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ORIGINAL ARTICLE

Nanofabrication and influences of titanium carbo-nitride coating tool on machinability behaviour of magnesium alloy nanocomposite

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Abstract

The trend of AZ31 alloy matrix composites is excellent in aerospace and orthopaedic applications because they provide excellent corrosion resistance, less weight, good vibration resistance, and superior fracture toughness during the machining operation, tool wear, and poor surface finish due to the presence of a non-homogenous abrasive particle in a soft matrix. This research attempts to investigate the machinability behaviour and study the influences of titanium carbo-nitride (TiCN) coating tool insert on tool wear and surface quality of AZ31/6wt% TiC alloy nanocomposite turned by CNC turner under the feed rate of 0.2 mm/rev, 1000–1500 rpm speed, and varied depth of cut of 0.5 to 2 mm. With the help of a pistol thermometer and dynamometer, the temperature and TiCN coating tool wear are monitored. After turning, an optical-type surface roughness tester machine measures each pass's surface quality. According to the evaluated results, the 1000 rpm with 0.5 mm depth of cut and 0.5 mm/rev feed is found to lower wear tool wear of 0.019 mm and 1500 rpm with 0.5–1 mm depth of cut and 0.5 mm/rev feed spotted lower surface roughness of 0.67 to 0.71 µm. Finally, the optimum tool wear surface was investigated by scanning an electron microscope to spot the nature of the tool wear oxidation.

Keywords AZ31 alloy nanocomposite · CNC turning · Surface roughness · TiCN coating tool · Tool wear

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1 Introduction

Magnesium alloy is a precious material with unique behaviour like high strength, 1/3 weight of aluminium, good machinability, and enhanced fracture toughness [1]. With the development, the magnesium alloy is used in automotive and aerospace applications [2]. Introducing ceramic reinforcement in magnesium matrix found superior mechanical and wear behaviour [3]. Moreover, this composite is developed from fly ash particles exposed to better mechanical behaviour [4]. Generally, magnesium alloy composite is synthesised by liquid-state processing because it has a flexible setup, is economical, efficient [5], and is suited for complex part manufacturing [6]. In recent decades, magnesium alloy composites have been fabricated by liquid stir processing under an inert nature, which helps to limit oxidation formation [7]. It reduced casting defects and improved the mechanical behaviour of composites [8]. However, hard ceramic particles in magnesium matrix found good abrasion behaviour, resulting in high tool wear, reduced metal removal rate, and poor surface finish [9].

Based on this machining difficulty, the various types of research were studied experimentally, and its process parameters were optimised via various advanced techniques like ANOVA [10], algorithm [11], linear programming [12], and numerical analysis [13]. As elsewhere reported, the component's tool wear and surface roughness were affected by the turning process parameters of cutting speed and feed rate [14]. In addition, the machining of magnesium alloy with low cutting force found good surface quality with extended tool life, as reported by Goindi et al. [15]. However, the temperature rise during the machining process increased due to the tool-to-workpiece interface [16]. Zakaria et al. [17] investigated the machinability studies on turning AZ31 magnesium alloy under dry and submerged convective cooling (SCC) route using a coated carbide tool insert. They found a built-of edge on dry-state machining. At the same time, the SCC showed that the interface temperature was reduced by 15%.

The magnesium alloy was turned using an uncoated tungsten carbide cutting insert for the conditions of dry and minimum quantity lubricant under different cutting speeds, feed, and depth of cut optimised via ANOVA. The least depth of cut (0.5 mm) with 0.1 mm/rev feed rate was found to be a suitable parameter for good surface quality and low tool wear [18]. Kawin et al. [19] experimentally investigated the effect of CNC turning process parameters on the surface roughness of Al–Si10–Mg composite, and its parameters were optimised via ANOVA L9 orthogonal array. The results showed that the turning parameters of 315 mm/min, 0.1 mm/rev, with 1 mm depth of cut have good surface quality compared to others. Balasubramanian et al. [20] developed a magnesium alloy composite with SiC via the squeeze cast technique and evaluated its mechanical and turning machinability characteristics. The composite was turned with the CNC work centre, and its optimum machining parameters were found using the ANOVA technique.

Moreover, the turning process parameters like cutting speed and feed rate were the most dominating factors affecting the surface integrity and carbide insert tool life [21]. Moreover, the cutting force was important for deciding the magnesium alloy's surface roughness and frictional temperature [22]. However, the internally cooled tool insert found an improved life compared to the conventional tool [23], and its thermal distribution was analysed via the CFD technique [24]. The multi-layer composite is machined using the coated tool, and its surface quality is evaluated. Coated tools exposed better surface quality with reduced wear than traditional machining tools. Zakaria et al. [25] studied the machinability behaviour of AZ31 alloy using convective cooling. With the excellence of convective cooling, the frictional temperature between the tool and the work surface is limited, and the built-up edge formation is minimised [25]. AZ31B alloy is turned, and studied its machinability behaviour. Its ultrasonic vibration-assisted turning enriches the machining quality with a better surface finish [26]. Zirconia toughened alumina/magnesium oxide-made tool insert used for machining the multi-walled carbon nanotube developed magnesium alloy composite under varied machining parameters. The coated tool exposed better cutting force, the reduced surface roughness of the machining surface, and improved tool life [27]. Moreover, cryogenic turning lowered cutting force and economy [28, 29]. However, the coated insert was found to have low tool wear, increased tool life, and exposed better surface quality than the conventional uncoated tool [30].

Here, various kinds of literature were addressed, and the tool wear and surface roughness were the problem for higher cutting speed turning with an uncoated tool insert. According to this, a novel of present investigation is proposed by TiCN coating tool insert. The influences of TiCN coating on tool wear and surface quality of magnesium alloy nanocomposite were measured experimentally with varied speeds of 1000–1500 rpm, 0.5–2 mm depth of cut under 0.2 mm/rev feed rate. The optimum machinability tool insert surface was subjected to microstructure studies.

2 Material and methods

2.1 Description of materials and tool insert

Due to significance characteristics [3], the 6 wt% TiC reinforced AZ31 alloy nanocomposite was fixed as the machining material, with a good yield and tensile strength of 155 and 236.2 MPa, respectively.

The titanium carbo-nitride (TiCN coating) coated tool insert was chosen as a turning tool due to the benefits of superior wear resistance, reduced heat generation during high friction, and extended tool life [31].

2.2 Nanocomposite fabrication

Magnesium alloy (AZ31) and titanium carbide (TiC-50 nm) particles were taken with a weight ratio of 94:6. An ingot form of AZ31 alloy was kept in a graphite crucible with a 5-kg capacity. Its furnace temperature was fixed at 300 °C to the semi-solid stage for AZ31 alloy under an inert (argon) atmosphere for 20 min. The temperature of the furnace was raised by 700 °C for a fully liquid state, and the significance of the inert argon gas during magnesium alloy melting supports limiting the oxidation formation results improved quality of composite casting [4, 6]. After the process, the molten metal temperature was reduced by 500 °C. In the meantime, the TiC nanoparticles were held in a muffle furnace with an applied temperature of 300 °C for 10 min. After preheating, the reinforcements were dropped into molten metal and mixed via mechanical stirring at 500 rpm for 10 min. Finally, it was dropped into a preheated (300 °C) tool steel die (200 mm length and 30 mm diameter). The developed magnesium alloy nanocomposite surface was cleaned and subjected to machining behaviour studies.

2.3 Turning operation for AZ31 alloy nanocomposites

Here, the diametral technique tested the circularity of the developed AZ31 alloy nanocomposite. The Super Jobber makes computer numerical controller (CNC-Fanuc) turning centre was utilised to perform the turning operation, and its full setup is shown in Fig. 1. The magnesium alloy nanocomposite 30-mm-diameter and 100-mm-length sample was weighed as W1 and kept into the electro-mechanical chuck. The TiCN coating tool insert was fixed into the tool post and used throughout the turning operation. During the completion of each pass, the workpiece was weighted as W2. The CNC turning operation was executed with a constant feed rate of 0.2 mm/rev, with varied speed (500–1000 rpm), and depth of cut (0.5–2 mm).

2.4 Characteristic evaluation

During the turning process, the tool insert temperature was monitored by a pistol thermometer with an accuracy of ± 0.5 °C. The pistol thermometer is not fixed, and during the operation, it is handled by hand and infrared points to the workpiece to measure the frictional temperature.

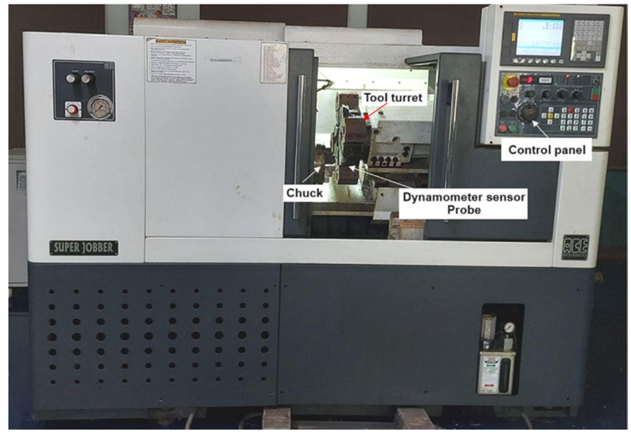

Fig. 1 Super Jobber makes CNC turning work centre

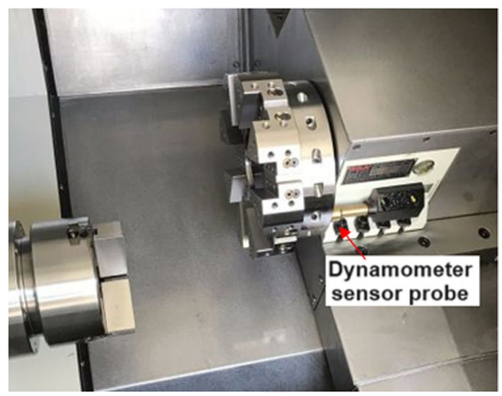

Fig. 2 Lathe tool dynamometer with sensor probe setup

With the help of the lathe tool dynamometer, the cutting force acting on the tool during the turning operation and its sensor connection is shown in Fig. 2. The TiCN-coated tool wear is observed via an optical profile projector and its measurement is checked with an electronic comparator with the accuracy of ± 0.1 µm.

The ZEISS–EVO 10 model scanning electron microscope analysed the tool wear surface. The turning composite surface quality was measured using Mitutoyo to make an SJ-301 model optical-type surface roughness tester followed by the ASTM D7127 standard. Three different places of each pass measured it, and an average of three was fixed as the mean value. Based on Eq. (1), the cutting speed of the turning process was calculated.

$$Cutting\ speed(v) = \frac{\pi * D * N}{1000} \quad (1)$$

where D is the diameter of the shaft in mm and N is the speed in rpm.

Table 1 Input process parameter and output response of machined AZ31 alloy nanocomposite

S. no	Speed	Feed	Depth of cut	Cutting speed	Cutting force	Temperature	Tool wear	Surface roughness
	rpm	mm/rev	mm	m/min	N	°C	mm	µm
	N	*f*	DOC	*v*	F_f	*T*	TW	Ra
1	1000	0.2	0.5	94.2	110.5	88	0.019	0.78
2			1	94.2	135.5	97	0.023	0.82
3			1.5	94.2	180.7	112	0.024	0.91
4			2	94.2	210.6	123	0.026	1.14
5	1500		0.5	141.3	120.8	90	0.022	0.67
6			1	141.3	191.6	102	0.025	0.71
7			1.5	141.3	230.3	126	0.03	0.88
8			2	141.3	250.5	136	0.031	1.04

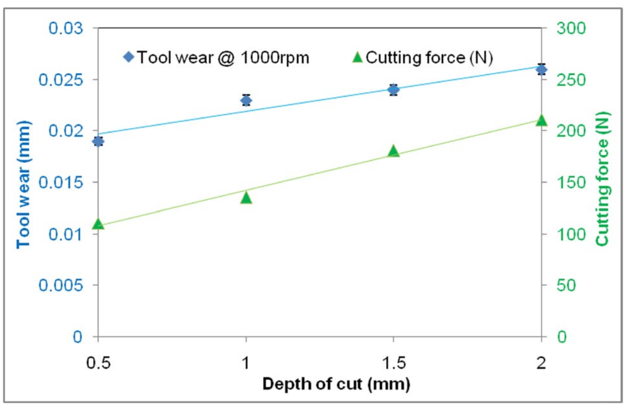

Fig. 3 TiCN coating tool wear at 1000 rpm

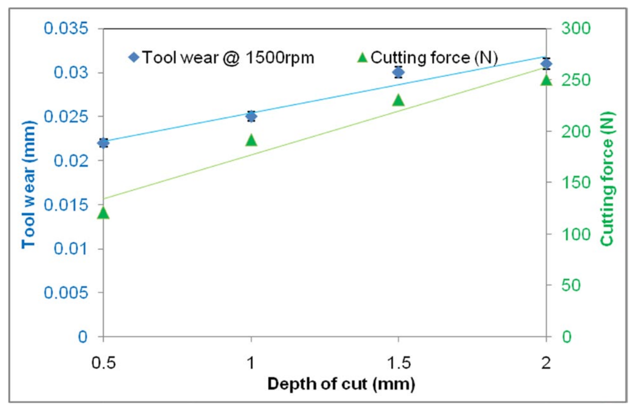

Fig. 4 TiCN coating tool wear at 1500 rpm

3 Results and discussions

Table 1 represents the turning input process parameters and measured output results of cutting force, temperature, tool wear, and surface roughness of AZ31 alloy nanocomposite.

3.1 TiCN coating inserts tool wear during the turning of AZ31 alloy nanocomposite

The TiCN coating tool wear during the CNC turning operation of AZ31 alloy nanocomposite machined by 1000 rpm speed with 0.2 mm/rev feed rate and varied depth of cut is shown in Fig. 3, along with the cutting force scatter plot. Due to higher hardness, the conventional tool was unsuitable for this operation due to high tool wear and poor surface finish [14].

The turning operation was performed by TiCN-coated inset with 1800VHN [31]. Based on the depth of the cut, the tool wear was progressively increased, which was directly proportional to the cutting force. Tool wear of 0.019 mm was noted during the 0.5 mm depth of cut, 100 m/min cutting speed (1000 rpm), and 0.2 mm/rev feed rate. The increase in the depth of cut as 1 mm, 1.5 mm, and 2 mm showed an increased tool wear of 0.023, 0.024, and 0.026 mm, respectively. However, there was no major tool wear compared to past literature [11]. In addition, the cutting force was a prime reason for tool wear [14]. In addition, the TiCN coating could withstand the maximum load and resist the abrasion wear against the work material.

Figure 4 illustrates the TiCN coating tool wear during the CNC turning operation of AZ31 alloy nanocomposite machined at 1000 rpm speed with 0.2 mm/rev feed rate and varied depth of cut. The secondary vertical axis indicates the cutting force during the turning operation, as noted by the dynamometer. Compared to 1000 rpm, the tool wear was higher due to an improved cutting speed of 150 m/min.

It was noted from Fig. 4 the TiCN coating tool wear was marginally increased by 0,022, 0.025, 0.03, and 0.031 mm with increased depth of cut as 0.5, 1, 1.5, and 2 mm, respectively. Depth of cut plays the main role in increased cutting

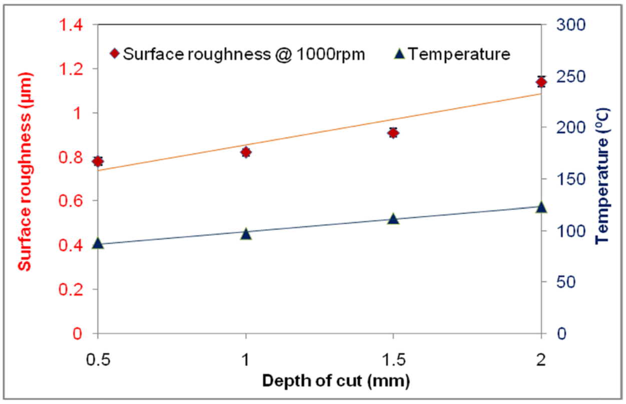

Fig. 5 Surface roughness of turned AZ31 alloy nanocomposite 1000 rpm

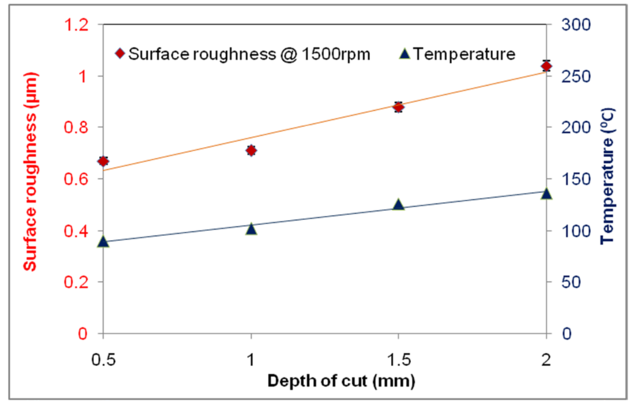

Fig. 6 Surface roughness of turned AZ31 alloy nanocomposite 1500 rpm

force, leading to increased frictional contact between the tool and workpiece. High frictional contact leads to built-up edge formation [17]. In addition, the high-speed turning operation executed with a low depth of cut found the lowest tool wear compared to all others. A similar tendency was reported by Viswanathan et al. [18] during the machining of magnesium alloy.

3.2 The surface roughness of the TiCN coating tool turned AZ31 alloy nanocomposite

The surface roughness of turned AZ31 alloy nanocomposite by TiCN coating tool is shown in Fig. 5 with a 5% allowable error. The secondary vertical axis represents the temperature during the turning operation.

It was observed from Fig. 5 that the surface roughness of 0.5-mm depth turned AZ31 alloy nanocomposite was 0.78 µm, while the depth of cut improved by 1 mm at 1000 rpm has shown the 0.82 µm due to the increased frictional temperature of 88 °C. The surface roughness was gradually improved by 0.91 and 1.14 µm on 1.5-mm and 2-mm depth of cut. The increased surface roughness was due to thermal mismatch during machining [13].

A higher thermal gradient was the reason for the increased surface roughness reported by Akgun [22]. However, the TiCN coating tool dissipated the heat energy, and the lowest surface roughness was noted by 0.-5 to 1-mm depth of cut. More than 1-mm depth of cut was found to increase the shot peening effect, which results in a metallurgical change.

Figure 6 represents the surface roughness of AZ31 alloy nanocomposite machined by TiCN coating tool insert with a constant feed rate of 0.2 mm/rev, 1500 rpm speed, and varied depth of cut of 0.5, 1, 1.5, and 2 mm, respectively. The error bar indicates the allowable limit of 5%, and the secondary axis shows the frictional temperature during the tool and workpiece interface.

Moreover, the surface roughness of high-speed machining (1500 rpm) was low because the magnesium alloy has good vibration resistance at higher speeds. Generally, magnesium alloy has good machinability and is stable with the maximum frictional force [5]. The marginal improvement in surface roughness was recorded by 0.67, 0.71, 0.88, and 1.04 µm during the 0.5-, 1-, 1.5-, and 2-mm depth of cut. Previous literature found 1.971-µm surface roughness during the turning operation using a 0.2-mm/rev feed rate with 500-rpm speed [20]. However, the 1500-rpm speed with 0.5-mm to 1-mm depth of cut found optimum surface roughness value, and compared to the 1000-rpm speed, the AZ31 alloy nanocomposite surface quality was improved by 16% and 15%, respectively. Moreover, the surface roughness of machined composite is progressively increased with increasing depth of cut due to the high heat generation between the tool insert, and the work surface and its temperature liberation are highlighted in Table 1. The thermal mismatch and chip evacuation during high-speed machining are the reasons for the improvement of the surface roughness of the machined composite sample.

Based on the tool wear and surface roughness studies, the AZ31 alloy nanocomposite was suitable for high-speed machining with 0.2-mm/rev feed rate and 0.5-mm to 1-mm depth of cut. It is cutting force, and the frictional temperature was optimum compared to past literature [16, 18]. So, the 0.5-mm and 1-mm depth of cut, 0.2-mm/rev feed rate, and 1500 rpm turned TiCN coating tool wear surface were analysed via SEM. The details are addressed below.

3.3 Nano-sized SEM micrographs of TiCN coating tool wear surfaces

Figure 7(a) and (b) illustrates the enlarged photographic view of the TiCN coating tool wear surface and its SEM micrograph. It was captured at 1000-rpm speed with a

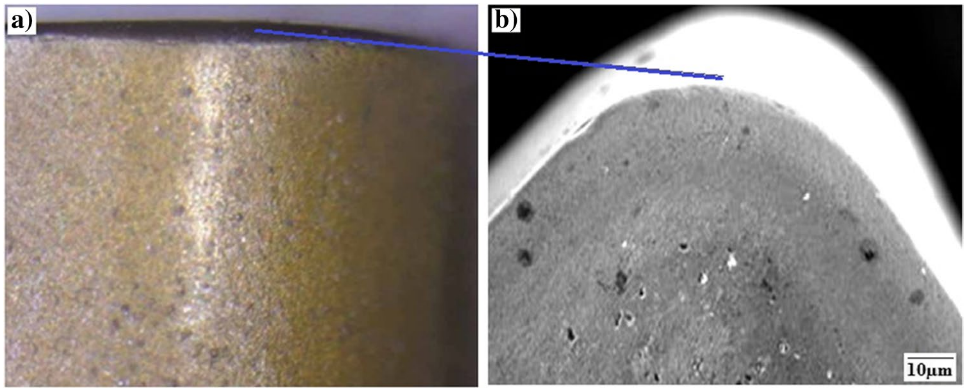

Fig. 7 TiCN-coated tool wear: **a** enlarged photographic view of the TiCN coating tool wear surface and **b** TiCN tool wear SEM micrograph at 1000 rpm

0.5-mm depth of cut at a feed rate of 0.2 mm/rev. The high cutting speed between the TiCN coating and AZ31 alloy nanocomposite found some nose wear. It was formed during the dry machining process [14, 15].

It was observed from Fig. 7(b) that the turning chip particles were diffused with the top surface of the TiCN coating tool. In addition, fine magnesium chips may lead to oxidation with TiCN coating tool surfaces found as black dots. Moreover, the hardness of the TiCN coating material was higher than that of the machining material, resulting in lower tool wear [31]. However, the tool wear could be varied by turning speed and depth of cut. The low depth and feed rate were found to have good tool life rather than the higher depth of cut reported by Saravanakumar et al. [10].

The actual photographic image and SEM images of the TiCN coating tool wear surface during the high speed (1500 rpm) turning operation at a constant feed rate of 0.2 mm/rev under 1-mm depth of cut are shown in Fig. 8(a) and (b). The 1500-rpm speed with 1-mm depth of cut showed the higher frictional temperature (102 °C) between tool and composite, resulting in a 0.025-mm wear rate. However, the TiCN coating tool has unique behaviour with higher hardness and effective thermal dissipation behaviour. The results of permissible nose wear with diffused magnesium particles are found in Fig. 8(b). It was due to higher frictional temperature and turned chip fine particles were diffused in the tool surface. It is evidenced in Fig. 7(b). Lower cutting speed may lead to nose wear, but improved frictional temperature-facilitated built-up formation [21, 22].

4 Conclusions

The turning operation of AZ31 alloy nanocomposite was successfully machined by using Super Jobber, making the CNC turning work centre with TiCN coated tool insert under the process parameters of 0.2-mm/rev feed rate, 1000- to 1500-rpm speed, and 0.5- to 2-mm depth of cut. The influence of the TiCN-coated tool insert on the machinability behaviour of tool wear and surface roughness of the machined composite was evaluated experimentally, and its key results are discussed below.

- Based on the machining and experimental evaluation, AZ31 alloy nanocomposite machined with 0.2-mm/rev feed rate and 1000–1500 under 0.5- to 1-mm depth of cut found the lowest tool wear.
- The speed of 1000 rpm with 0.5- to 1-mm depth of cut under 0.2-mm/rev feed operated TiCN coating tool was found to have the lowest wear rate. Compared to the

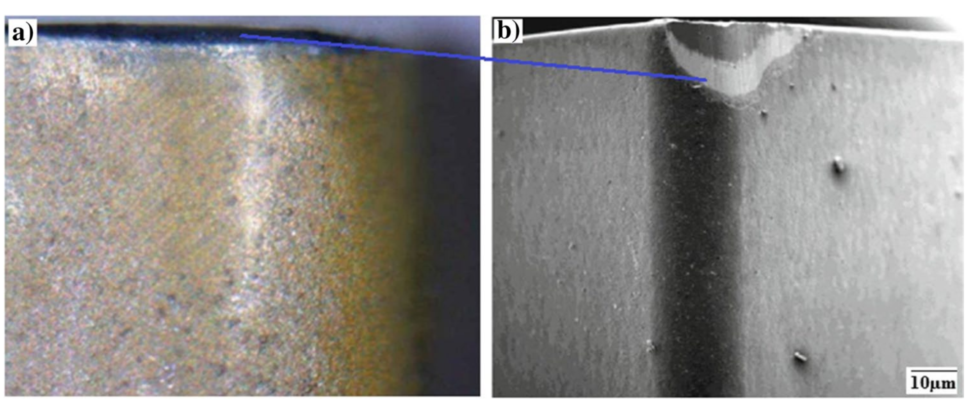

Fig. 8 TiCN-coated tool wear: **a** enlarged photographic view of the TiCN coating tool wear surface and **b** TiCN tool wear SEM micrograph at 1500 rpm

2-mm depth of cut, it was increased by 37% and 13%, respectively.
- TiCN coating tool operated with 1500 rpm, 0.5-mm to 1-mm depth of cut under 0.2 mm/rev found 41% and 24% improved tool life compared to high depth of cut machining process.
- Similarly, the high speed (1500 rpm) with 0.5-mm to 1-mm-depth turned composite showed a high surface quality of 55% and 46% compared to 2-mm-depth turned composite.
- Additionally, the nanosize captured SEM micrograph proved their abrasion effect during the TiCN coating tool turning operation, and the nose wear was found to be due to the low cutting speed of 150 m/min.
- The micro-machining characteristics and behaviour of the AZ31 alloy nanocomposite are planned for future extension.

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Data availability All the data required are available within the manuscript.

Declarations

Ethics approval This is an observational study. "Nanofabrication and influences of titanium carbo-nitride coating tool on machinability behaviour of magnesium alloy nanocomposite": The Research Ethics Committee has confirmed that no ethical approval is required.

Consent to participate Informed consent was obtained from all individual authors included in the study.

Consent for publication We give our consent for the publication of the "Nanofabrication and influences of titanium carbo-nitride tool on machinability behaviour of magnesium alloy nanocomposite" to be published in *The International Journal of Advanced Manufacturing Technology*.

Competing interests The authors declare no competing interests.

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