Effects of magnetic field on microstructures and mechanical properties of titanium alloys in ultra-precision diamond turning

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Abstract

In this study, a magnetic field was superimposed in single point diamond turning (SPDT) of titanium alloys, aimed at enhancing the mechanical and microstructural properties of machined titanium alloy surface. The experimental results showed that the grain size decreased under an influence of magnetic field, showing grain refinements and reductions of grain pile up near grain boundaries on the machined surface, which grain pile up in machining of titanium alloys denotes as coarse colonies of alpha laths near grain boundary happening in the plastic deformation process. Also, microhardness and ductility of the machined surfaces were enhanced simultaneously by using a magnetic field in SPDT. The study proposes a novel machining technology to enhance mechanical properties and the grain structure of machined titanium alloys in SPDT.

Keywords: Titanium alloys; Single point diamond turning; Grain refinement; Mechanical properties; Magnetic field

1. Introduction

Titanium alloys are generally used for medical components; especially orthopedic applications that necessitate long term stability. One of the main issues affecting the functional performance of titanium alloys in orthopedic implants is an insufficient resistance to wear and a formation of debris generated by fractures during their service time [1], which would lead to an inflammation and osteolysis of the implanted body parts [2,3]. In order to resolve these problems, various techniques have been applied to enhance the surface properties of titanium alloys [4–6], contributing to the surface modification of titanium alloys to improve the microstructure, surface hardness, and wear properties of the material's surface [7–9]. Machining is one of the techniques used to impose large plastic strain in materials for promoting a formation of grain refinement and evolution of mechanical properties [9–11].

One of the approaches for the grain refinement are an application of a magnetic field during a grain recrystallization process in a solidification state of metal, which is the new approach for a grain evolution in recent years [12]. Successful cases have been demonstrated in literature for the grain refinement of metal in the solidification state using a magnetic field. Experimental results showed that extensive grain refinements were observed in the materials when the magnetic field intensity increased in the metal solidification [13–15]. Ban et al. [16] applied a magnetic field during the solidification of aluminum alloys and found that the grain boundary changed from continuous to discontinuous, which decreased the grain size and offered the grain refinement of the materials. Li et al. [17] also demonstrated that the application of a magnetic field enabled the grain refinement of materials. They conducted the experiment by employing a magnetic field during the solidification of austenitic stainless steel and concluded that the application of a magnetic field could remarkably refine the microstructure of materials. In machining processes, the extremely high cutting heat is generated at the tool/workpiece interface, especially for titanium alloys with low thermal conductivity, which melts the machined surface. The same principle of grain refinement by a magnetic field during the solidification state can be applied to the use of a magnetic field in the machining processes to refine the surface grains; the melted materials generated from the machining process would be refined in the presence of a magnetic field. Furthermore, evolutions of the mechanical properties such as microhardness [18,19] and ductility [20,21] are induced from the grain refinement. Therefore, microstructure evolutions and grain refinements would be expected on the machined surfaces by using a magnetic field during the machining processes. In this study, a magnetic field is introduced into ultra-precision machining in order to enhance the microstructure and mechanical properties of machined titanium alloy surface. The results show that the microstructure and mechanical properties of the machined surface evolved when the samples underwent diamond turning in the presence of a magnetic field.

2. Theory

In this study, titanium alloys suffered from nucleation and grain growth in the solidification process after single point diamond turning (SPDT). In order to obtain the grain refinements, the promotion of nucleation in solidification should be facilitated. In the experiments, titanium alloys were rotated in between a magnetic field during SPDT. An eddy current was generated on the machined surface of the workpiece within the magnetic field. Consequently, Lorentz force was generated by the interaction between the eddy current and the magnetic field, which is written as:

$$F = I \times B \quad (1)$$

Where B is the magnetic intensity and I the eddy current. It is well known that an electromagnetic force reduces voids and improves the uniformity of composition elements [22]. Lorentz force enables to eliminate the convection in the metal solidification, which is induced by the interaction between the eddy current and the applied magnetic field [23,24].

Studies have shown that the interaction of a static magnetic field and the generated eddy current induced by Lorentz force will produce a vibrating electromagnetic field. When the magnetic field and the eddy current influence the molten metal in the solidification state simultaneously, a cyclic magnetic force will generate and function as the periodic compression and tension force, leading to liquid oscillations [25,26] and a cavity formation as a result [27,28]. Under the continuous application of a magnetic field and an eddy current on the molten state of metal, the cavities would grow with the periodic compression and tension force until they collapse and are eliminated. Consequently, the strong shock waves are generated because of the collision of the cavities, which offer sizable pressures to increase the melting point of the molten metal [29]. As a result, the liquid vibration enhances the nucleation inside the metal. On the other hand, the passive convection introduced by the electromagnetic force causes the growth of equiaxed grains [30,31]. The grain boundary migrations during the recrystallization are enhanced in the presence of a magnetic field, which leads to the generation of low angle boundaries that increase the boundary area, thereby contributing to a decrease in grain size [32,33]. In addition, Shercliff [34] found that a static magnetic field can generate metal liquid flows in melting during metallurgy processes caused by the interaction of the magnetic field with the variations of the Seebeck coefficients at the solid–liquid interface, which indirectly increase the nucleation of grain in the solidification process. Studies have found that the grain refinements using a magnetic field in the metal solidification state are successful for various materials such as aluminum alloys [13,35] and magnesium alloys [36]. The enhancement of metal flows using a magnetic field have been applied in many cases of solidification of metallic alloys [37,38].

3. Experimental setup

Two samples of a two-phase titanium alloy, Ti6Al4V, were used as the workpieces for the experiments. The diameter and length of each of the two samples were 16mm and 50mm respectively. In the experiments, titanium alloys were undergone single point diamond turning (SPDT). Two magnets were preinstalled in an ultra-precision machine by the designed frame which titanium alloys were placed in between of two magnets. During the SPDT process, titanium alloys were rotated in between two magnets. Therefore, molten titanium alloys generated in SPDT within a magnetic field would cause molten titanium alloy suffering an eddy current and the influence of a magnetic field, which received the positive influences for grain structures and mechanical properties on the machined surface. The experimental set up is shown in Figure 1 with a graphical illustration. The applied magnetic field intensity was 0.02T. The radius and height of diamond tool used in the experiments were 1.468mm and 10.172mm respectively. Depth of cut, feedrate and spindle speed were set as 3μm, 8mm/min and 1500rpm respectively. Moore Nanotech 350FG (4 axis Ultra-precision machine) was used as the equipment for SPDT, and Wyko NT8000 Optical Profiling System was used to measure the surface roughness. The microhardness of the machined surface was measured by Vickers Hardness Tester (Future technology), and the microstructures on the machined surface were observed under scanning electron microscopy (SEM) machine Hitachi HT3030. The sample that underwent SPDT in the presence of the magnetic field is named MFS (magnetic field sample) while the sample that underwent normal SPDT in the absence of the magnetic field is named NMFS (non-magnetic field sample). The flatness of the machined surface of SPDT is sufficient for undergoing Vicker hardness test and SEM imaging as the slope of machined surface of SPDT is normally less than 0.5μm. Therefore, the polishing process was skipped for SEM imaging and microhardness testing. The samples were undergone an edging process with a strong acid in order to reveal the grain and grain boundaries. Also, Vickers hardness measurement was conducted on the machined surface before the etching process to ensure the accuracy of hardness measurement for the machined surface. For the operating conditions for SEM, the working distance was 8mm, the voltage was 5.2kV and the current was 1nA.

Due to the limitation of online measurement of cutting temperature in SPDT of titanium alloys, an indirect approach would be used for showing the melting process of titanium alloys in SPDT. According to literature, the main tool wear mechanism of titanium alloys in SPDT is adhesive wear, which adhesive tool wear must include the melting process of workpiece. Therefore, SPDT of titanium alloys should include the molten state of titanium alloys. Also, the microstructure of titanium alloys in as-received condition is shown in Figure 2.

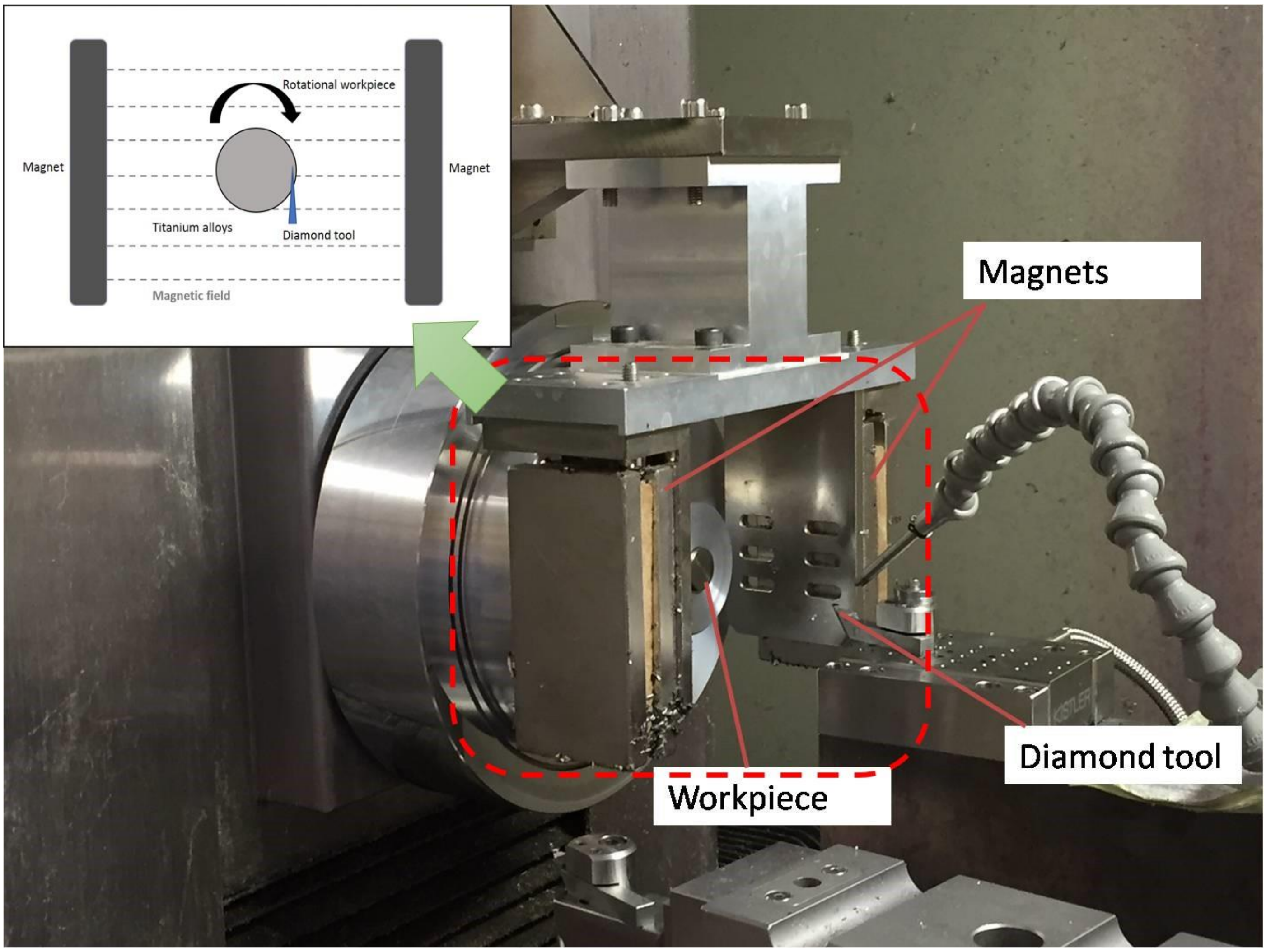


Figure 1. Experimental setup of SPDT using a magnetic field with an illustration graph

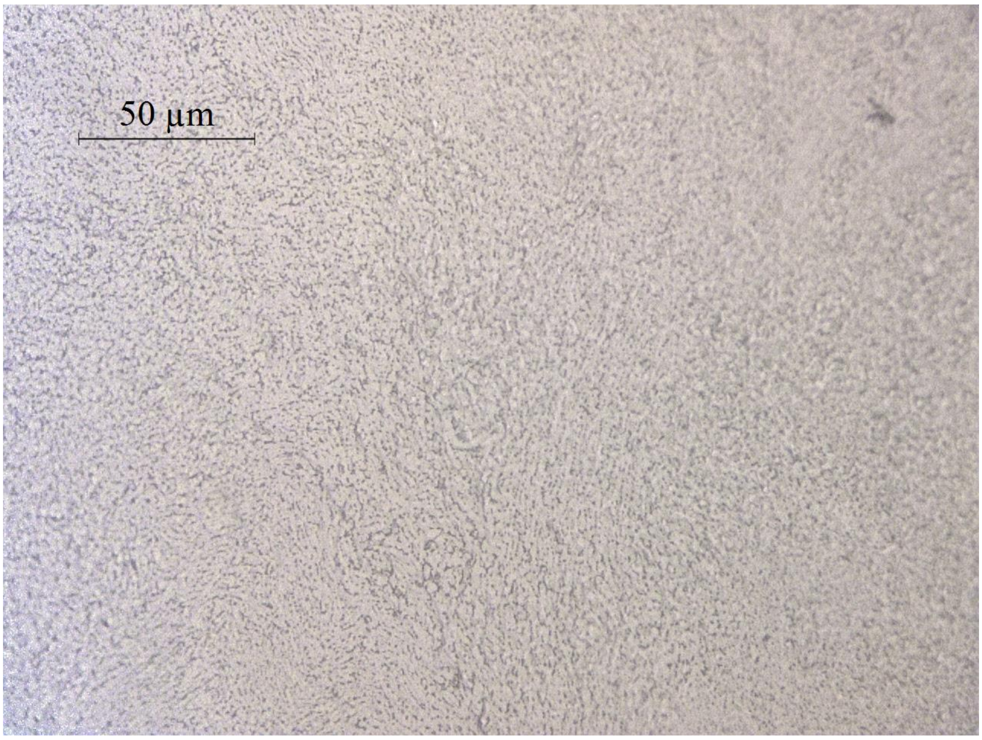


Figure 2. The microstructure of titanium alloys in as-received condition

4. Results and discussion

4.1 Reduction of grain size

Actually, adhesive tool wear is one of the main tool wear characteristics in diamond turning of titanium alloys [39], melting of metal is followed by adhering metals on the tool, which finally causes adhesive tool wear [40], therefore, melting of titanium alloys in SPDT were proven indirectly by the main wear mechanism of SPDT of titanium alloys. A direct generation of a compressive force in a liquid metal for a grain refinement of solidified metal structure with high temperature melting point is extensively used by many industries [41]. This study applied a magnetic field to provide such compressive force in material processing. Figures 3 shows the grain structures with different scales of MFS and NMFS obtained from SEM. Under the influence of an interaction between a magnetic field and eddy current in the solidification of a molten titanium alloy surface, the grain size of the machined surface of MFS was significantly smaller than that of NMFS in all scale measures. The average grain diameter of samples was measured by image software, the average grain diameter of MFS was measured as 92.5μm while that of NMFS was 116μm. The reduction percentage of average grain diameter by the influence of magnetic field was 20.3%. This provides a strong evidence of grain refinement in the machined surface of titanium alloys in SPDT using a magnetic field. As the change of the other cutting parameters such as magnetic field intensity, feedrate, depth of cut and spindle speed would cause the uncertainty in an identification of the source of evolution of grain size in this study, and, therefore, the effects of other cutting parameters on grain size would be discussed intensively in future and become the focus of the next research.

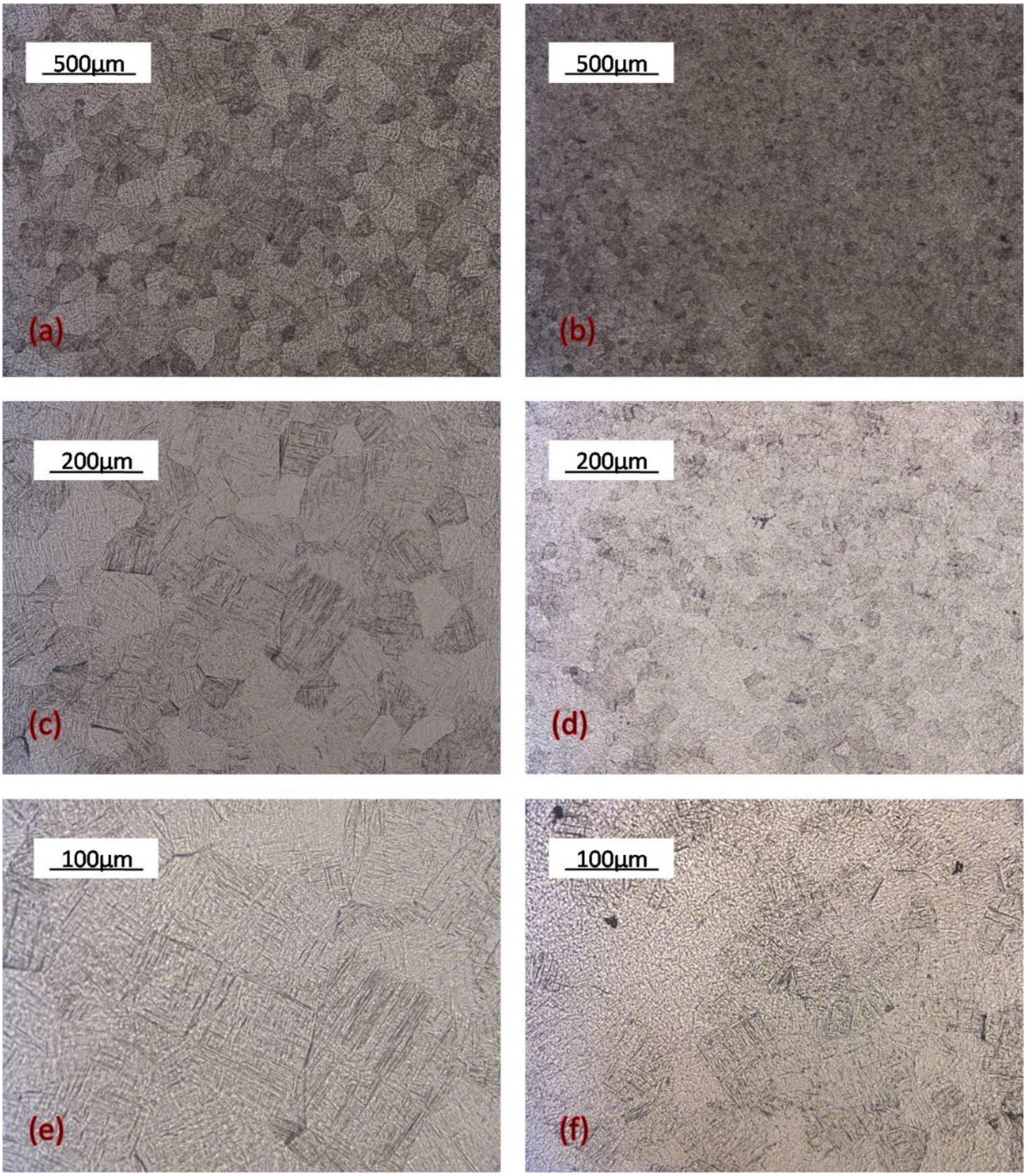
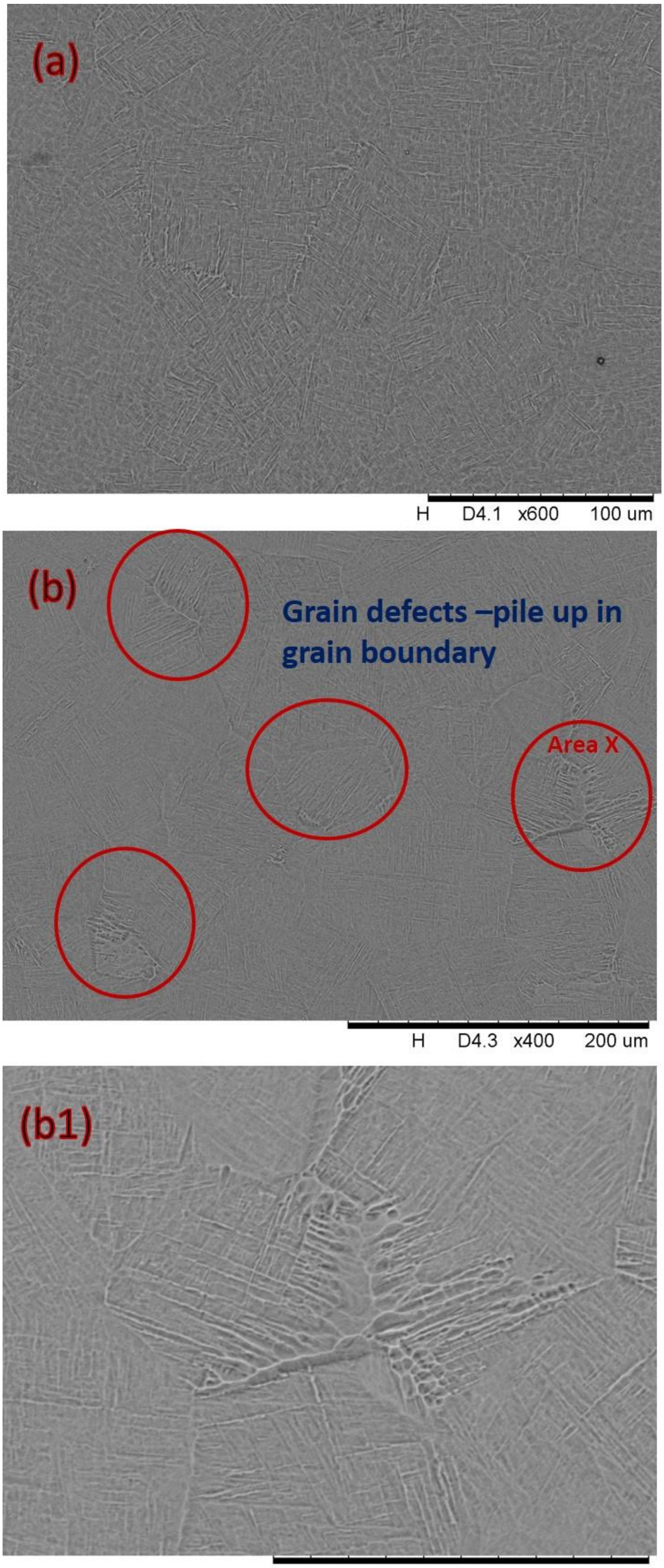


Figure 3. Microstructures of NMFS in the scale of (a) 500µm (c) 200µm (e) 100µm, and the microstructures MFS in the scale of (b) 500µm (d) 200µm (f) 100µm

It has been reported that grain defects such as cracks and misoriented grains, which have been caused by the thermal solutal convection [42,43], have appeared during the grain growth in the metal solidification. A static magnetic field has been used for reducing related fluctuations and therefore the grain defects have been reduced [23,38]. This technology has been extensively applied to give damping to the flow irregularities to minimize the solutal striation and eliminate defects in crystals during the metal solidification [23,44]. The principle of grain defect reduction by using a magnetic field can also be applied to the machined surface of SPDT in the presence of a magnetic field. Actually, in a machining process, high local stress concentration is inserted at the grain boundaries by the diamond tool, consequently, grain pile-ups due to the unique misorientation between the grains and the geometric incompatibility of the slip and twinning systems across the respective boundaries would happen [45]. Literature reported that grain size has a significant impact on slip motion, causing dislocations distributed over the workpiece. Therefore, grain pile up is one of the microtheoretical backgrounds for metal crystal plastic deformation, fracture, fatigue and creep mechanical properties [46]. The high cutting temperature melts the machined surface in SPDT, exposing the molten metal surface to the magnetic field and minimizing flow irregularities during solidification, which they can therefore reduce grain defects in the machined surface. The grain structures of both MFS and NMFS are shown in Figures 4. According to Figures 4(b), there showed grain defects in many areas over the machined surface of NMFS. Refer to Figure 4(b1), the higher modification of the defect area X in Figure 4(b), it clearly showed that the grain structures contained defects, showing the grain pile up in the grain boundaries. Actually, the pile up in the grain structures are due to the rejection of metal solute from the other melted metals during the metal solidification [47,48]. In comparison to the MFS, under the influence of magnetic field, the grain pile up in grain boundaries was eliminated, contributing to the reduction of grain defects.



Figures 4. Grain structures of (a) MFS and (b) NMFS. (b1) Higher minification of area x in (b)

4.2 Hardness improvement

Literature reported that the grain refinement benefits to the hardness enhancement [12,49–51]. According to the results from this study, surface hardness of MFS increased because of the grain refinement and the reduction of grain defects in the machined surface under the influence of magnetic field. Table 1 shows the results of Vickers microhardness of the MFS and NMFS over different areas of the machined surface. The linear cutting distance denoted that the cutting tool moved linearly from the beginning edge to the end edge of the workpiece at the center position. Actually, titanium alloys are polycrystalline materials, which the difficulty of finding the preferred grain orientation at the same crystallographic orientation for both samples was existed. Therefore, three different locations at the same machined surface were selected and five trials at every chosen location were conducted, which 15 trials of micro-indentation in total at each machined surface were conducted in this study for ensuring the comparability of the profiles of indentation and minimize the effects of crystallized orientation on the measure hardness and ductility. According to Table 1, all measured points on the machined surface of MFS had higher values of Vickers hardness in comparison to that of the NMFS. For surface hardness at the linear cutting distance of 7.5mm, the surface hardness of MFS is about 14% higher than that of NMFS. In addition, the variation of surface hardness over the whole machined surface of MFS was lower than that of NMFS, as shown in Table 1. In statistical analysis, the standard deviation of surface roughness over the machined surface for MFS was 2.72 while that of NMFS was 7.32. The slight change of microhardness over the machined surface for MFS would benefit to fatigue life of titanium alloys [52], lengthening operational time for medical applications especially for implants.

Table 1. Vickers microhardness of machined surface for the MFS and NMF

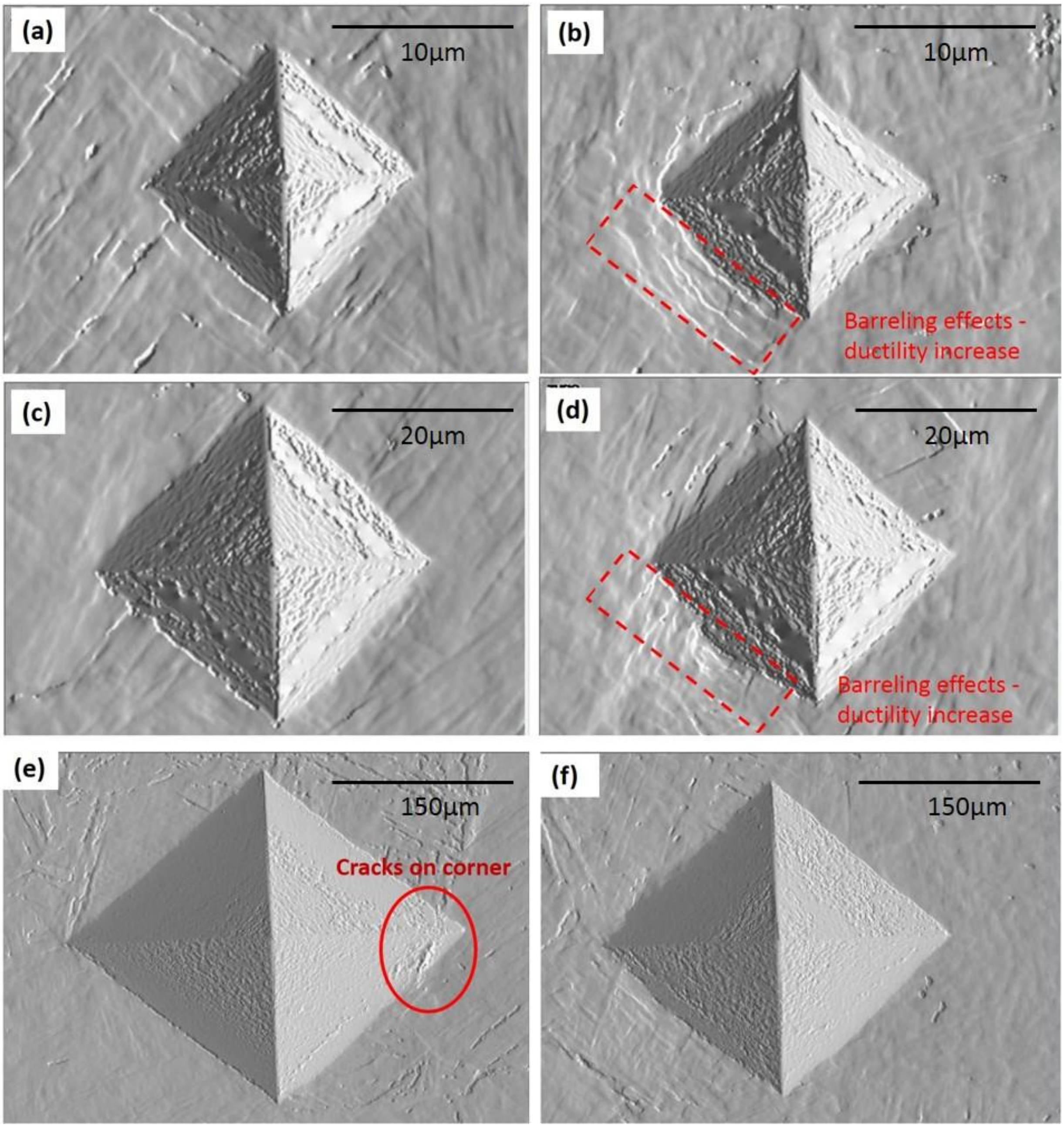
Linear cutting distance (mm)	Surface Vickers hardness (HV)	
	NMFS	MFS

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
2.5	342	348	339	344	343	343.2	382	376	383	374	380	379
7.5	333	327	328	331	324	328.6	372	373	370	375	379	373.8
12.5	345	336	337	334	323	335	375	379	383	374	378	377.8

4.3 Ductility improvement

Ductility of the machined surface of both MFS and NMFS was evaluated through the micro indentation test by Vicker indentation. The loads applied into the hardness tests were 5kg, 10kg and 80kg. The time for the indentation was 15s. The impressed diagonals produced by the indentation tests at different loading on NMFS and MFS are shown in Figure 5(a-f). According to Figure 5(b) and Figure 5(d), there consisted of material pile-up and wavy ridge patterns near the edge of impressed diagonals of MFS. These are the typical patterns for an increase of ductility of the materials which are known as the barreling effect [53,54]. Actually, it is a preferential deformation for material surface layer [55], the surface textures which were inferior to the plastic flow in the metal surface were removed under the influence of a magnetic field in SPDT. By contrast, for the NMFS, as shown in Figure 5(a) and Figure 5(c), the sides of the impressed diagonals of NMFS were much solid, clean and non-wavy texture displayed around the impressed diagonals, which they showed that the barreling effect was existed, it implied that lower of ductility of the surface in comparison of that of MFS. The above results showed ductility of titanium alloys was enhanced in SPDT under the magnetic field influence. Another evidence of the enhancement of ductility of MFS is provided in Figures 5(e-f), which show the impressed diagonal at a much higher loading of 80kg. According to Figure 5(e), the corner of impressed diagonal of NMFS demonstrated clear cracks. On the contrary, the shape of the impressed diagonal of MFS was entire and complete without showing a crack as shown in Figure 5(f). The comparison of the impressed diagonal between the MFS and NMFS showed higher ductility of MFS than that of NMFS. Actually, ductility and hardness are always contrast with another, an increase in ductility normally decreases hardness of materials [55,56]. The proposed machining technology provides one of feasible approaches to solve the above situation, contributing to increase hardness and ductility simultaneously by using a magnetic field.

In order to show the sufficient refinement of microstructures near indents of MFS, optical images of the microstructures near indents of MFS and NMFS were obtained and are shown in Figure 6. According to Figure 6, the grain size near indents of MFS was relatively smaller than that of NMFS, the above strengthens and validates the statements made in study that the ductility improvement by a magnetic field on the basis of barreling effect.



Figures 5. Shapes of impressed diagonals on machined surfaces of NMFS at loading (a) 5kg (c) 10kg (e) 80kg, and MFS at (b) 5kg, (d) 10kg, (f) 80kg

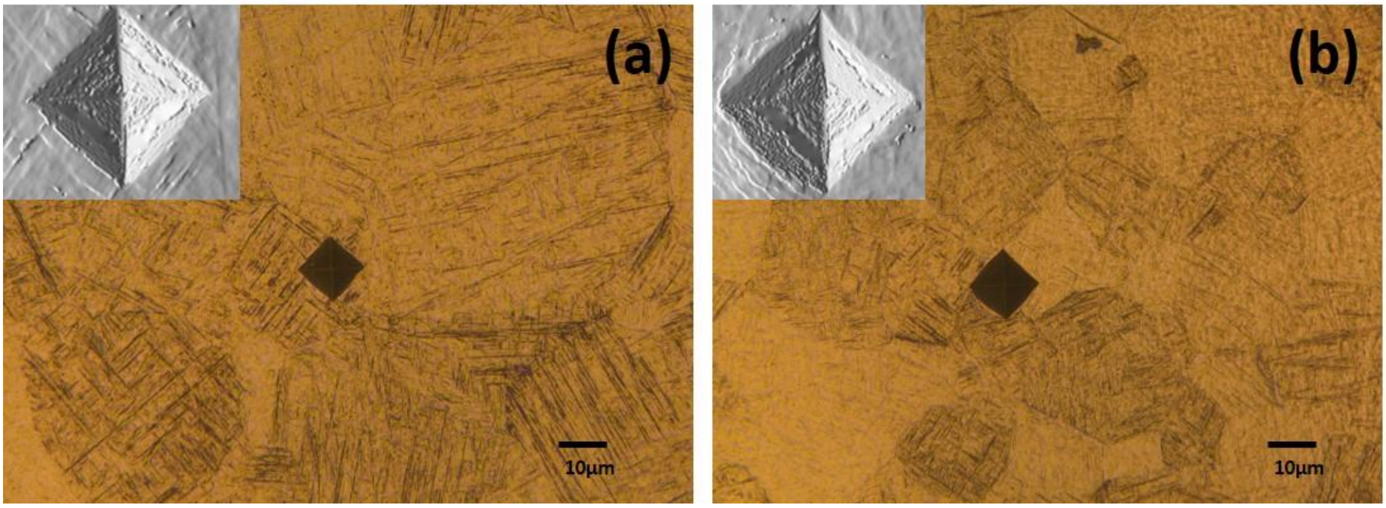


Figure 6. optical images of the microstructure near indents of (a) NMFS at Figure 5(a) and (b) MFS at Figure 5(b)

5. Conclusion

In this study, a magnetic field was applied into SPDT of titanium alloys to provide the evolutions of grain structure and mechanical properties to the machined surface of titanium alloys. A magnetic field is commonly used to refine the grain structure in the metal solidification state and has been widely applied into various industries. The same logic is employed in ultra-precision machining in this study. The experimental results showed the positive and consistent findings with above, with supporting results of enhancements in the grain structure and mechanical properties of machined surface. The grain structures, microhardness and ductility of titanium alloy surface by SPDT under the magnetic field influence were all facilitated, which the above contribute to increasing the function and working performances of titanium alloys in medical uses especially for the implant purpose.

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Declarations of interest: none

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