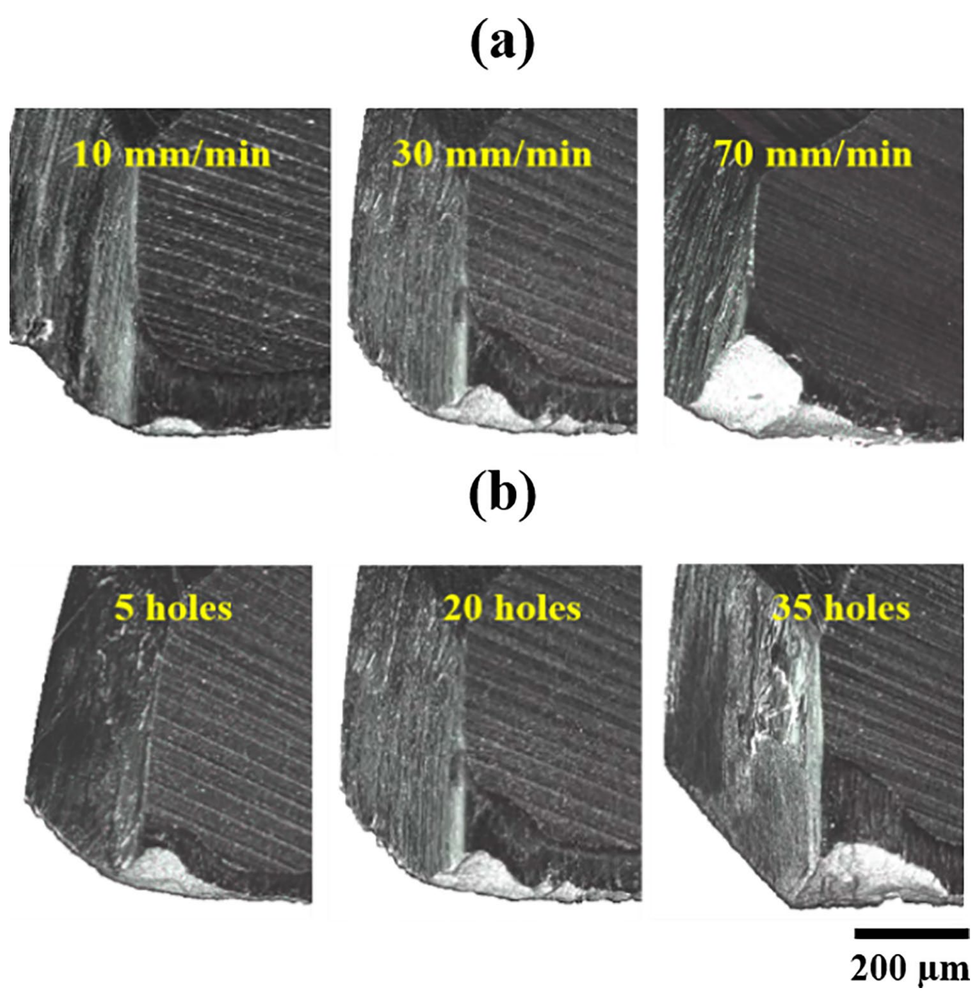

Fig. 6 3D optical microscope images of drill bit corner chipping with **a** varying feed rates at 800 rpm constant spindle speed, **b** at different nos. of holes drilled with constant feed and spindle speed (30 mm/min and 800 rpm)

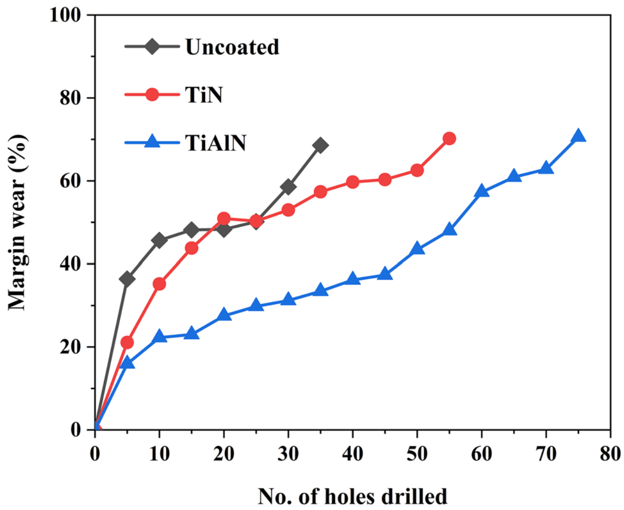

Fig. 7 Margin wear of uncoated, TiN coated, and TiAlN coated drill bits while machining IN 718

(assuming that the coating available in the market is the best in quality) for benchmarking the coating developed in the present study. The former (in-house coated) outperformed the latter (commercially available) by ~50% (75 holes as against 50 holes) at optimized process parameters.

In the context of underlying wear mechanisms, tool wear in coated and uncoated drill bits started with corner chipping/periphery wear, consistent with that reported previously [4]. The chipping at the corner can be associated with two different phenomena: thermo-mechanical effect and complex geometry of drill bit. In the drilling operation, the corner of a drill bit is subjected to the highest stress concentration. In addition, the sliding friction acting between the margin side (corner of margin and cutting edge) and

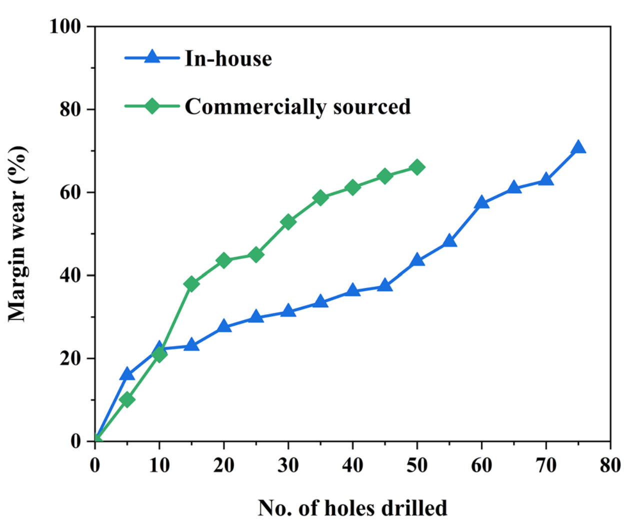

Fig. 8 Margin wear of in-house coated (TiAlN) and commercially sourced (TiAlN coated) drill bits while machining IN 718

drilled hole wall generates a higher temperature at the mating interface. Such a phenomenon determines the overall drilling performance. Secondly, the rake angle of the drill bit varies from highly negative at the chisel point to highly positive at the corner. Such a complex geometry of the drill bit results in reduced included angle leading to lower chipping resistance [28]. Adding to these phenomena, relatively hard workpiece material promotes early tool chipping, leading to a premature fracture at the corner and the cutting edge. If the above arguments and explanation are correct, relatively softer EN 24 should not exhibit untimely fracturing. The machining of EN 24 at optimized process parameters (spindle speed 3500 rpm, feed rate 175 mm/min) confirms that the absence of chipping and formation of BUE at the cutting edge (as shown in Fig. 9b) is in clear support of the aforementioned argument. Therefore, it may be generalized that most conventional materials (steels in general), being relatively softer, promote the transfer of workpiece material onto the tool surface during machining. However, it is noteworthy that such an adhered layer gets removed in the subsequent machining cycles. The adhered layer takes part of the tool material along with it, resulting in attrition wear [29]. In contrast, as IN 718 workpiece is harder and retains hardness up to higher temperatures (hot hardness), it contributes to the chipping of tool material. Thus, it can be concluded that the workpiece properties often play a considerable role in adjudging the wear mode and consequent tool life. This is especially true in the case of machining of hard materials such as IN 718.

Interestingly, in the case of coated drill bits, the chipping and partial abrasion of the coating layer began at an initial stage of the machining and were followed by chipping at the cutting edges. Such failure modes need a thorough investigation of responsible mechanisms. Figure 9a depicts the worn-out region of the cutting edge classified into BUE and three other zones. Table 4 summarizes the corresponding EDS (energy-dispersive spectroscopy) analysis. Tool wear starts with partial abrasion of the coating layer, which is evident in Zone 1. In Zone 1, the presence of W and Ni confirms that the coating abraded off partially, which consequently exposed the tool surface. An adhered (transferred) layer of workpiece material (IN 718) is also present in this zone. In Zone 2, the presence of Ni and Ti confirms the combined presence of the transferred layer (adhered layer) and the coating layer. In Zone 3, however, Ti is dominant, indicating that the coating in this region remains intact. We performed an EDS line scan across the region (Fig. 10) to confirm this aspect. Only major constituent elements of tool, workpiece, and coatings are shown for a simple and clear graphical representation. The line scan distinctly shows the variation of W, Ni, Ti (main elements present in tool, workpiece, and coating, respectively) and demonstrates the underlying mechanism.

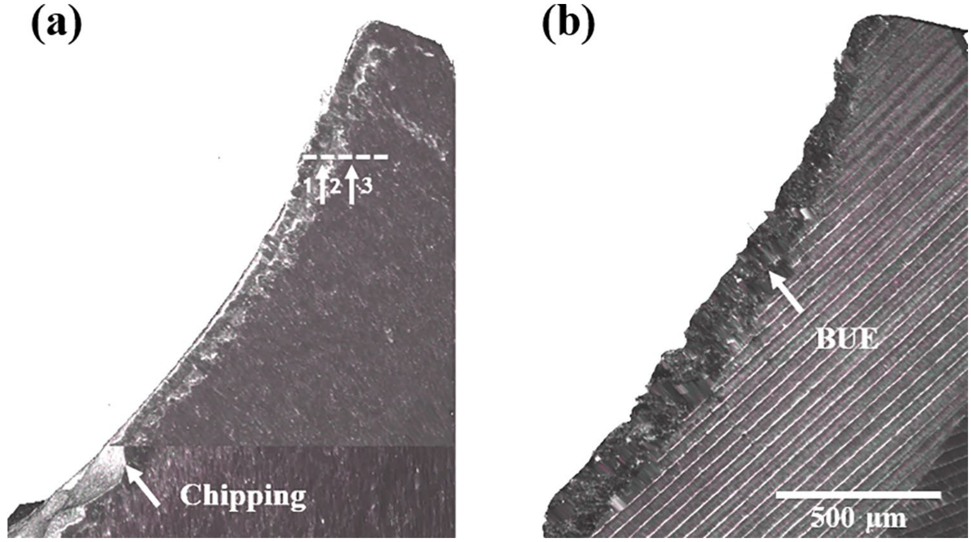

Fig. 9 Worn-out region of cutting edge while drilling **a** IN 718, chipping is shown by an arrow; **b** EN 24, BUE formation is indicated by an arrow, with WC drill bit

Therefore, it is clear that the tool wear starts with partial coating abrasion, later progressing into the flank wear.

The coating layer abrasion suppressed the flank wear of the tool at the initial stage of machining, resulting in improved tool life. Under current operating conditions, TiN and uncoated drill bits did not exhibit any significant adhesion of the workpiece layer (Fig. 11). In contrast, TiAlN coated drill bit indicated the presence of the transferred layer (adhered layer) on the tool surface, which got removed later on during the progress of machining (Figs. 11 and 12). Generally, such an adhered workpiece layer protects the tool surface. At least to a limited extent, by delaying the abrasive action of hard particles present in IN 718, it results in longer tool life [30].

Therefore, in the interest of improved tool life, it is worthwhile to understand the reasons behind the formation of the transfer layer and its net effect on overall tool life. The formation mechanism of the transfer layer over the tool surface is attributed to the high temperatures generated at the cutting zone. Such high temperatures lead to micro-welding of the workpiece over the tool surface. Generally, heat generation at the cutting zone depends on multiple factors of the machining system, such as workpiece, tool material, machining parameters, and cooling media [20]. Low thermal conductivity of workpiece material, cutting speed, and higher friction at the tool-workpiece interface are other major contributing factors towards excessive heat generation. In the present study, the workpiece-tool combination and cooling scheme were maintained identical throughout the experiments. Hence, the only differentiating factor was the coating. The coating application over the tool surface alters the coefficient of friction between interacting surfaces (Fig. 13). Accordingly, the higher friction coefficient between IN 718 and TiN/TiAlN coatings as compared with the uncoated WC substrate indicates more heat generation during the drilling operation, especially in the case of the

Table 4 Elemental composition of 3 zones and BUE, as depicted in Fig. 9a

Zone	Major element (wt%)			Remarks
	Tool	Workpiece	Coating	
	W	Ni	Ti	
BUE	-	57	-	Workpiece
Zone 1	34	36	-	i. Transferred (adhered) layer ii. coating abrasion
Zone 2	-	32	24	i. Transferred (adhered) layer ii. coating
Zone 3	-	-	61	Coating intact

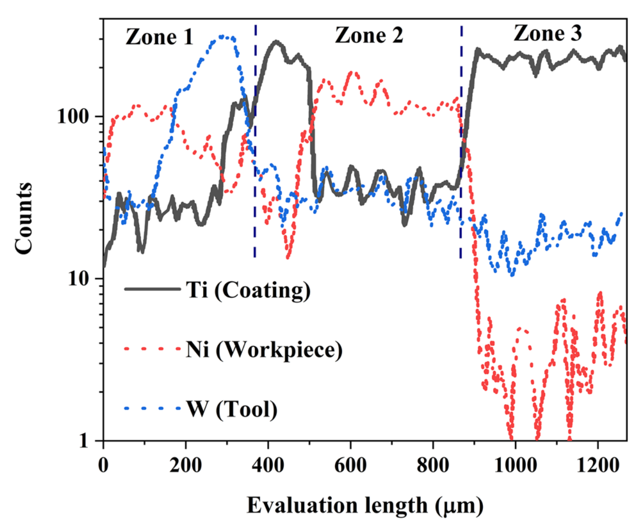

Fig. 10 Variation in concentration (EDS line scan) of major elements along the evaluation length as depicted in Fig. 9a

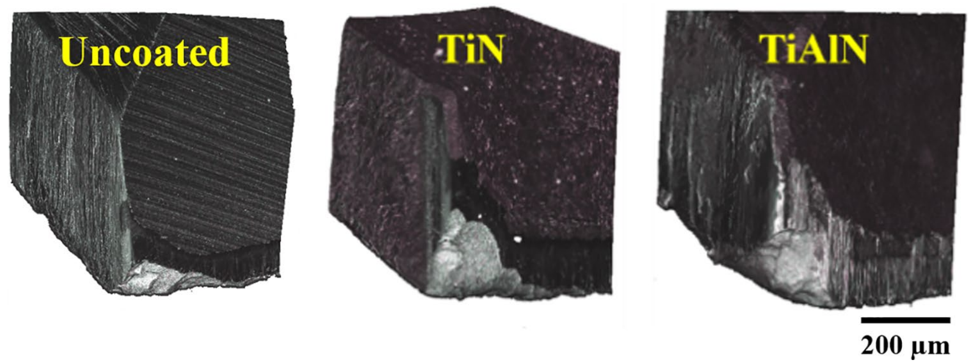

Fig. 11 Corner wear images of uncoated, TiN and TiAlN coated drill bits at the end of tool life

TiAlN coated tool. Though a higher friction coefficient negatively affects the cutting-edge temperature and ease of machining [31], in the present case, higher coating hardness dominantly contributed towards the improved tool life. The superior performance of TiAlN also stems from its ability to form a thermal-resistant passive layer of Al_2O_3 [15]. The low thermal conductivity of TiAlN also helps in altering the heat partition between the tool and chips. Such heat partition leads to more heat dissipation through chips, thereby protecting the cutting-edge underneath from exposure to higher temperatures [27]. At the same time, the possibility of further improvement in tool life by reducing the coefficient of friction between the interacting surfaces may also be explored by resorting to new-generation coatings [5].

3.4 Surface roughness

The surface integrity of a machined surface was assessed in terms of surface roughness as an attribute of surface damage that occurred during machining. Understanding the surface integrity often helps to understand the tool life as well. The poor surface characteristics affect the appearance, reliability, and functional properties of a component. For instance, the presence of tensile residual stresses on the surface affects the fatigue life of a machined component, resulting in its premature failure.

The surface roughness produced after machining is a combination of two factors, namely, the ideal roughness and natural roughness. The ideal roughness is the best possible finish obtained from a particular tool shape under specified machining conditions. On the other hand, natural surface roughness results from the inconsistency of cutting operations such as vibration and tool alignment [18, 25]. In the current work, since cutting parameters were identical for all the experiments, their contribution to the variation in surface roughness can be conveniently ignored. The extent of tool wear or tool chipping influences the tool geometry directly. Therefore, its effect on the final surface roughness of the machined surface is understandable.

Figure 14 shows the variation in Ra values of the drilled hole (middle part) for uncoated, TiN coated, and TiAlN coated drill bits at the end of the respective tool life. As the tool damage is the maximum at the end of tool life, we considered the worst-case scenario of surface roughness (i.e., the surface roughness of the last hole drilled). The roughness values varied between 1.12 and 2.66 µm for an uncoated drill bit, 1.24 and 2.05 µm for TiN coated drill bit, and 0.51 and 2.65 µm for TiAlN coated drill bit.

Table 5 shows the variation in surface roughness at the top, middle, and bottom sections of a hole. The higher values of roughness at the entry of the drill bit are because of the initial tool chatter. The tool chattering is a combined effect of tool chipping and a relative hardness of workpiece material, eventually resulting in a more irregular surface. If we ignore these initial higher Ra values, we observe that the roughness of the last drilled hole reduced in the case of TiN and TiAlN coated drill bits as against the uncoated drill bit. The roughness plots presented in Fig. 15 reveal that the surface

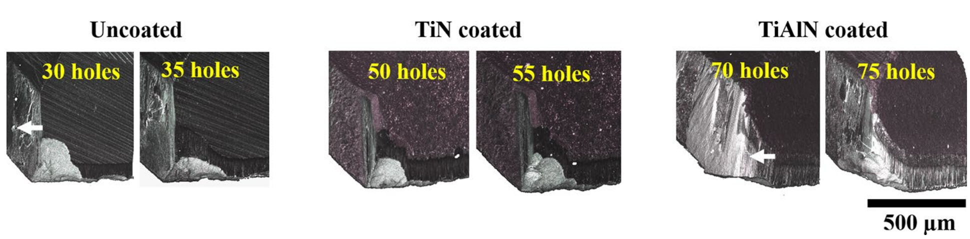

Fig. 12 Optical microscope images of uncoated, TiN coated, and TiAlN coated drill bit margins depicting BUE (transferred/adhered layer) formation and consequent removal. BUE in case of uncoated and TiAlN coated is shown with arrow

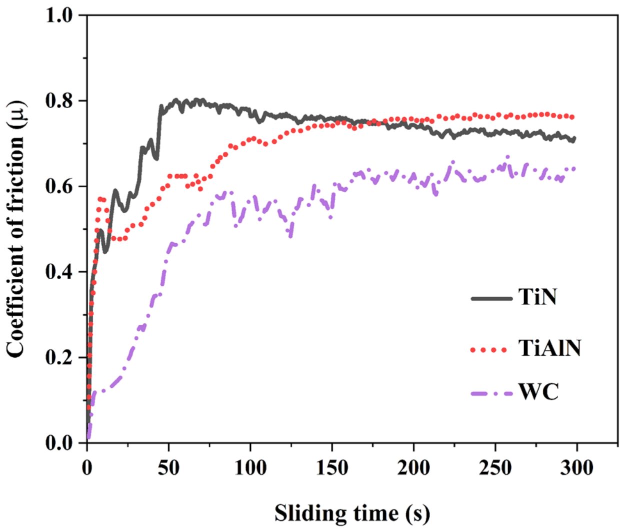

Fig. 13 Coefficient of friction (CoF) between workpiece material (IN 718) and WC, TiN, and TiAlN

Table 5 Ra (μm) values of last hole drilled at the end of respective tool life

Region	Uncoated	TiN coated	TiAlN coated
Top	2.662 ± 0.088	2.047 ± 0.047	2.651 ± 0.034
Middle	2.094 ± 0.016	1.056 ± 0.034	0.838 ± 0.014
Bottom	1.126 ± 0.014	1.239 ± 0.024	0.509 ± 0.015

finish obtained with coated drill bits is significantly better than that obtained with the uncoated drill bit. Though the extent of tool damage and built-up-edge (transferred layer) formation were more in the case of TiN and TiAlN coated drill bits, these drill bits resulted in lower roughness values. The underlying reason can be understood by considering the heat generation during the drilling operation. A higher amount of heat generation during cutting softens workpiece material, facilitating easy chip removal and smoother surface finish [32, 33].

Figure 16 shows the 3D optical images of the middle section of the last machined hole drilled with uncoated, TiN coated, and TiAlN coated drill bit. Accordingly, a relatively smoother surface can be observed in the case of TiAlN coated drill bit, while workpiece deposits are observed over the surface machined with the uncoated drill bit. The reason behind such an observation could be a higher cutting temperature in the case of TiAlN coated bit, as mentioned before. Such an increase in cutting temperature (heat generated) is attributed to a relatively higher friction coefficient between TiAlN and IN 718 (Fig. 13) and the low thermal conductivity of TiAlN coating. Furthermore, the extent of tool damage (chipping) in the case of TiN and TiAlN coated drill bits

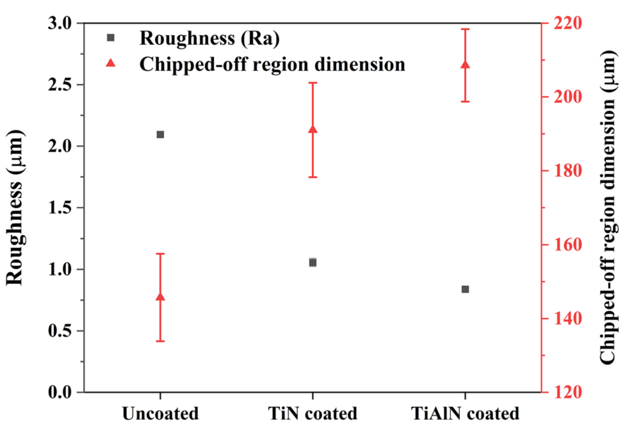

Fig. 14 Ra values of middle section of last hole drilled with uncoated, TiN coated, and TiAlN coated drill bits and dimension of chipped-off region of margin-cutting edge corner of drill bits at the end of respective life

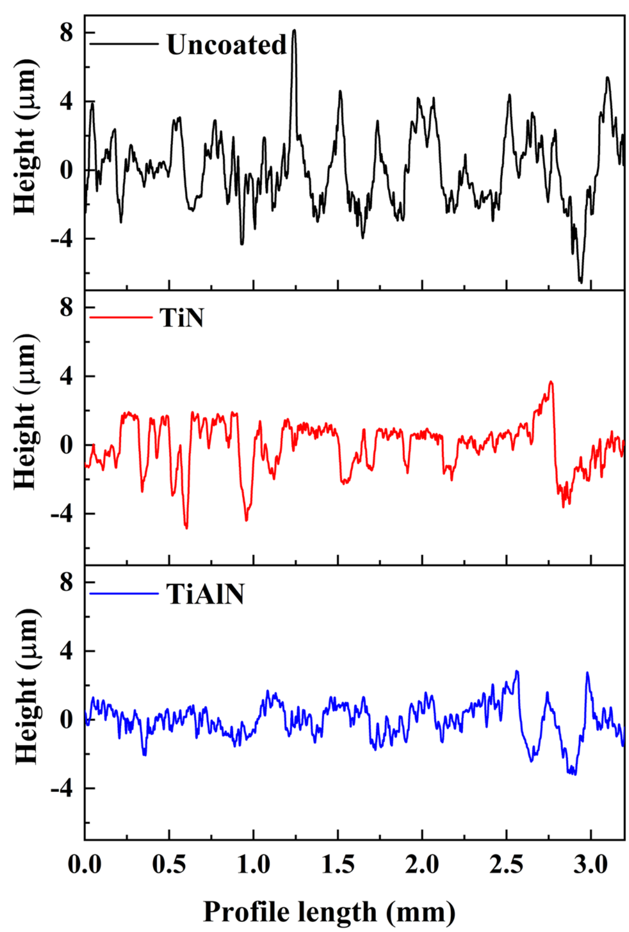

Fig. 15 Roughness plots of last hole drilled with uncoated (Ra = 1.708 μm), TiN (Ra = 1.102 μm) coated, and TiAlN (Ra = 0.809 μm) coated drill bits

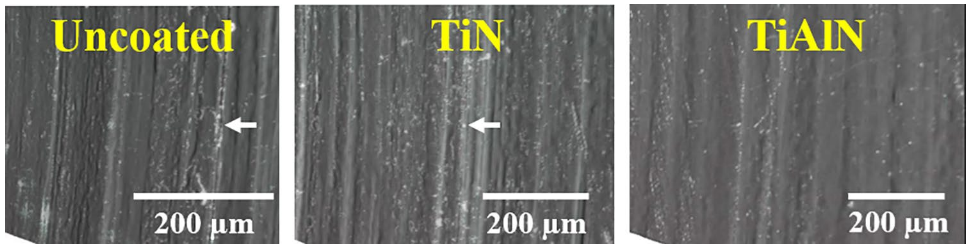

Fig. 16 3D optical images of middle section of last hole (at the end of the life) drilled with uncoated, TiN coated, and TiAlN coated drill bits. Workpiece deposits (uncoated) and severe feed marks (TiN) are indicated by arrow

was more than that observed in the case of uncoated (Fig. 11). Such chipping/tool damage may increase the contact area between the tool and the workpiece, resulting in higher friction and subsequent heat generation, which ultimately facilitates easy chip removal. To verify such an argument, the quantified chipped-off region of the last hole drilled (with uncoated, TiN coated, and TiAlN coated drill bit) and associated roughness values are plotted in Fig. 14. The figure indicates an inverse relationship between surface finish and the extent of tool damage. Figure 17a illustrates the chipped off region of the cutting edge of uncoated, TiN coated, and TiAlN coated drill bits wherein the TiN and TiAlN coated drill bits exhibit more intense chipping as compared to the uncoated drill bit. Further analysis, as shown in Fig. 17b, indicates that in the case of uncoated drill bit, the maximum deviation in the dataset (chipped tool) from the reference (the unused tool) is in the range of 100–140 µm. In contrast, TiN and TiAlN coated drill bits exhibit deviations from 200 to 400 µm and 300 to 500 µm, respectively. Therefore, the combination of Figs. 16 and 17 can provide a platform for understanding

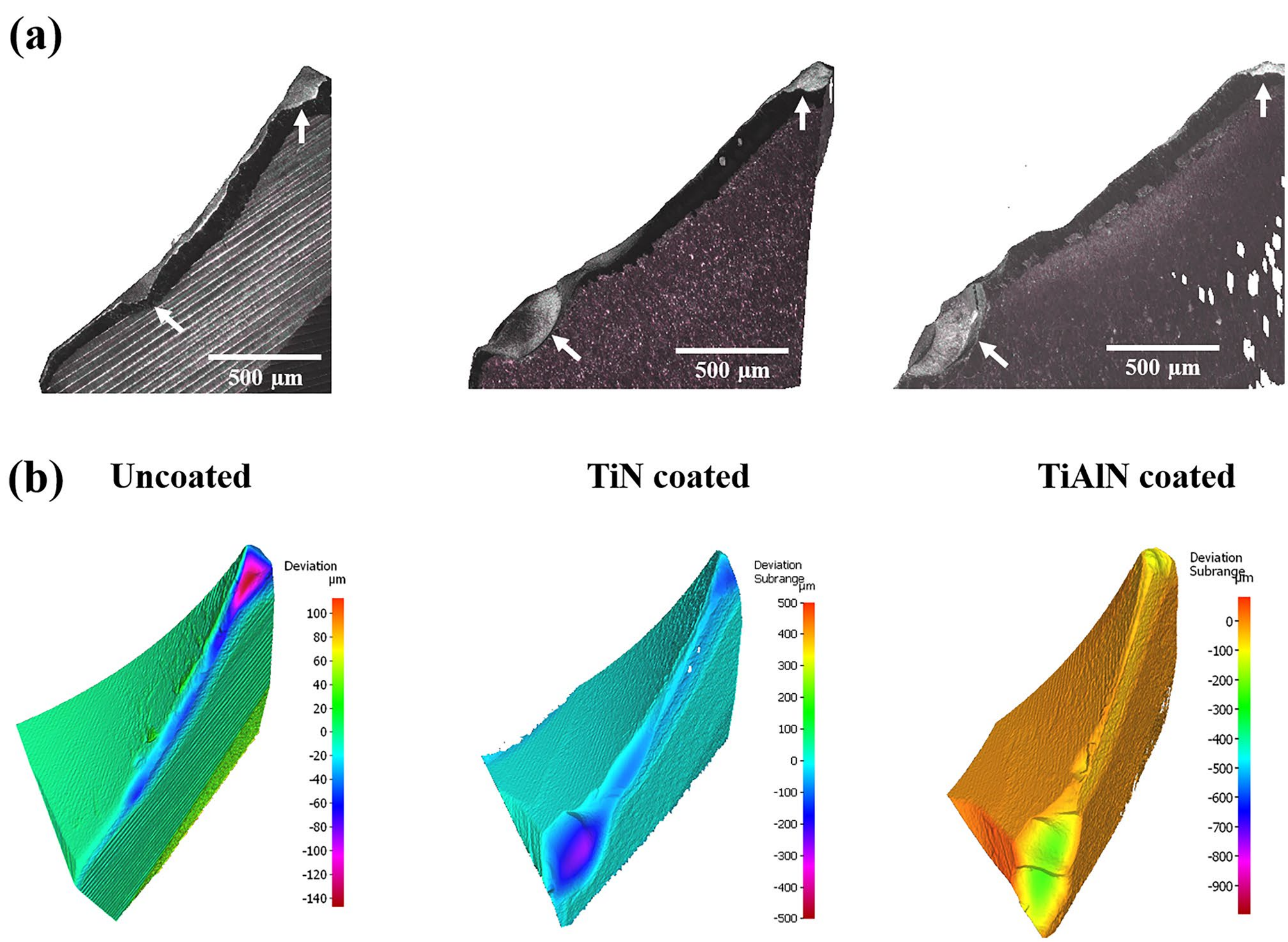

Fig. 17 **a** Cutting-edge chipping at the end of tool life in case of uncoated (left), TiN coated (middle), and TiAlN coated drill bits (chipped off region shown by arrow), **b** dataset deviation of uncoated, TiN coated, and TiAlN coated tools from corresponding reference dataset (uncoated drill bits)

the relationship between the surface roughness and the magnitude of tool damage.

Based on the discussion above, we can consider the tool chipping as a significant factor responsible for understanding the variation in surface roughness of a given drilled hole. Based on the results obtained in the present study, it is clear that protective coatings such as TiN and TiAlN improve the tool life without degrading the surface finish. In reality, coatings have improved the surface finish in the present case.

4 Conclusions

The present work assesses the real-time performance of TiN coated and TiAlN coated WC drill bits while machining (wet condition) difficult-to-cut IN 718. The main findings of the investigation are as follows:

- The TiAlN and TiN coated drill bits performed 2 times and 1.6 times better than an uncoated drill bit, respectively. The in-house TiAlN coated drill bit also outperformed the commercially available TiAlN coated drill bit by giving an extra 50% life.
- Dominant failure modes observed in all cases were corner (margin and cutting-edge) chipping, cutting edge chipping, and flank wear.
- The coated drill bits wore in 3 stages – abrasion of the coating layer, chipping (at the corner, cutting edge), and flank wear. Under the machining conditions employed in the present study, the predominant wear mechanisms were abrasive and adhesive. While we observed abrasive wear in all cases (uncoated, TiN coated, and TiAlN coated drill bits), adhesive wear was more dominant in TiAlN coated drill bit. Such phenomenon can be attributed to a higher amount of heat generation, caused by a higher friction coefficient between IN 718 and TiAlN and the low thermal conductivity of TiAlN coating.
- The surface roughness of machined holes varied along the depth of the drilled hole. In all cases – uncoated, TiN coated, and TiAlN coated drill bits – roughness at the top region of the hole was higher than the middle and bottom region. The reason behind such observation is the initial chattering of the tool at the start of the drilling operation. TiAlN coated drill bit resulted in minimum roughness against uncoated and TiN coated drill bits at the end of respective tool life.

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Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

References

1. Ezugwu EO, Wang ZM, Machado AR (1998) The machinability of nickel-based alloys: a review. J Mater Process Technol 86:1–16. https://doi.org/10.1016/S0924-0136(98)00314-8
2. Dudzinski D, Devillez A, Moufki A, Larrouquère D, Zerrouki V, Vigneau J (2004) A review of developments towards dry and high speed machining of Inconel 718 alloy. Int J Mach Tools Manuf 44:439–456. https://doi.org/10.1016/S0890-6955(03)00159-7
3. Chen YC, Liao YS (2003) Study on wear mechanisms in drilling of Inconel 718 superalloy. J Mater Process Technol 140:269–273. https://doi.org/10.1016/S0924-0136(03)00792-1
4. Sharman ARC, Amarasinghe A, Ridgway K (2008) Tool life and surface integrity aspects when drilling and hole making in Inconel 718. J Mater Process Technol 200:424–432. https://doi.org/10.1016/j.jmatprotec.2007.08.080
5. Khanna N, Agrawal C, Gupta MK, Song Q (2020) Tool wear and hole quality evaluation in cryogenic Drilling of Inconel 718 superalloy. Tribol Int 143:106084. https://doi.org/10.1016/j.triboint.2019.106084
6. Uçak N, Çiçek A (2018) The effects of cutting conditions on cutting temperature and hole quality in drilling of Inconel 718 using solid carbide drills. J Manuf Process 31:662–673. https://doi.org/10.1016/j.jmapro.2018.01.003
7. Akhtar W, Sun J, Sun P, Chen W, Saleem Z (2014) Tool wear mechanisms in the machining of Nickel based super-alloys: a review. Front Mech Eng 9:106–119. https://doi.org/10.1007/s11465-014-0301-2
8. Arunachalam RM, Mannan MA, Spowage AC (2004) Surface integrity when machining age hardened Inconel 718 with coated carbide cutting tools. Int J Mach Tools Manuf 44:1481–1491. https://doi.org/10.1016/j.ijmachtools.2004.05.005
9. Boothroyd G, Knight W (2005) Fundamentals of Machining and Machine Tools. CRC Press, Boca Roton
10. Finkeldei D, Sexauer M, Bleicher F (2019) End milling of inconel 718 using solid Si_3N_4 ceramic cutting tools. Procedia CIRP 81:1131–1135. https://doi.org/10.1016/j.procir.2019.03.280
11. Altin A, Nalbant M, Taskesen A (2007) The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools. Mater Des 28:2518–2522. https://doi.org/10.1016/j.matdes.2006.09.004
12. Tanaka H, Sugihara T, Enomoto T (2016) High speed machining of Inconel 718 focusing on wear behaviors of PCBN cutting tool. Procedia CIRP 46:545–548. https://doi.org/10.1016/j.procir.2016.03.120
13. Khan SA, Soo SL, Aspinwall DK, Sage C, Harden P, Fleming M et al (2012) Tool wear / life evaluation when finish turning Inconel 718 using PCBN tooling. Procedia CIRP 1:283–288
14. Halim NHA, Haron CHC, Ghani JA, Azhar MF (2019) Tool wear and chip morphology in high-speed milling of hardened

Inconel 718 under dry and cryogenic CO_2 conditions. Wear 426–427:1683–1690. https://doi.org/10.1016/j.wear.2019.01.095

15. Jindal PC, Santhanam AT, Schleinkofer U, Shuster AF (1999) Performance of PVD TiN, TiCN, and TiAlN coated cemented carbide tools in turning. Int J Refract Met Hard Mater 17:163–170. https://doi.org/10.1016/S0263-4368(99)00008-6
16. Jawaid A, Koksal S, Sharif S (2001) Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy. J Mater Process Technol 116:2–9. https://doi.org/10.1016/S0924-0136(01)00850-0
17. Leyendecker T, Lemmer O, Esser S, Ebberink J (1991) The development of the PVD coating TiAlN as a commercial coating for cutting tools. Surf Coatings Technol 48:175–178. https://doi.org/10.1016/0257-8972(91)90142-J
18. Ramanujam R, Vignesh M, Tamiloli N, Sharma N, Srivastava S et al (2018) Comparative evaluation of performances of TiAlN, AlCrN, TiAlN/AlCrN coated carbide cutting tools and uncoated carbide cutting tools on turning Inconel 825 alloy using Grey Relational Analysis. Sensors Actuators A Phys 279:331–342. https://doi.org/10.1016/j.sna.2018.06.041
19. Bhatt A, Attia H, Vargas R, Thomson V (2010) Tribology International Wear mechanisms of WC coated and uncoated tools in finish turning of Inconel 718. Tribiology Int 43:1113–1121. https://doi.org/10.1016/j.triboint.2009.12.053
20. ASM International (1989) ASM Handbook: Machining, vol. 16. ASM International, Metals Park, pp 1089–1120
21. Chen HW, Chan YC, Lee JW, Duh JG (2010) Oxidation behavior of Si-doped nanocomposite CrAlSiN coatings. Surf Coatings Technol 205:1189–1194. https://doi.org/10.1016/j.surfcoat.2010.08.156
22. Uhlmann E, Fuentes JAO, Gerstenberger R, Frank H (2013) Surface & Coatings Technology nc-AlTiN/a-Si_3N_4 and nc-AlCrN/a-Si_3N_4 nanocomposite coatings as protection layer for PCBN tools in hard machining. Surf Coat Technol 237:142–148. https://doi.org/10.1016/j.surfcoat.2013.09.017
23. Prengel HG, Jindal PC, Wendt KH, Santhanam AT, Hegde PL, Penich RM (2001) A new class of high performance PVD coatings for carbide cutting tools. Surf Coatings Technol 139:25–34. https://doi.org/10.1016/S0257-8972(00)01080-X
24. Ducros C, Benevent V, Sanchette F (2003) Deposition, characterization and machining performance of multilayer PVD coatings on cemented carbide cutting tools. Surf Coatings Technol 163–164:681–688. https://doi.org/10.1016/S0257-8972(02)00656-4
25. Puneet PC, Valleti K, Venu GA (2017) Influence of surface preparation on the tool life of cathodic arc PVD coated twist drills. J Manuf Process 27:233–240. https://doi.org/10.1016/j.jmapro.2017.05.011
26. Yamamoto K, Sato T, Takahara K, Hanaguri K (2003) Properties of (Ti, Cr, Al) N coatings with high Al content deposited by new plasma enhanced arc-cathode. Surf Coat Technol 175:620–626. https://doi.org/10.1016/S0257-8972
27. Chen L (2007) Mechanical properties of (Ti, Al) N monolayer and TiN /(Ti, Al) N multilayer coatings. Int J Refract Met Hard Mater 25:72–76. https://doi.org/10.1016/j.ijrmhm.2006.01.005
28. Iyer R, Koshy PÃ, Ng E (2007) Helical milling : an enabling technology for hard machining precision holes in AISI D2 tool steel. Int J Mach Tools Manuf 47:205–210. https://doi.org/10.1016/j.ijmachtools.2006.04.006
29. Diniz AE, Machado ÁR, Corrêa JG (2016) Tool wear mechanisms in the machining of steels and stainless steels. Int J Adv Manuf Technol 87:3157–3168. https://doi.org/10.1007/s00170-016-8704-3
30. Xue C, Chen W (2011) Adhering layer formation and its effect on the wear of coated carbide tools during turning of a nickel-based alloy. Wear 270:895–902. https://doi.org/10.1016/j.wear.2011.02.018
31. Puneet C, Valleti K, Venu Gopal A, Joshi SV (2018) CrAlSiN nanocomposite thin films for high-speed machining applications. Mater Manuf Process 33:371–377. https://doi.org/10.1080/10426914.2017.1303157
32. Arunachalam RM, Mannan MA, Spowage AC (2004) Residual stress and surface roughness when facing age hardened Inconel 718 with CBN and ceramic cutting tools. Int J Mach Tools Manuf 44:879–887. https://doi.org/10.1016/j.ijmachtools.2004.02.016
33. Addona DMD, Raykar SJ, Narke MM (2017) High speed machining of Inconel 718: tool wear and surface roughness analysis. Procedia CIRP 62:269–274. https://doi.org/10.1016/j.procir.2017.03.004

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