Experimental Study on Tool Life of Coated/uncoated Carbide Inserts during Turning of Ti6Al4V

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Abstract. For more than three decades, the machining industry has been employing coated tools to enhance productivity via improving tool life. Nonetheless, the problems associated with machining titanium alloys have been still prevalent. Advanced alloy materials such as diamond-like carbon (DLC) coatings are developed to combat these issues. In this study, the performance of a DLC coated tool is assessed and its tool wear mechanisms investigated. For the cutting conditions used during these trials, it has been identified that the DLC coated tool exhibited severe tool wear due to delamination and diffusion in comparison with the uncoated carbide tools. In conclusion, it is suggested that the performance of the DLC coated tools can be enhanced by applying alternate strategies to remove heat from the cutting region.

Keywords: Tool life, coated inserts, turning, Ti6Al4V, tool wear, tool makers microscope.

Introduction

Machining of titanium and its alloys is challenging due to the high mechanical strength and low thermal conductivity of these alloys, which not only induces severe thermomechanical dynamic stresses on the cutting tools but also ensures that most of the heat generated during cutting to stay within the tool [1]. In addition to this, titanium is highly reactive with most tool materials and coatings at typical temperatures generated during machining further reduces the tool life. These problems severely impair the productivity when machining titanium alloys [2]. The application of hard coatings on carbide cutting tool surfaces is a technique used to improve productivity. Apart from having excellent adhesion with the cutting tool substrate, high hot hardness and chemical inertness with the workpiece materials, these coatings are successful because the coating has the potential to extend tool life and subsequently enhance productivity when machining. Therefore, advanced tool coatings are being developed and tested within severe cutting environments such as that present during machining of titanium alloys to not only protect the structural integrity of the cutting tool surface during the cutting operation but also assist in dissipating the heat away from the cutting zone [3]. Diamond and diamond-like carbon (DLC) coatings possess very high hardness, high thermal conductivity and low thermal expansion coefficient along with low friction coefficient during the cutting operation [4]. Kuljanic et al. [5] reported that polycrystalline diamond (PCD) coated tools showed better tool life in comparison to uncoated carbide tools. Yet, the use of PCD cutting tools and coatings has been limited during titanium manufacturing due to high costs. Alternatively, DLC coatings show similar properties as that of diamond coatings at a much lower cost. In this paper, the performance of a DLC coated carbide insert is compared with an uncoated cutting tool in terms of tool wear and chip formation when turning the Ti6Al4V alloy.

Experimental Methodology

A set of machining trials were conducted in order to assess the performance of the diamond-like carbon (DLC) coated carbide tool inserts in comparison to uncoated carbide inserts during turning of an ASTM Grade 5 Ti workpiece. The chemical composition of the workpiece is provided in Table 1. The 45 mm diameter workpiece was mill annealed prior to the machining trials.

A Hyundai Quick Turn 50 MEII CNC Lathe was employed for the turning trials under dry cutting conditions. A SECO CNMG120408 MF1890 cutting tool insert with 0.8 mm nose radius and 15° clearance angle was used. One of the inserts was an uncoated WC-Co insert while the other was DLC coated. The DLC coatings were applied at the Fraunhofer Institut für Werkst off- und Strahltechnik Dresden, Germany. The coatings were deposited using a laser-induced vacuum arc evaporation technique wherein a deposition pulsed arc plasma is produced from a target (cathode) material placed in the laser arc chamber. The coatings were approx. 2 µm thick containing tetrahedral-bonded amorphous carbon with up to 80% sp3 hybridised carbon-carbon covalent bonding. The coating had a hardness of 40-70 GPa and a Young's modulus of 400-600 GPa [6].

Machining was carried out at a cutting speed of 75 m/min, a feed rate of 0.25 mm/rev, and a depth of cut of 2 mm. The turning operation was performed over 50 mm intervals for the first three lengths of cut and then the entire length of 150 mm was machined until the tool failure criterion was obtained. A length to diameter ratio greater than 10 was maintained during the turning trials, as higher ratios (a) are not recommended as per ISO 3685:1993 standards, and/or (b) can result in excessive chatter during machining [7].

Table 1 Chemical composition of the workpiece

C	Fe	Al	V	Cr	Sn	Ni	Ti
0.03	0.15	5.7	3.9	0.03	<0.01	<0.01	Bal

Results

Tool wear. The maximum tool flank wear was recorded after each cutting trial using a toolmaker's microscope. Machining was halted when the maximum flank wear VBmax reached 0.6 mm as per ISO 3685:1993 standards. The flank wear results obtained for both coated and uncoated inserts are presented in Figure 1. It can be seen that the DLC coated carbide tool exhibited greater rates of wear than the uncoated carbide tool, i.e., the coated tool reached the failure criterion after about 165 s of cutting when compared with about 190 s of cutting time by the uncoated tool. The damage to the tools after the last cut is shown in Figure 2. Severe damage to the DLC coated cutting tool insert can be observed in Figure 2 (b) along with welding of the chips to the tool.

Chip formation: It was also noticed that small washer type helical chips were produced at the beginning of the initial cut; however slightly longer chips were formed when the uncoated tool wear (VBmax) reached about 0.3 mm. When VBmax was beyond the tool wear criterion of 0.6 mm, sparks were noticed during turning which may be due to excessive heat being generated in the cutting region. When turning using the DLC coated insert, VBmax of about 0.4 mm was observed after machining 300 mm lengths of the material; however, when the turning operation was continued, the chips started to weld to the crater area of the tool insert. Furthermore, long curly chips were produced during the last cut, when the tool wear criterion had been exceeded. According to Palanisamy et al. [8] and Bermingham et al. [9], the formation of long tubular chips is a clear indication that the inserts had reached the end of their life. Sometimes these chips were caught in the direction of tool movement which resulted in damage to the insert. Hence, it is important to remove these chips from the cutting area either with coolants or an air blast1.

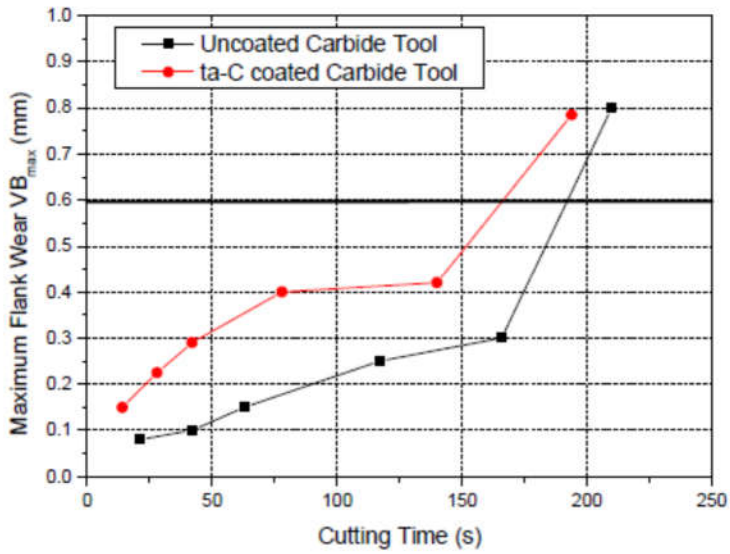

Figure 1 Maximum flank wear for uncoated and DLC coated inserts when turning Grade 5

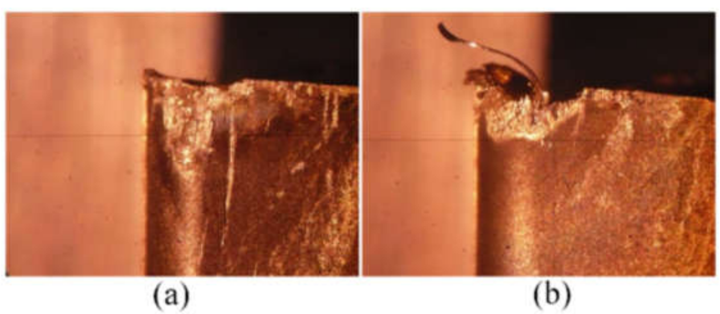

Figure 2 Damage to the tool cutting edges on (a) uncoated and (b) DLC coated insert after the last

Discussion The DLC coated carbide insert reached the tool failure criterion quicker than the uncoated carbide insert as shown in Figure 1. This might be due to fracture of the coating at the beginning of the cut, which accelerates tool wear via abrasion. Delamination of the coating and the rapid development of crater wear after the first cut was observed during this study as shown in Figure 3. Nouri et al. [3] studied the effect of various coatings on cemented carbide inserts when machining titanium alloys. They reported that delamination of these coatings was the initial wear mode which occasionally resulted in slight cracking and/or chipping of the cutting tool surface. On the other hand, Minton et al. [10] reported a better performance of diamond-coated tools with specially designed internal cooling systems in spite of noticing the delamination of the diamond coatings from the tool surface during the initial stages of cutting. Hence, these observations indicate that even though the DLC coatings possess high thermal conductivity, it is essential to provide an alternative means to remove heat from the cutting region to boost the performance of the DLC coated tool. Another reason for the shorter life of the DLC coated tool compared to the uncoated carbide tool life may be the dissolution of the carbon from the coating into the chip flowing away from the cutting region. Mehrotra and Quinto [11] showed that the high coating hardness provides resistance to crater wear developed at high cutting temperatures as a result of chemical wear such as diffusion, oxidation or graphitization, however observations from this study (Figures 2 and 3) have indicated otherwise. In a recent study, Bermingham et al. [12] reported that diffusion related tool wear is a dominant wear mechanism, sometimes in conjunction with adhesive wear, when machining titanium alloys.

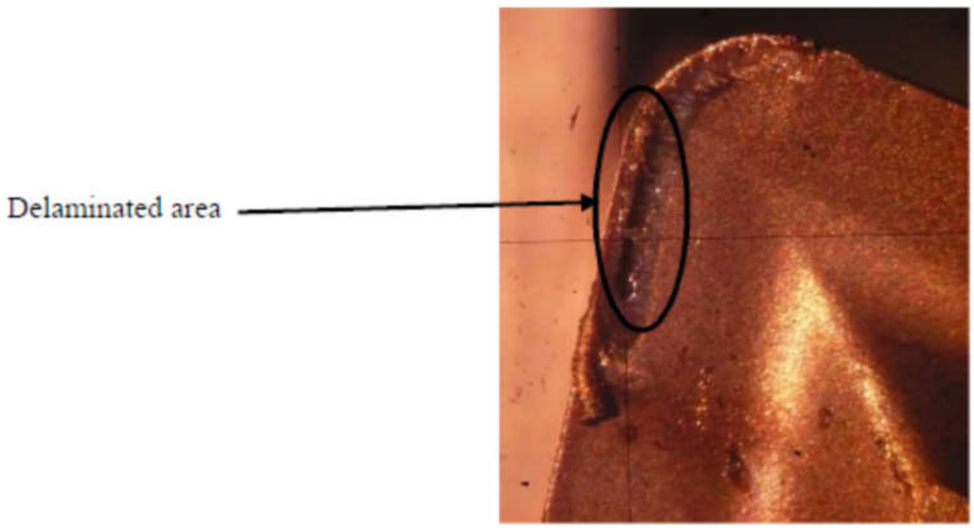

Figure 3 Delamination of the DLC coating after the first cut

Moreover, Müller-Hummel and Lahres [13] reported a problem of graphitization reactions taking place at the cutting interface between the diamond coatings on the tools and the titanium workpiece, thereby increasing the wear rates of the cutting tool. Likewise, Pu et al. [14] studied the oxidation behaviors of CVD diamond films and reported a high rate of film degradation at high temperatures in air. This implies that the DLC coating may be unstable at the high mechanical and thermal stresses that are present during machining of titanium alloys.

Several studies on DLC coated tools have been conducted on various workpiece materials such as plain carbon steel [15], aluminium alloys [16], and glass-fiber reinforced plastics [17]. In most cases, it has been reported that DLC coatings improved tool life. Nevertheless, it was reported that DLC coated tools did not out-perform the standard cutting tools used for conventional machining of hard materials [18]. Bhowmick and Alpas [19] noticed short tool life of the DLC coated carbide drills when drilling Ti-6Al-4V alloy in dry cutting condition, which was attributed to the strong adhesion of titanium to the cutting tool similar to the obervation made in this current study. However, when the same alloy was placed in a cooling bath at -80°C and thermally assisted drilling was performed at 400°C, a significantly prolonged tool life was achieved along with low drilling torque and good surface finish. For the particular cutting conditions employed in this study, the DLC coated cutting tool did not exhibit better tool life but it is not entirely clear why this is the case. Nor it is clear if other DLC coated inserts will also perform worse. Further work needs to be undertaken to test the effect of coating process parameters and DLC coating type over a more comprehensive set of machining conditions. In a previous study, the authors reported that the DLC coated endmill showed an improvement in tool life during milling of a Ti6Al4V workpiece compared to the standard TiAlN coated cutting tool. These observations provide further complexity to the interpretation of the current results. This might suggest that DLC coatings perform better in intermittent cutting operations such as milling where more than one cutting edge is involved in the machining operation rather than continual cutting operations such as in turning where a single-point cutting tool insert continuously engages with the workpiece during machining.

Conclusion: Turning trials were conducted on an ASTM Grade 5 titanium workpiece using diamond-like carbon (DLC) coated tools and the results were compared with machining experiments performed using uncoated carbide cutting tools. The DLC coated cutting tools showed shorter tool life compared to the uncoated tools. It was observed that delamination was the initial wear mode for the DLC coated cutting insert, thereby promoting diffusion wear. The performance of these hard coatings may be improved by providing alternate sources of heat removal from the cutting zone. It is also suggested that DLC coated tools are better suited to intermittent cutting operation such as milling. It is possible Delaminated area Advanced Materials Research Vol. 974 139 that DLC coated tools may perform better than observed in this study under different cutting conditions.

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