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An experimental investigation on the machining characteristics of Nimonic 75 using uncoated and TiAlN coated tungsten carbide micro-end mills

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ABSTRACT

We report the machining characteristics and machinability of a nickel based superalloy in this study. A micro-milling operation is loaded on Nimonic 75 using uncoated and TiAlN coated tungsten carbide micro-end mills. A full factorial design of experiments was devised to optimize the machining conditions to reduce the flank wear on the tool surface. The optimized machining conditions for uncoated micro-tools were found to be a cutting speed (v_c) of 13 m/min and a feed rate (f_z) of 6 mm/min. Following this, the tools were coated with TiAlN using a semi-industrial four-cathode reactive pulsed direct current unbalanced magnetron sputtering system. Further experiments were then performed using these optimized machining conditions using both uncoated and TiAlN coated micro-tools in order to ascertain the tool wear and surface integrity. The change in geometry of the machined slot was estimated based on the variation in tool radius of the micro-end mill with progression of the operation. A direct comparison was made between the results observed using both uncoated and TiAlN coated tungsten carbide to illustrate the effect of the nanocomposite TiAlN coating. It was seen that TiAlN coated micro-tools exhibited a superior performance as compared to the uncoated ones with respect to tool life and micro-burr formation.

Introduction

The recent advances in the manufacturing sector have necessitated the miniaturization of machine tools. Working with these miniaturized tools often results in low power consumption, high productivity rate and smaller sizes of work stations [1]. Due to these inherent advantages, micro-machining techniques such as micro-drilling, micro-milling, etc. have captured the attention of the scientific and industrial community. A particular application of these techniques is seen in the micro-cutting of 'difficult-to-machine' materials, which are widely employed in aerospace, automotive, medical and nuclear industries [1–3]. Commonly used nickel-based superalloys such as Inconel, Nimonic, Rene, etc. fall into this category. These superalloys find exclusive usage in the turbine and combustor sections of aircraft engines due to their ability to exhibit high fracture strength, phase stability, increased resistance to wear and creep, etc. at elevated temperatures. However, on the contrary, poor thermal and mechanical properties of these superalloys limit their machinability, thus categorizing them as 'hard-to-cut' materials. Chief among these undesirable properties is the presence of high percentages of abrasive carbides, leading to accelerated wear on the tool surface [4,5]. It is also seen that these materials evince a phenomenon known as the 'work-hardening effect', thus leading to high cutting forces and formation of burrs. Apart from this, it is observed that these superalloys adhere to the surface of the tool material, thus leading to galling and welding of the chip material on the workpiece. These characteristics cause low rates of material removal in the workpiece and high tool wear which subsequently lead to higher machining costs [6–8].

Micro-machining of these superalloys have been effectuated using both conventional and non-conventional machining techniques. Non-conventional techniques such as micro-electrical discharge machining (micro-EDM) and laser machining are mostly

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used to produce effusion cooling holes in the guide vanes of nozzles and turbine blades. However, both these techniques suffer from a few limitations which have propelled researchers to look at a few other methods. It has been reported that micro-EDM leads to high drilling costs at very low drilling speeds apart from disturbing material properties in the heat affected zone [9]. A severe damage to the back wall was observed when a laser technique was used to sculpt airfoil blades and fuel injector nozzles [10]. The aforementioned limitations have prompted the use of conventional machining techniques for drilling micro-holes or slotting micro-grooves in these superalloys. The use of a conventional technique results in deeper holes with better straightness and roundness [10,11]. Apart from being independent of material properties, this technique also produces micro-holes and micro-slots with smoother surfaces. However, even these techniques suffer from a few drawbacks such as tool fracture caused by low rigidity of the micro-tool, higher tool wear on the flank surface, tool run out, etc. [12,13].

One particular way to overcome this difficulty is by using a hard material (such as cemented carbide) and depositing nanocomposite coatings such as TiN, TiAlN, TiAlSiN, etc. on its surface [14–16]. Carbide micro-tools have been perennially used in the micro-cutting of these superalloys due to their high fracture toughness and resistance to thermal shock. Among the above mentioned coatings, it is revealed that depositing a nanocomposite coating of TiAlN leads to higher process efficiencies due to its higher oxidation resistance, hardness, and resistance to corrosion. In addition to this, it is possible to operate with higher cutting speeds when using micro-tools coated with TiAlN as compared to their uncoated counterparts due to the low thermal conductivity of TiAlN [17–19].

A quick survey of the literature indicates that micro-milling has largely been performed on Inconel 718 superalloy. Ucun et al. [17] investigated the influence of various coatings on tool wear in the micro-milling of Inconel 718 nickel superalloy. In another experiment, Ucun et al. [20] varied the operating parameters and reported their influence on surface roughness in the micro-end milling of Inconel 718. Kuram and Ozcelik [21] employed a design of experiments (DOE) strategy and set up a Taguchi L_9 orthogonal array to report the influence of spindle speed, feed rate and depth-of-cut on cutting forces and surface roughness in the micro-milling of Inconel 718. Ucun et al. [22] articulated on the machining characteristics of Inconel 718 superalloy using uncoated and DLC coated ultra-fine carbide micro-mills. It was seen that the use of a DLC coating significantly increased the surface finish and reduced the tool wear of the carbide micro-mills.

Nimonic, on the other hand has not captured the attention of researchers as compared to Inconel 718. The literature indicates that there are no reports on the machining characteristics of Nimonic superalloys using uncoated and coated micro-tools. In order to bridge this gap, we have attempted a micro-milling operation on Nimonic 75 using uncoated and TiAlN-coated tungsten carbide micro-end mills under wet machining conditions. A nanocomposite TiAlN coating was deposited on tungsten carbide micro-end mills using a four-cathode reactive pulsed direct current unbalanced magnetron sputtering system. The performance of the uncoated and the TiAlN coated tungsten carbide micro-end mills was then ascertained by employing a full factorial experiment with cutting speed and feed rate as the control variables. The effects of these parameters on tool wear, burr formation, slot geometry and surface roughness were noted. Machining conditions which led to a high surface finish and productivity rate were identified and classified as optimum machining parameters. Further tests were performed with these optimized parameters using both uncoated and TiAlN coated micro-tools to determine the wear behaviour, surface integrity and flank wear. The results obtained from these experiments were then analyzed and elucidated to discern the effect of the TiAlN coating on the above mentioned output parameters.

Experimental procedure and test conditions

Experimental details

Micro-end milling tests were carried out on a homogenous Nimonic 75 rectangular block of dimensions 100 mm × 30 mm × 3 mm. The nominal composition of the alloy is given in Table 1. On analysing its microstructure, it was found that the alloy consisted of a large number of HCP particles of M_7C_3 at the grain boundaries and a FCC solid-solution matrix of aluminium and titanium in the form of grain boundaries. The hardness of this workpiece was measured as 40–41 HRC.

The experiments were performed using a sub-micron grade tungsten carbide micro-end mill (SGS Solid Carbide Tools) having 10% wt. cobalt. The geometrical features of the micro-end mill are shown in Table 2. The grain size of the end-mill was measured and found to be between 500–900 nm. Experimental tests were carried out using a CNC 3-axes vertical machining centre (VICTOR TAICHUNG) characterized by a maximum spindle speed of 50,000 RPM and a spindle power of 9 kW. The tool run-out was measured after mounting the tool on the machine spindle using a Digital Dial Test Indicator (MITUTOYO) and found to be 1 μm. A spindle speed (*N*) of 5175 RPM was used in this study. A water soluble semi-synthetic oil (TASHCUT, S40), was mixed with water in a 1:20 ratio and used as the coolant with a set flow rate of 1.67 l/min.

Tool cleaning

Prior to the deposition of the TiAlN coating, the high speed micro-end mills were cleaned in an ultrasonic agitator using commercial cleaning solutions to remove contaminants and adhered particulates. A mixture consisting of 3% Rodaweg solution and 97% distilled water was used for this cleaning purpose. This was followed by rinsing the micro-mills in distilled water for 1 min. Ensuing this, a 1% Galvex solution mixed with 99% distilled water was used for further cleaning by placing the tool in an ultrasonic agitator for around 3–4 min. The aforesaid step was followed by rinsing the micro-tools in distilled water for a span of 1 min before placing them in an ultrasonic bath filled with distilled water for 2 min. Finally, the micro-end mills were dried with dry

Table 1
Composition of Nimonic 75 superalloy (% wt).

Elements	Cr	Al	Ti	Fe	Si	Ni
W%	18.0	1.0	1.0	3.0	1.0	76.0

Table 2
Geometrical properties of the cutting tool used during cutting tests.

Parameters	Values
Tool	Micro-end mill
Cutting diameter	0.79 mm
No of flutes	2 flute (square end)
Length of cut	1.20 mm
Helix angle	30°
Rake angle	Positive
Overall length	38 mm
Shank diameter	3.17 mm
Edge radius	5 μm
Tolerance	+0.00/−0.01 mm

nitrogen before placing them in the vacuum chamber for the deposition of nanocomposite TiAlN coatings.

Characterization of TiAlN coatings

Nanostructured TiAlN coatings were deposited on the surface of the micro-end mill using a semi-industrial four cathode reactive direct current unbalanced magnetron sputtering system. The details of the sputtering technique are described elsewhere in the literature [18]. The thickness of the coating was measured using a Field Emission Scanning Electron Microscope (FESEM, SUPRA 40 VP, CARL ZEISS) and found to be 2 μm. The cutting edge radius of the micro-tool after TiAlN coating was found to be 5 μm. In order to ascertain the hardness of the nanolayered multi-layered TiAlN coating, hardness measurements were performed in a nanoindenter (CSM Instruments, load range 0.5–300 mN) at a load of 10 mN using a Berkovich diamond indenter. Ten indentations were made on each sample and the values reported herein represent the average of the ten values. Further details on the nanoindentation measurements are expounded in a different article [18]. The surfaces of these coatings were then characterized using an atomic force microscope (AFM, BRUKER, SPMS Nanosystem) in non-contact mode with a tip radius of 15 nm, in order to ascertain the surface roughness. The results revealed that tungsten carbide coated with TiAlN showed a surface roughness of 13 nm as compared to its uncoated counterpart which showed a surface roughness of 9 nm.

Machining parameters and experimental design

Owing to the limited research in micro-machining of Nimonic 75, preliminary experiments were conducted to optimize the cutting speed and feed rate, since it is well established that these are the most significant parameters affecting machining characteristics. In this regard, a full factorial design of experiments was performed by varying the cutting speed and feed rate according to industrial standards. The control variables for this experiment along with their respective values are shown in Table 3a. The depth-of-cut per pass in each run was kept constant at 120 μm and grooves were slotted for a machining length of 100 mm using uncoated tungsten carbide micro-end mills. Fig. 1(a) shows the schematic diagram of a sample run of the experiment performed and a schematic illustration is shown in Fig. 1(b). The parameters of the run at which the lowest tool wear was observed were labelled as optimized machining parameters. The optimized machining parameters for this experiment were found to be a cutting speed of 13 m/min and a feed rate of 6 mm/min. The tools were then coated with TiAlN and used along with uncoated tools to slot grooves for machining lengths of 30, 150 and 300 mm using these optimized parameters. These coated tools were then observed under a FESEM in order to ascertain the influence of operating parameters and cutting length on tool wear. The percentage decrease in tool diameter was determined by observing the changes in the slot geometry using FESEM. In addition to this, the influence of operating conditions on surface roughness at different machining lengths were determined using a 3D surface profilometer (NANOMAP 500 LS AEP TECH) in contact mode with a stylus tip radius of 100 nm. Finally, the formation of micro-burrs and burr height at different machining lengths was measured using FESEM and analyzed.

Results and discussion

The load vs. displacement curve was measured for a standard tungsten carbide and TiAlN coated tungsten carbide sample and the curves obtained from these tests are shown in Fig. 2(a).

Table 3a
Various factor levels for optimization in micro-milling process.

Symbol	Control factor	Level – 1	Level – 2	Level – 3	Level – 4
A	Cutting speed (m/min)	11.0	13.0	15.0	18.0
B	Feed (mm/min)	6.0	8.0	10.0	–
C	Test material	Nimonic alloy 75			
D	Tool type	Uncoated WC			
E	Machined length (mm)	100			
F	Coolant	Water soluble oil			
G	End mill size (μm)	790			
H	Depth of cut (μm)	120			

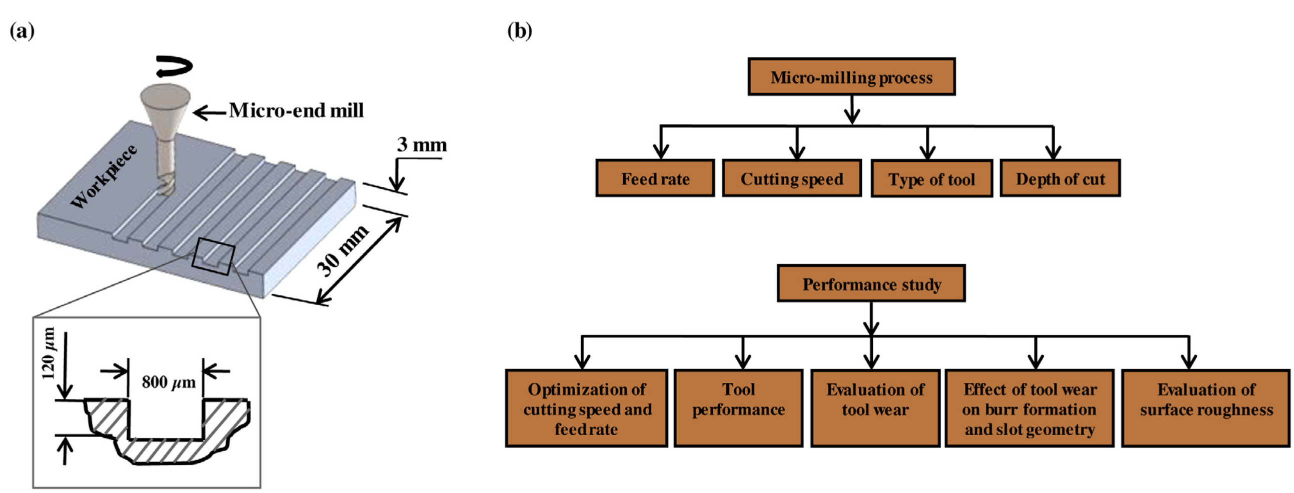

Fig. 1. (a) Schematic illustration and (b) layout of the micro-milling process.

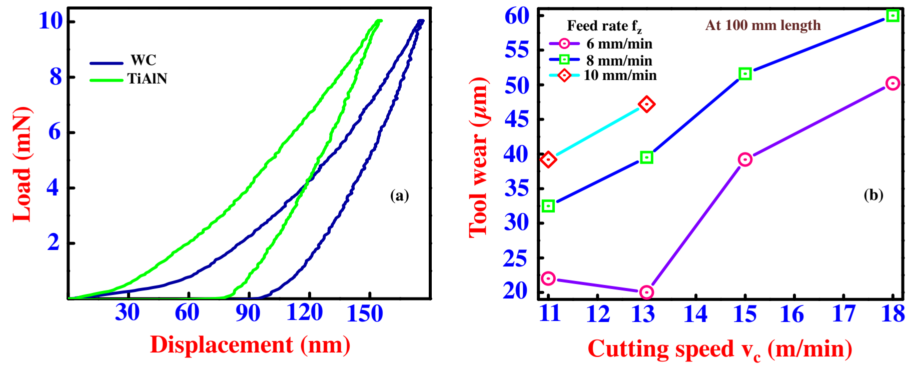

Fig. 2. (a) Load vs. displacement graphs for uncoated and TiAlN coated WC micro-end mill. (b) Variation in tool wear with different cutting speeds and feed rates.

Table 3b
Design of experiments with different levels of cutting speeds and feed rates.

Test results				
Exp. no.	Cutting speed (A) (m/min)	Feed rate (B) (mm/min)	Feed per tooth (mm/rev)	Tool flank wear (μm)
1	11	6	0.00137	22.0
2	13	8	0.00154	39.5
3	15	10	0.00167	Tool breaks
4	18	6	0.00083	50.2
5	11	8	0.00183	32.5
6	13	10	0.00193	47.2
7	15	6	0.00100	39.2
8	18	8	0.00116	60
9	11	10	0.00228	39.2
10	**13**	**6**	**0.00115**	**20.0**
11	15	8	0.00133	51.6
12	18	10	0.00139	Tool breaks

The load was increased at a steady rate to the maximum value (10 mN) and then decreased at the same rate back to zero. The hardness was then calculated from the Oliver-Pharr relation:

$$H = \frac{P_{max}}{A}$$

where P_{max} is the peak indentation load and A is the contact area. It was found that TiAlN coated tungsten carbide exhibited a hardness of ~38 GPa while the hardness of uncoated tungsten carbide was measured to be ~24 GPa.

Optimization of machining parameters

Due to the poor machinability of nickel based superalloys that arise from their work hardening effect, it becomes imperative to operate at machining conditions which lead to an extended tool life. In order to achieve this purpose, a full factorial design of experiments was conducted with the objective of reducing the flank wear observed on the tool surface. The results of the flank wear for each run are tabulated in Table 3b and the variations at different cutting speeds and feed rates for a constant machining length of 100 mm using uncoated tungsten carbide are plotted in Fig. 2(b). It may be noted that for each run, three experimental trials were conducted and the values reported herein represent the average of the three trials. The value for each trial was between 7% and 12% of the reported value. High wear on the flank surface could be inferred at high values of cutting speed as compared to high feed rates. Thus, it can be hypothesized that the cutting parameter plays a major influence in determining flank wear. It was also noticed that the uncoated tungsten carbide micro-end mill wears away rapidly at very high values of cutting speeds and feed rates. This can be ascribed to the poor thermal conductivity of Nimonic 75 which results in temperature gradient and pressure closer to the interface separating the workpiece and cutting tool. Additionally, poor surface finish was obtained when operating at low values of cutting speed and feed rate [23,24]. It was also observed that machining at higher cutting speeds (ν_c = 15 m/min and 18 m/min) and feed rates (f_z = 8 mm/min and 10 mm/min) leads to accelerated tool wear and finally tool breakage. Thus, from the above experiments, it was concluded that tool wear on the flank surface could be minimized when operating at a cutting speed of 13 m/min and a feed rate of 6 mm/min. These optimized cutting parameters were hence recommended to further slot grooves for machining lengths of 30, 150 and 300 mm using both uncoated and TiAlN coated micro-mills.

Performance evaluation of uncoated and TiAlN coated WC micro-end mills

Slots of 30, 150 and 300 mm were machined using coated and uncoated tools at an optimized cutting speed of 13 m/min and feed rate of 6 mm/min. The experiments revealed a steady increase in the tool wear of uncoated micro-tools up to a machining length of 300 mm. The FESEM images captured for both uncoated and TiAlN coated micro-tools after machining a length of 300 mm are depicted in Fig. 3(a) and (b), respectively. It was observed that the cutting edge of the uncoated tool started exhibiting rapid wear upon machining a length of 150 mm. Additionally, the sharpness of the tool started to decrease, perhaps due to the intense workload which increases the temperature at the tool-workpiece interface as discerned from Fig. 3(a) [25–27]. On the other hand, TiAlN coated micro-end mills showed appreciable resistance to wear even after machining a length of 300 mm. The tip of the tool remained unaffected and there was no significant change in its radius. The cutting edge radius for the uncoated tool as shown in Fig. 3(a) was measured as R_1: 21 μm and R_2: 19 μm while that for a TiAlN coated tool was found to be R_3: 9 μm and R_4: 11 μm.

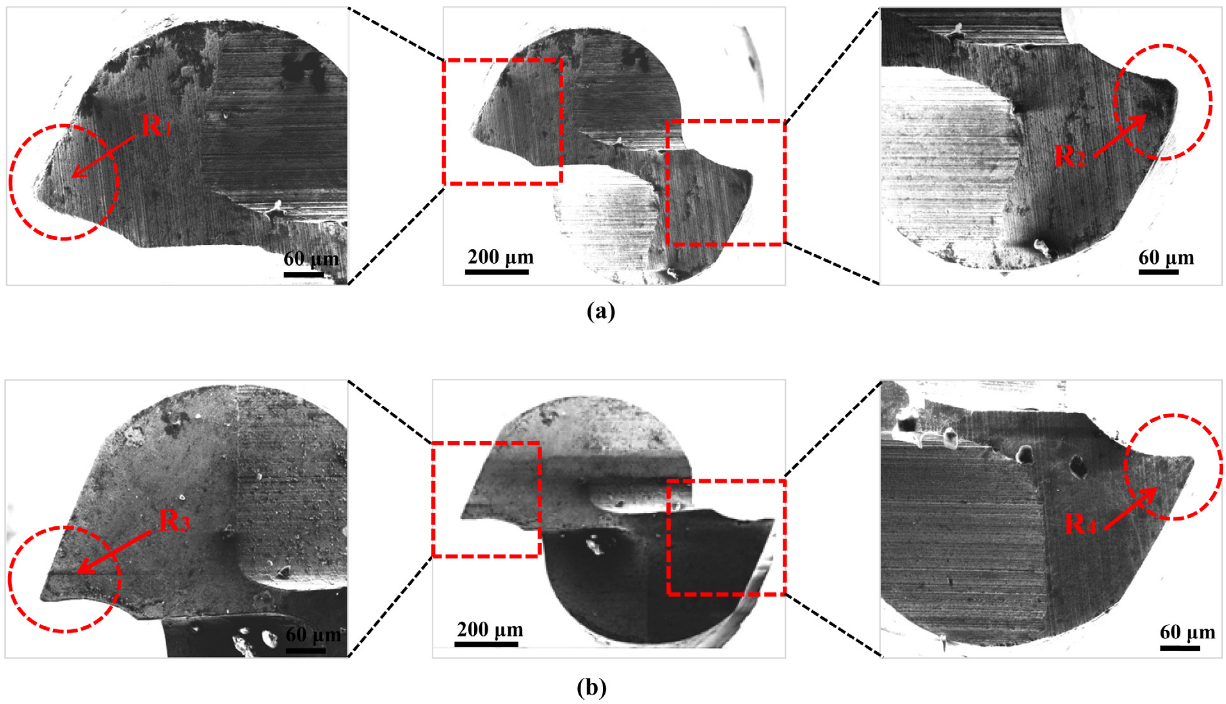

Fig. 3. Performance evaluation of: (a) uncoated and (b) TiAlN coated WC micro-end mill after slotting a length of 300 mm.

Evaluation of tool wear

Fig. 4 illustrates the growth of tool wear with machining length for both TiAlN coated and uncoated micro-tools. It can be postulated from Fig. 4 that the stresses occurring over the coated micro-end mill is much less than that over the uncoated micro-end mill. The wear on the uncoated micro-tool was found to be greater than that of the TiAlN coated micro-tool by a factor of 1.97 and 1.67 at the end of 150 mm and 300 mm length of cut respectively. This can be attributed to the high hardness of the nanocomposite TiAlN coating along with the formation of a micro-thin oxide layer of Al_2O_3 as a result of the reaction between the TiAlN and the oxygen in the surrounding. The Al_2O_3 layer provides thermal insulation to the cutting tool which protects the tool from wearing out, thus extending its tool life. Apart from this, the TiAlN coating also increases the wear resistance of the cutting edge [6,18,27–29]. Due to an increase in tool wear, the tool radius increased from 5 μm to 11 μm for the TiAlN coated micro-tool and 5 μm to 21 μm for the uncoated micro-tool for 300 mm length of cut. The defects observed on a micro-end mill at the end of the machining operation are shown in Fig. 5(a) and (b). Significant edge chipping and rounding of the tool tip were observed in case of uncoated tools as compared to coated ones. This is due to the high work load on the tool tip which subsequently generates heat during machining. As a consequence, the workpiece material melts and adheres to the micro-tool, thus damaging the tool edge and affecting the overall quality of the tool tip [30–32]. In case of TiAlN coated micro-tools, mild abrasion of the coating at the cutting edges and minor delamination of the coating is observed after machining a length of 300 mm, as shown in Fig. 5(b). However, these coated tools were still found to be suitable for further machining. The poor thermal conductivity of the workpiece material results in a high temperature closer to the interface separating the tool and the workpiece. The higher wear on uncoated micro-tools was a direct outcome of this fact. A better surface finish was produced when operating with coated micro-tools since the protective layer reduces the heat and the friction produced during micro-milling [33,34].

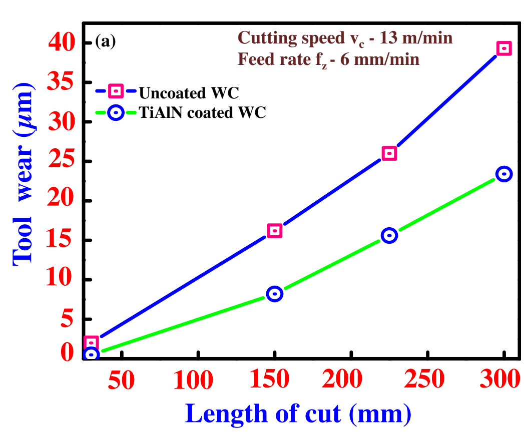

Fig. 4. Growth of tool wear with machining length for both TiAlN coated and uncoated tools.

Analysis of burr formation and slot geometry

Fig. 6(a)–(d) show the FESEM images of the slots at a cutting length of 30 mm and 300 mm using uncoated and TiAlN coated micro-tools. It can be clearly seen that a large top burr is present when using uncoated micro-tools as compared to TiAlN coated micro-tools. As the machining length increases from 30 mm to 300 mm, a severely damaged cutting zone was obtained while using uncoated micro-tool (Fig. 6(b)). However, the formation of burrs was found to be less when machined using a TiAlN coated micro-tool for the same machining length (Fig. 6(d)). This is a direct outcome of the increase in tool wear with cutting length for a machining operation. Fig. 6(e) shows a significant improvement in the size of burr height when a TiAlN coated micro-tool is used as compared to the uncoated tool. In addition, burr size increases with cutting length which is attributed to the increase in cutting edge radius. It can also be deduced that burr height shows an approximate linear variation with machining length in case of uncoated micro-tools [35,36].

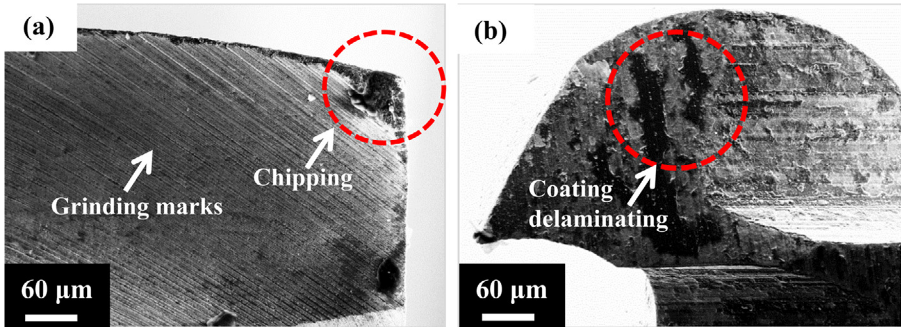

Fig. 5. Various defects formed on: (a) uncoated and (b) TiAlN coated micro-end mill after machining a length of 300 mm.

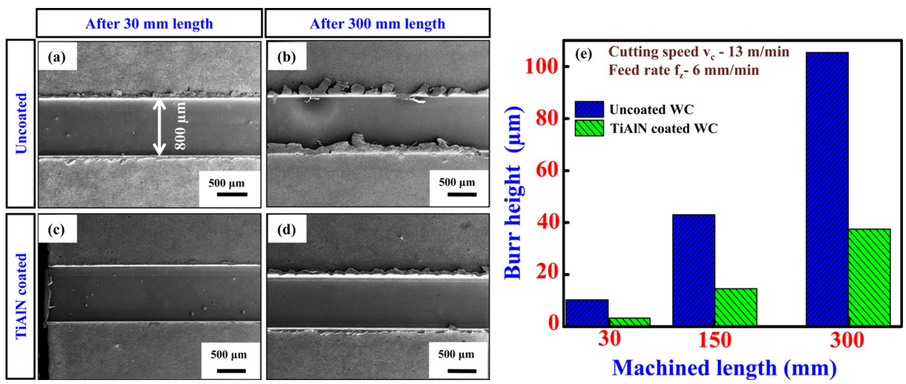

Fig. 6. Analysis of burr formation in: (a)-(b) uncoated and (c)-(d) TiAlN coated micro-end mills after slotting 30 and 300 mm machined lengths, (e) variation of burr height with machining length.

As compared to burrs, slot geometry showed a strong correlation with machining length. In order to study this variation, the width of the top and bottom surfaces of the micro-channels were analyzed. Fig. 7 shows the effect of tool wear-out on the size of the machined slot. It was noticed that the size of the machined slots were influenced by the progressive flank wear and corner wear of the micro-end mill. This causes a change in the width of the slot being machined as can be seen from Fig. 7(a) and (c). Slot geometry is also influenced by the steady wear acclimatized on the micro-tool with machining length. Fig. 7(b) and (d) shows the variation in burr height of uncoated and coated tools after machining a length of 300 mm. Due to an increase in tool wear, the cutting edge radius of the micro-tool increases significantly and consequently affects the shape of the machined slot, thus leading to intense burr formation. This observation is perceptible in case of an uncoated micro-tool [24,37]. As a result of this tool edge deterioration, the width of the slot decreases from its top surface to its bottom surface [38]. This can be seen in Fig. 7(e)

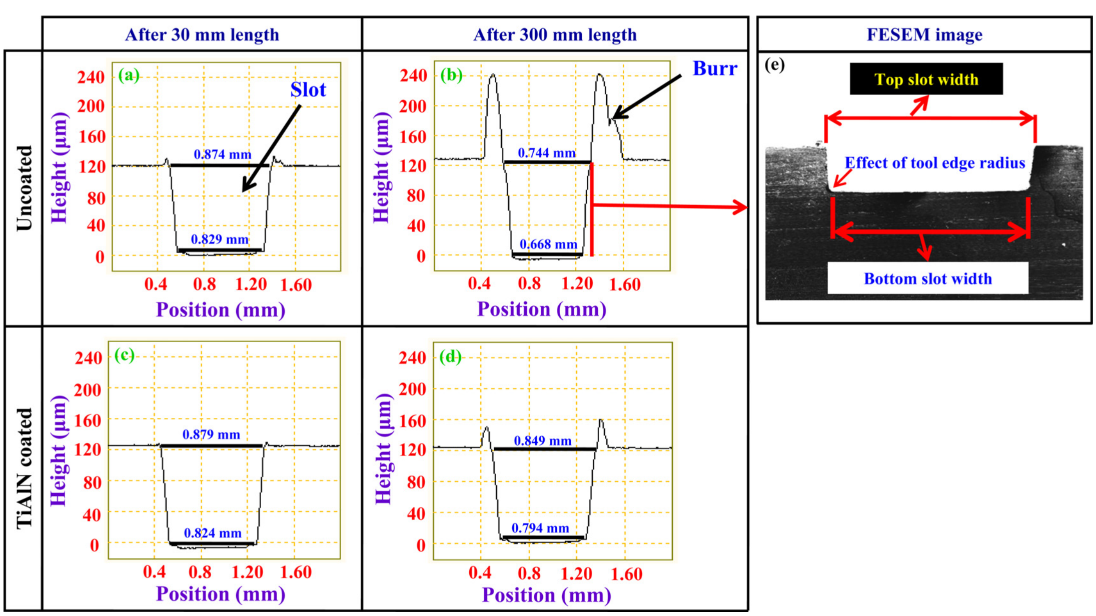

Fig. 7. Variation of slot shape after slotting 30 and 300 mm machined lengths using: (a)-(b) uncoated tool and (c)-(d) TiAlN coated tool (e) FESEM image of slot shape for an uncoated tool after 300 mm machined length.

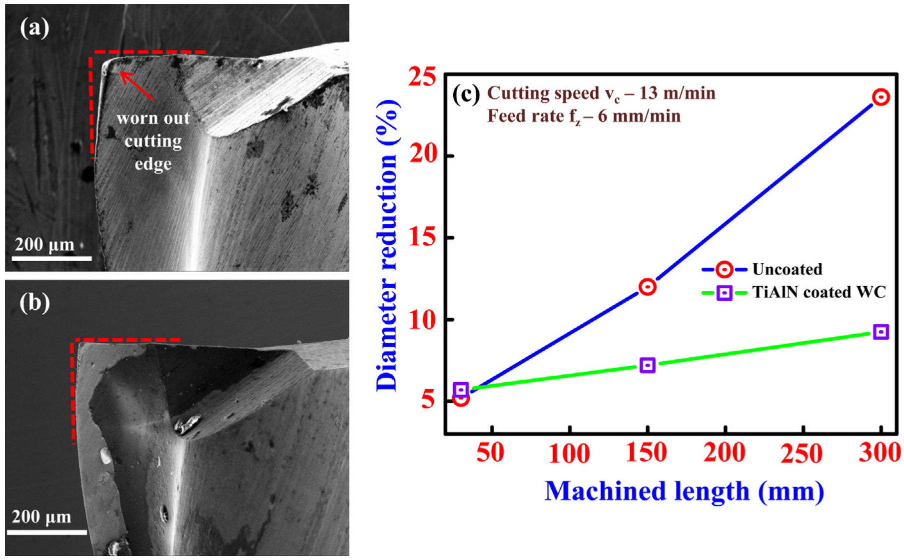

Fig. 8. FESEM image of used (a) uncoated micro-end mill and (b) TiAlN coated micro-end mill, (c) variation in tool diameter with machined length for both uncoated and TiAlN coated micro-end mill.

which shows the change in original and machined slot size for uncoated micro-tools. Coated tools show little deviation in slot width with machining length as can be seen in Fig. 7(c) and (d).

The surface integrity of the machined slots can also be ascertained qualitatively by measuring the variation in the diameter of the micro-tool. Fig. 8(a) and (b) shows the FESEM image of the uncoated and TiAlN coated micro-end mill after machining a length of 300 mm respectively. The decrease in diameter in case of an uncoated micro-tool was found to be higher than the coated micro-tool. The percentage decrease in tool diameter with machining length for both uncoated and coated micro-mills is shown in Fig. 8(c). It can be noted that TiAlN coated micro-tools show a lesser percentage reduction in diameter as compared to uncoated tools. This observation can be attributed due to the high hardness of TiAlN coated micro-tools and the lower coefficient of friction (approximately equal to 0.6) between the workpiece surface and the micro-tool [18,29]. In contrast to this, accelerated tool wear was observed in case of uncoated micro-tools due to the low hardness value [21,39,40].

Study of surface roughness

In any metal cutting process, surface roughness depends on feed rate, cutting speed and tool radius. Fig. 9(a) shows the variation in surface roughness with feed rate at different cutting speeds for an uncoated micro-tool. A steady increase in surface roughness could be observed for various feed rates at cutting speeds of 15 m/min and 18 m/min. However, inconclusive results

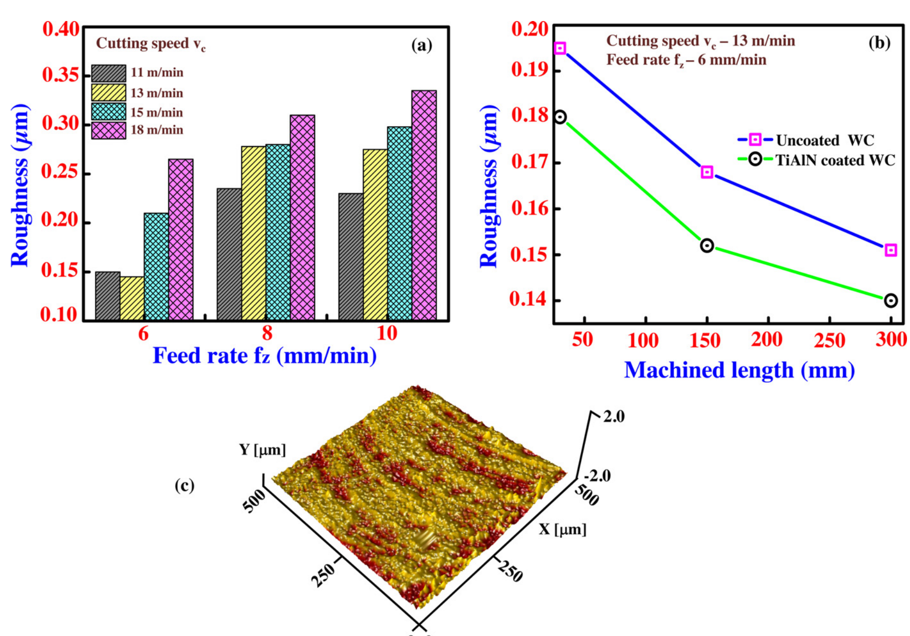

Fig. 9. (a) Dependence of surface roughness on feed rate and cutting speed values. (b) Variation in surface roughness after a cutting length of 30, 150 and 300 mm. (c) 3D topographic image of the machined surface after a cutting length of 300 mm using TiAlN coated micro-tools.

were drawn when machining at other speeds. This behaviour may possibly be attributed to the softening of the workpiece material and subsequent adhesion to the tool surface which occurs in the interface separating the tool and the workpiece at high temperatures [41]. It is also hypothesized that machining at higher speeds using an uncoated tool causes higher surface roughness due to the increased rubbing action between the hard abrasive particles of the tool surface and the workpiece material. The variation in surface roughness with machining length for both uncoated and coated tools at a cutting speed of 13 m/min and feed rate of 6 mm/min is shown in Fig. 9(b). It can be seen that the surface roughness for an uncoated carbide micro-tool is higher than that of the TiAlN coated micro-tool. The surface finish at the beginning of the cutting process for a coated and uncoated tool was measured to be 0.178 μm and 0.195 μm respectively. However, with an increase in machining length, smoother surfaces were obtained. Uncoated micro-tools produced a surface roughness of 0.151 μm as compared to TiAlN-coated micro-tools which showed a roughness value of 0.139 μm. However, as the machining length increases to 300 mm, a less rough surface was obtained as compared to a machining length of 30 mm as shown in Fig. 9(c). This is in agreement to literature results which report that a TiAlN coated micro-tool produces a better surface finish compared an uncoated tool. This may perhaps be due to the increase in the nose edge radius of the micro-tool as a result of the coating [41,42].

Conclusions

The performance of a TiAlN-coated tungsten carbide was studied by comparing its machining characteristics to an uncoated tool in the micro-end milling of Nimonic 75 superalloy. The cutting performance was determined with respect to tool wear, slot geometry, burr formation and surface roughness. The findings obtained are as follows:

1. The predominant mode of failure of the cutting tool was through flank wear and chipping at the tip and edge of the tool. However, coating the micro-tool with TiAlN increased the resistance of the cutting tool to wear significantly. In this context, the reduction of tool diameter, depending on wear, was seen to be less for the TiAlN-coated tool.
2. Flank wear increased at higher cutting speeds and feed rates for both uncoated and coated micro-tools. The uncoated tool was severely damaged at cutting speeds of 15 m/min and 18 m/min, with respective feed rates at 8 mm/min and 10 mm/min.
3. At the beginning of the cutting process, there was no significant difference between the burrs obtained with uncoated and TiAlN coated micro-tools. However, increasing the cutting distance causes the burrs to increase for an uncoated tool. TiAlN-coated micro-tools exhibited a superior performance than uncoated tools in this regard.
4. The deviations in dimensions and surface quality of the slotted grooves were explained by critical observations such as tool wear and tool diameter reduction.
5. TiAlN coated tungsten carbide micro-tools exhibited superior performance as compared to their uncoated counterparts with regard to tool wear and surface integrity.

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