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Titanium machining with new plasma boronized cutting tools

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ABSTRACT

Titanium is a commonly used material in various critical applications such as aerospace and biomedical applications. In this article, for the first time in the literature, development and implementation of a novel plasma boronizing process on Tungsten Carbide (WC) cutting tools is introduced. Plasma boronizing on WC tools is performed with gas combination of 10% BF_3, 40% Argon and 50% H_2 at different temperatures and durations. Performance enhancements of plasma boronized WC tools on Titanium (Ti–6Al–4V) machining are investigated under various cutting conditions. It is found that new plasma boronizing of WC is a very cost effective solution for significantly increasing tool life in Titanium machining.

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1. Introduction

Titanium alloys are widely used in advanced engineering applications such as aerospace and biomedical industries due to their excellent corrosion resistance, high strength-to-weight ratio, high strength at elevated temperatures and biological compatibility. However, titanium alloys are regarded as extremely difficult to cut. Low thermal conductivity of titanium alloys induces a high amount of heat generation during the cutting operation that causes severe tool wear [1]. In addition, the high chemical affinity of titanium with majority of tool materials at high temperatures gives rise to a strong adhesion of the workpiece to the tool surface, thus leading to chipping and premature tool failure [2]. Due to the stated problems, high tooling costs occur eventually; therefore creating a cost effective cutting tool performance enhancement through coating or tool material comes into prominence. Successful results can be achieved by using tool materials such as cubic boron nitride (CBN) and polycrystalline diamond (PCD) [3–6]; however the high cost of these tools decreases their use in industrial applications. Most coating materials have a tendency to interact with Ti–6Al–4V that provokes build-up edge formation [7]. Early removal of some coatings is a problem in titanium machining. One of the reasons behind the removal of coatings is thought to be thermal expansion coefficient difference between the substrate and the coating layers. Due to this when a high temperature gradient exists, thermal cracking occurs [8]. Some grades of uncoated tungsten carbide tools can be readily used in machining of Ti–6Al–4V [4] and WC tools have lower cost compared to coated tools.

When the current situation is considered, it is observed that there is a need for an economical method of enhancing the WC tool performance in titanium machining. Plasma boronizing of WC tools is found to be promising method in this area of interest. In this study by employing a novel approach, new boron plasma implemented WC inserts have been produced and the machining tests on Ti–6Al–4V alloy have been carried out. Uncoated WC inserts have been plasma boronized at different conditions. Effects of plasma boronizing conditions are investigated on orthogonal machining and face milling operations. It is found that plasma boronizing process under certain conditions decreases the tool wear significantly and improves tool life almost triple.

2. Plasma and plasma boronizing

Plasmas consist of ionized gases, positive–negative ions and electrons in addition to neutral species. Not only there are fully ionized gases with a 100% ionization degree but also very low ionized gases with ionization degree as low as 10^{-4} to 10^{-6}.

2.1. Glow discharge plasma mechanism

If the potential energy difference is sufficiently high between two electrodes placed in a gas mixture (Fig. 1), the latter is going to break down into positive ions and electrons, giving rise to a gas discharge. The gas breakdown mechanism can be explained as follows; a few electrons are emitted from the electrodes. If a sufficient potential energy difference is applied between two electrodes, the electric field in front of the cathode accelerates the electrons and the electrons collide with the gas atoms. The most crucial collisions are the inelastic collisions, and this leads to excitation and ionization. The excitation collisions, which then lead to de-excitations with the emission of radiation, called glow discharge. The ionization collisions create new electrons and ions, and afterwards these electrons and ions are accelerated by the electric field toward the cathode, where new electrons by ion

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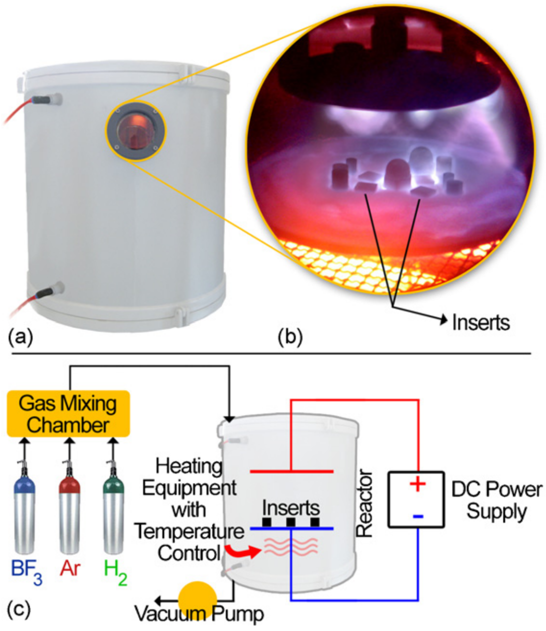

Fig. 1. (a) Plasma boronizing reactor, (b) plasma generation, and (c) schematic overview of the setup.

induced secondary electron emission are released. This process keeps going on continuously and these processes make the glow discharge a self-sustaining plasma.

2.2. Plasma boronizing

Plasma boronizing is a thermo-chemical surface modification and diffusion process in which boron atoms diffuse into the surface of the tool to produce hard boride zone. The plasma boronizing setup consists of a boron releasing gas supplied into a reactor where boron ions are formed in a glow discharge. Under suitable conditions excited boron particles are generated in the glow discharge.

Plasma boronizing of tungsten carbide tools was performed in a newly developed setup (Fig. 1) with a gas mixture of 10% BF_3, 40% Argon, and 50% H_2 at different gas temperatures and durations. Table 1 shows temperatures and duration of the plasma boronizing of identical tungsten carbide inserts. BF_3 is dissociated in the plasma and the boron is deposited on the WC insert surface and diffuses into the insert material to form boride phase. This phase is expected to improve machining performances by increasing wear resistance of the tools.

Plasma boronizing of inserts was performed at various temperatures and durations (Table 1). Four inserts were plasma boronized for each insert set given in Table 1. When the scanning electron microscope (SEM) images were analyzed it was observed that plasma boronizing process caused boron to penetrate under the surface of WC inserts significantly. SEM images of nonboronized and plasma boronized insert from insert set 4 are shown in Fig. 2. It illustrated that approximately 185 µm deep boron penetrated zone was generated (Fig. 2b). Distribution of the boron through the cross-section of the insert was scanned along the line represented in Fig. 3. Results have shown that boron amount decreases rapidly beyond the boron penetration zone. Microhardness values were measured as 1448 HV for nonboronized insert set 1 and as 3100 HV in the boron penetrated zone for insert set 4.

Table 1
Plasma boronizing parameters.

Insert set	Reactor temperature (°C)	Duration of plasma boronizing (h)
1	Nonboronized WC tool	–
2	600	6
3	700	4
4	800	1
5	850	1

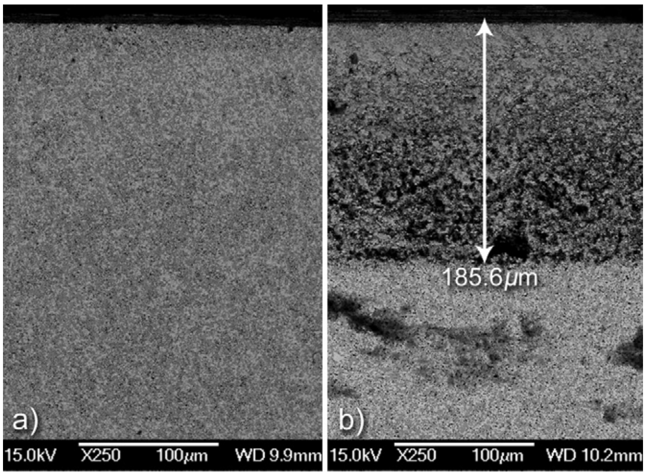

Fig. 2. SEM images of inserts: (a) cross-section of nonboronized insert 1, (b) cross-section of plasma boronized insert 4 and illustration of 185 µm plasma boronized zone under the surface.

Cutting forces were measured in orthogonal machining and oblique face milling tests on Ti–6Al–4V to compare the performances of the inserts. It was found that the certain sets of WC tools, depending on plasma boronizing parameters, show lower resultant cutting forces and much better wear resistance than nonboronized inserts.

3. Experimental machining tests

Four sets, each set including four cutting inserts, were plasma boronized using the conditions listed in Table 1. These plasma boronized inserts and four nonboronized WC inserts (all having 6° rake angle and 8° clearance angle) were used in orthogonal machining and in oblique face milling experiments for performance comparisons. In all these tests, cutting forces were measured using a three-axis Kistler dynamometer (model 9257B). For the comparisons of wear, nonboronized insert and four sets of identical plasma boronized inserts (Table 1) were used in slot face milling tests. In all the experiments, workpiece material was Ti–6Al–4V grade 5.

3.1. Orthogonal machining tests

Orthogonal cutting experiments were performed for each insert set. Orthogonal conditions were assured by creating 1.2 mm width disks on a rigid cylindrical workpiece. Experiments were conducted at 70 m/min cutting speed and feed rates of 0.2–0.275–0.35 mm/rev. In the orthogonal machining tests, it was observed that there was no major difference in the friction angle which was around 19°. The results were also showed that there is no significant difference between shear stress values (Table 2).

3.2. Face milling tests

A face mill tool with a diameter of 80 mm which can hold the SPKN type inserts was used. In the experiments a three component dynamometer was used for collecting force data. A single insert for each test was attached to the face mill holder for determining cutting forces acting on the insert. For a cutting depth of 0.5 mm, slot cutting operations were performed for all four sets of plasma boronized inserts and nonboronized inserts.

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