Magnetic field assisted diamond turning of titanium alloys

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Titanium alloys are known for their high strength, rigidity with low density, and exceptional biocompatibility, thus play an important role in aerospace, biomedical and automotive industries. However, they have a poor machinability due to low thermal conductivity and low elastic modulus. In this paper, the use of magnetic field assisted diamond turning (MFDT) to improve thermal conductivity and thereby increase the machinability of Ti-6Al-4 V alloys. The results suggests that the continuous and narrow chips are formed in applying the magnetic field, while under non-magnetic field conditions, the chips present discontinuous morphology and cracks. In addition, under the non-magnetic field condition, the roughness of the workpiece surface shows a concentration phenomenon, while after applying the magnetic field, the roughness of the workpiece surface presents a uniform distribution. Finally, there is a small difference between the microhardness values of the workpiece surface with and without magnetic field, and the microhardness values of the workpiece surface from the edge to the centre show a stable trend under the magnetic field condition, while it fluctuates greatly under the non-magnetic field condition.

NOMENCLATURE

MFDT = Magnetic field assisted diamond turning
LAM = Laser-assisted machining
UAM = Ultrasound-assisted machining
MFAM = Magnetic field assisted machining
LTUAM = Longitudinal torsional ultrasonic-assisted milling

1. Introduction

Titanium alloys are widely used for machining precision and ultra-precision parts in the aerospace, biomedical and automotive industries due to their high strength, rigidity with low density, and exceptional biocompatibility [1]. However, because the titanium alloys have a property of the low thermal conductivity and low elastic modulus, which are easily to cause the heat accumulation in the processing zone [2], and the presence of localized heat at the tool/workpiece interface contributes the tool wear and decreases the tool life, which exerts a negative impact on the surface finish and surface integrity of the workpiece [3]. As a result, titanium alloys have the poor machinability and are generally regarded as difficult-to-cut materials, suggesting that achieving excellent machining quality in titanium alloys is a great challenge. In order to decrease the turning temperature, reduce the tool wear and improve the machined surface quality, some researchers carried out numerous investigations in a cryogenic processing environment by applying liquid nitrogen, high-pressure cooling, etc. [4-6]. For example, Agrawal et al. [7] studied the effects of the cryogenic and wet machining on tool life, surface roughness, costing and carbon emissions in turning Ti-6Al-4V alloy, the results indicated that in comparison of the wet machining, the tool life was extended with a less wear, surface roughness was decreased, the costing and carbon emissions were reduced under the cryogenic machining conditions. However, although many beneficial effects have been obtained in turning Ti-6Al-4V alloy by using this method, machining accuracy is difficult to ensure due to thermal expansion and shrinkage of the workpiece. On the other hand, the utilization of liquid nitrogen and high-pressure cooling exists a frostbite risk in researchers.

Furthermore, external energy fields have also been applied to assist the ultra-precision machining of titanium alloys, such as laser-assisted machining (LAM) [8], ultrasound-assisted machining (UAM) [9] and magnetic field assisted machining (MFAM) [10]. Rashid et al. [8] used the LAM to process the titanium alloys, the laser was applied into the workpiece surface as a heat source to decrease the yield strength of the material, the findings suggested that the LAM evidently reduced the cutting force under a certain range of cutting parameters. However, despite numerous studies demonstrated that the use of LAM significantly decreased cutting forces, the rate of diffusion-controlled tool wear was increased, even in the presence of chip reduction [11-13]. Zheng et al. [9] thoroughly investigated the microstructural evolution of the surface metamorphic layer induced by longitudinal torsional ultrasonic-assisted milling (LTUAM) of titanium alloys, the results indicated the surface metamorphic layer under the under ultrasonic vibration appeared a larger plastic deformation compared to conventional milling. Moreover, the grain size in surface metamorphic layer obtained a refinement and the dominant deformation mechanism was dislocation slip and dynamic recovery after the LTUAM. However, UAM has many limitations and is not flexible enough. For example, ultrasonic vibration systems assisted machining in gear was limited by machine tool sizes, gear shape, and the gear material [14]. Furthermore, Fan et al. [15] performed the investigation on magnetic field assisted finishing for titanium alloys, and the designed magnetic field generator was integrated with four permanent magnets as a tool to realize the alternating magnetic zone, the experimental results presented that surface roughness and surface scratches of workpiece obtained a significant decrease by applying MFDT, which indicates that the application of MFDT is beneficial to improve the surface quality of the workpiece. In short, due to titanium alloys have a vital application in industrial field and the MFDT can exert a positive role in enhance the machinability of the workpiece, thus this paper implemented a research on MFDT in titanium alloys, aiming to further facilitate the widespread utilization of MFDT technology in the high-quality machining of titanium alloys and to establish a theoretical basis for its application to other difficult-to-machine materials.

2. Materials and methods

The experiments are carried out on a 5-axis ultra-precision lathe (Moore Nanotech 350FG), as illustrated in Fig. 1. The workpiece is fixed to the circular fixture, which is positioned on an aerostatic bearing spindle, with two permanent magnets posited at two sides. These workpiece materials are Ti6Al4V alloy bars with the length of 25 mm and the diameter of 12 mm. This experiment uses a single crystal diamond tool (Contour, UK) with a radius of 1.057 mm. The nominal rake angle and clearance angle are 0 and 15, respectively. Two sets of samples were prepared with the same machining parameters, including a depth of cut of 4 μm, a feedrate of 4 mm/min, and a spindle speed of 1500 rpm. The magnetic field intensity was set at 0 T and 0.015 T, respectively. The analysis on the machined surface involves the use of a white light interferometer (Nexview™, Zygo Corp., USA) to capture high-resolution surface topologies and precise surface roughness values (Sa). This allows for a thorough evaluation of how magnetic field affects the surface integrity in UPM, and the microhardness variations would be obtained by using a load of 300 g for 10s with the Vickers hardness tester (DURAMIN-40 A3).

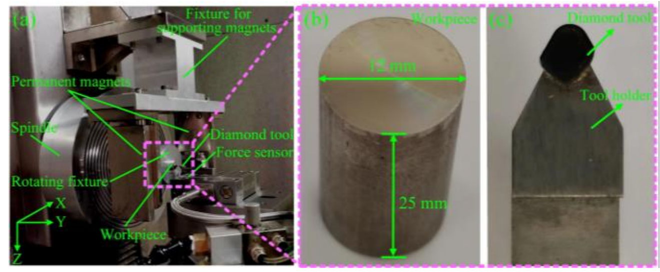

Fig. 1 The magnetic field assisted diamond turning of system

3. Results

3.1 Turning chips

Turning chips, as a by-product of the turning process, are an vital evaluation index of the machinability and machining characteristics of titanium alloys [16].Fig. 2 demonstrates the chip morphologies with and without magnetic field, as shown in Fig. 2a-b, which display the chip morphologies under the condition of magnetic field, it can be clearly observed that the chip is discontinuous with the existence of cracks, indicating that the existence of a plastic fracture in machining process [17], and the edge of the chip exhibits a serrated shape, which means that the turning performance is low in machining titanium alloys. However, when the magnetic field intensity was kept at 0.015 T, as shown in Fig. 2c, the chips show long and continuous shape with flat edges, and the more detailed chip observation is performed from the rake face and flank face (Fig. 2d-f), it can be found that numerous lamella structures in the rake face chips, and flank face chips display a smooth appearance without cracks. Furthermore, the chip of non-magnetic field sample has a narrower width in comparison of the chip of magnetic field sample. Through the above analysis, it can be known that a relatively high machining performance was achieved when the magnetic field was applied in turning titanium alloys.

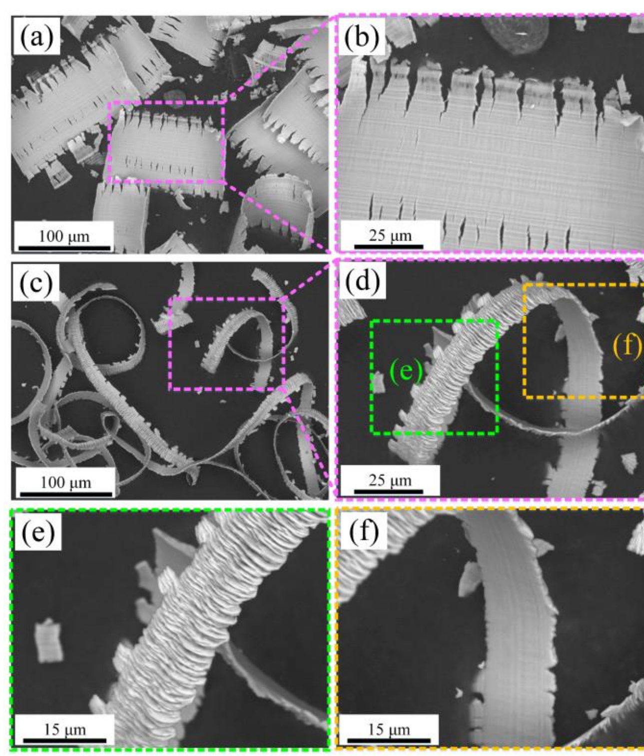

Fig. 2 SEM images of chip morphologies: (a) The low magnification

chip image without magnetic field, (b) a magnifying image of chip marked by red box in (a), (c) The low magnification chip image with magnetic field, (d) a magnifying image of chip marked by red box in (c), (e) the rake face chips marked by green box in (d), the flank face chips marked by orange box in (d)

3.2 Surface morphology

Fig. 3 shows the surface morphology of the workpieces with and without magnetic field, it can be obtained that the Sa value are 0.094 μm and 0.079μm, respectively. In addition, by observing Fig. 3a, the surface roughness of the workpieces appears to be significantly concentrated at a magnetic field intensity of 0 T, whereas the surface of the workpieces exhibits a homogenized roughness at a magnetic field intensity of 0.015 T based on the observation of Fig. 3b, which suggest that magnetic fields can effectively homogenize surface roughness.

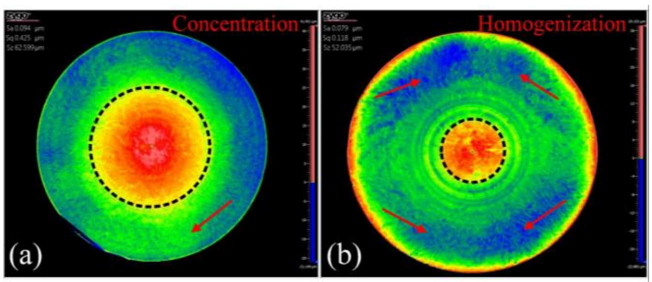

Fig. 3 Machined surface morphologies under various magnetic field conditions: (a) 0 T, (b) 0.015 T

3.3 Microhardness distribution

The microhardness is one of the most critical parameters for characterising the mechanical properties of machined samples [18], thus the microhardness testing was carried out by using the Vickers hardness tester. As displayed in Fig. 4a, the spacing between each hardness point is 0.5 mm, and the first and last test points are 0.5 mm and 5.5 mm from the sample edge, respectively. According to the results in Fig. 4b, the microhardness values showed a small variation between the magnetic and non-magnetic field samples. Furthermore, the microhardness value of non-magnetic field sample exhibit a huge fluctuation, while the microhardness value of non-magnetic field sample has a small fluctuations, which represents that the surface of magnetic field sample formed a more uniform microstructure.

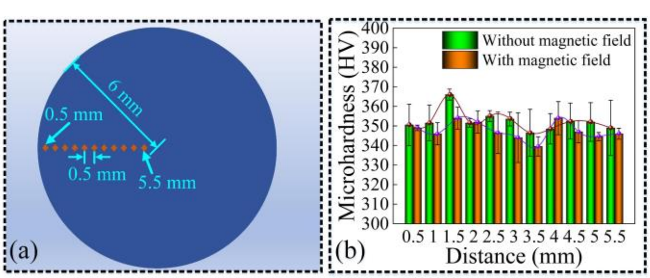

Fig. 4 Microhardness distribution: (a) testing location, (b) testing result

4. Conclusions

In this paper, chip formation, workpiece surface morphology and microhardness distribution on the workpiece surface under magnetic field and non-magnetic field conditions were mainly investigated. The experimental results showed that the use of magnetic field assisted diamond turning can produce continuous and narrow chips, while the chips showed discontinuous morphology and cracks under the non-magnetic field. In addition, under the condition of non-magnetic field, the surface roughness of the workpiece has a concentration phenomenon, while after applying the magnetic field, the surface roughness of the workpiece was uniformly distributed. Finally, the microhardness values of the workpiece surface differed very little between the conditions with and without magnetic field, and the microhardness values of the workpiece surface from the edges to the centre showed a stable trend under the magnetic field, instead of fluctuating greatly under the conditions of non-magnetic field.

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