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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