An investigation of surface uniformity, chip formation and microhardness of magnetic field assisted diamond turning of titanium alloys

Jiuxing Tang, Suet To, Wai Sze Yip#

State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong Special Administrative Region

Corresponding Author / Email: lenny.ws.yip@polyu.edu.hk, TEL: + 852 27666598

KEYWORDS: Magnetic field assisted diamond turning, Titanium alloys, Surface quality, Ultra-precision machining

Titanium alloys, renowned for their strength-to-weight ratio and biocompatibility, are significant in aerospace, biomedical, and automotive sectors. However, their low thermal conductivity and elastic modulus pose machining challenges in ultra-precision machining (UPM). This study explores Magnetic Field Assisted Diamond Turning (MFDT) to address this, aiming to enhance the machinability of Ti-6Al-4V alloy machining in ultra-precision machining (UPM). The results suggest that continuous and narrow chips are formed in applying the magnetic field, while under non-magnetic field conditions, the chips present discontinuous and cracks. Surface roughness analysis revealed the localized roughness area decreased to a consistently even finish at the surface center under magnetic field influence, indicating of improved surface uniformity. Finally, MFDT produced a consistently stable microhardness distribution from the workpiece edge to the center, unlike non-magnetic field conditions, emphasizing its impact on uniform material properties of a machined surface. This study contributes to improving the machining quality of titanium alloys by MFDT.

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 components in the aerospace, biomedical and automotive industries due to their high strength, rigidity with low density, and exceptional biocompatibility [1]. However, because titanium alloys have the property of low thermal conductivity and elastic modulus, which easily 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. To enhance machining efficiency and surface finish while mitigating tool degradation, researchers have explored cryogenic processing techniques, incorporating liquid nitrogen and high-pressure cooling systems [4-6]. A notable study by Schoop et al. [7] assessed the impact of cooling machining on the finish machining of Ti-6Al-4V alloy. They found that cryogenic machining not only improved the surface and sub-surface properties but also yielded very low tool wear. Despite these advantages, the approach presents challenges in maintaining machining accuracy due to workpiece expansion and contraction from temperature fluctuations. Additionally, the use of liquid nitrogen and high-pressure cooling introduces safety concerns regarding frostbite for personnel, necessitating careful operational protocols.

In order to improve ultra-precision machining for titanium alloys, a typical difficult to cut material, researchers have used external energy fields such as laser-assisted machining (LAM) [8], ultrasound-assisted machining (UAM) [9] and magnetic field assisted machining (MFAM) [10]. Rashid et al. [8] employed LAM, leveraging laser heat to soften the material, leading to reduced cutting forces under specific parameters. However, this technique was found to accelerate diffusion tool wear, despite its force-reducing benefits [11-13]. On the other hand, 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 represented the surface metamorphic layer under the ultrasonic vibration appeared a larger plastic deformation compared to conventional milling. Moreover, the grain size in the 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]. Fan et al. [15] performed the investigation on magnetic field assisted finishing (MFDT) 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. Given the critical role of titanium alloys in industry and the promising impact of MFAM on machinability, this study focuses on advancing MFAM for 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 except for the magnetic field intensity, including depth of cut of 4 μm, feedrate of 4 mm/min, and 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 are obtained using a Vickers hardness tester (DURAMIN-40 A3) loaded with 300 g for 10 seconds.

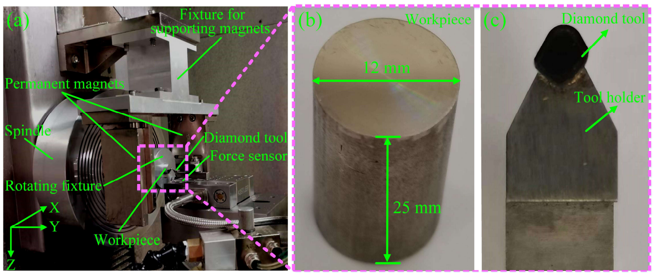

Fig. 1 Experimental setup of MFDT

3. Results

3.1 Chip formation

Chip formation is a vital evaluation index of the machinability and machining characteristics of titanium alloys [16]. Figure 2 illustrates a comparative analysis of chip formation with and without the application of a magnetic field. In Figures 2a-b, chips produced under magnetic field conditions exhibit a fragmented and discontinuous nature with cracks, of a plastic deformation and fracture mechanism during machining [17], and the edge of the chips exhibit a serrated shape, suggesting inferior cutting performance in non-magnetic field machining of titanium alloys. On the other hand, Figure 2c reveals a significant difference when the magnetic field intensity is set at 0.015 T. The chips show long and continuous shape with flat edges, and the more detailed chip observation is performed from the free surface and under surface (Fig. 2d-f), it can be found that numerous lamella structures in the free surface chips, and the under surface chips display a smooth appearance without cracks. Notably, the chips from non-magnetic field machining are narrower, further highlighting the difference in chip formation dynamics.

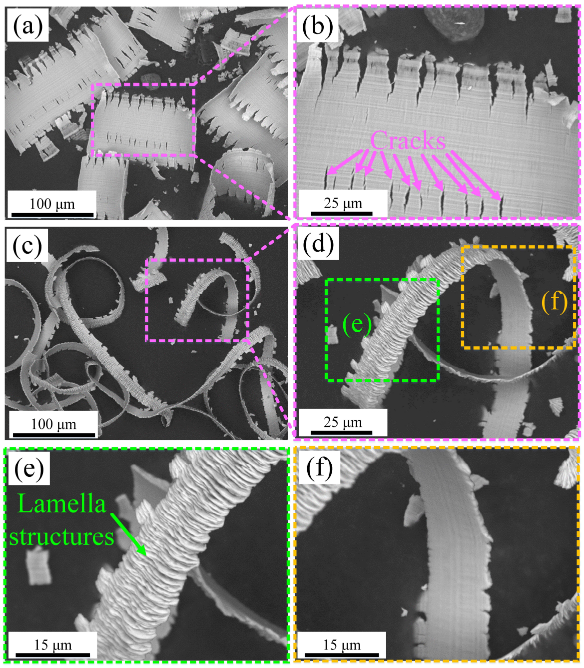

Fig. 2 SEM images of chip morphologies: (a) The low magnification chip image without magnetic field, (b) a magnifying image of chip marked by red box in (a), (c) The low magnification chip image with magnetic field, (d) a magnifying image of chip marked by red box in (c), (e) the free surface chips marked by green box in (d), (f) the under

surface chips marked by orange box in (d)

3.2 Surface uniformity

Figure 3 presents a comparative analysis of workpiece surface quality under magnetic field-assisted and conventional machining conditions. The surface roughness parameter Sa reveals a marked difference, with values of 0.094 μm for the non-magnetic field condition and a reduced value of 0.079 μm when a magnetic field of 0.015 T is applied. A closer examination of Figure 3a, representing the non-magnetic field scenario, shows a surface image with more pronounced height variations, indicating a lack of uniformity. Conversely, Figure 3b, showcasing the effect of a 0.015 T magnetic field, exhibits a surface with significantly reduced peak heights in the central area, leading to a more homogenous appearance across the entire surface.

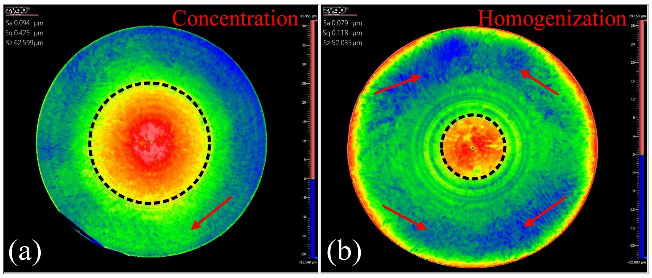

Fig. 3 Machined surface images under various magnetic field intensities: (a) 0 T, (b) 0.015 T

3.3 Microhardness distribution

Microhardness is a pivotal characteristic in assessing the mechanical integrity of machined surfaces [18], making it imperative to compare the microhardness profiles under magnetic field-assisted and conventional diamond turning. Figure 4a illustrates the measurement layout, with hardness points spaced 0.5 mm apart, with distance from 0.5 mm to 5.5 mm from the workpiece edge. 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 exhibits a large fluctuation, while the microhardness value of magnetic field sample has small fluctuations, which represents that the surface of magnetic field sample formed a more uniform microstructure compared to non-magnetic field sample.

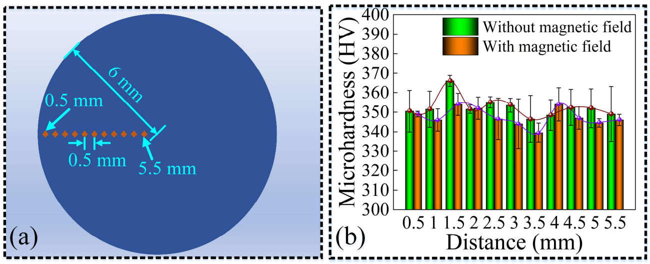

Fig. 4 Microhardness distribution: (a) testing location, (b) testing result

4. Conclusions

In this paper, chip formation, surface quality and microhardness distribution on the workpiece surface under magnetic field and non-magnetic field conditions were mainly investigated. This study highlights the significant benefits of magnetic field-assisted diamond turning for titanium alloys. The application of a magnetic field during machining resulted in continuous, narrow chips, compared to the discontinuous, cracked chips under non-magnetic field condition. Surface quality improved significantly, with a higher surface uniformity under magnetic field. And, although microhardness averages remained similar, the magnetic field sample shows a more stable microhardness change, contrasting with the instability in the non-magnetic field sample.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (Project No.: 52205498/K-ZGFT), and the Research Committee of The Hong Kong Polytechnic University (Project code: RJSH).

REFERENCES

1. W.S. Yip, S. To and Z. Sun., "Hybrid ultrasonic vibration and magnetic field assisted diamond cutting of titanium alloys," J. Manuf. Process., Vol. 62, pp. 743-752, 2021.
2. C. Che-Haron and A. Jawaid., "The effect of machining on surface integrity of titanium alloy Ti-6% Al-4% V," J. Mater. Res. Technol., Vol. 166, No. 2, pp. 188-192, 2005.
3. P.J. Arrazola, A. Garay, L.M. Iriarte, M. Armendia, S. Marya and F. Le Maître, "Machinability of titanium alloys (Ti6Al4V and Ti555.3)," J. Mater. Res. Technol., Vol. 209, No. 5, pp. 223-2230, 2009.
4. P. Huang, H. Li, W.L. Zhu, H. Wang, G. Zhang, X. Wu, S. To and Z. Zhu, "Effects of eco-friendly cooling strategy on machining performance in micro-scale diamond turning of Ti-6Al-4V," J. Clean. Prod., Vol. 243, pp. 118526, 2020.
5. A. Iqbal, W. Zhao, J. Zaini, N. He, M.M. Nauman and H. Suhaimi, "Comparative analyses of multi-pass face-turning of a titanium alloy under various cryogenic cooling and micro-lubrication conditions," Int. J. Lightweight. Mater. Manuf., Vol. 2, No. 4, pp. 388-396, 2019.
6. J.A. de Oliveira, S.L.M. Ribeiro Filho, C.H. Lauro and L.C. Brandão, "Analysis of the micro turning process in the Ti-6Al-4V titanium alloy," Int. J. Adv. Manuf. Technol., Vol. 92, No. 9-12, pp. 4009-4016, 2017.
7. Schoop, Julius, Wisley Falco Sales, and I. S. Jawahir, "High speed cryogenic finish machining of Ti-6Al4V with polycrystalline diamond tools," J. Mater. Process. Technol., Vol. 250, pp. 1-8, 2017.
8. C. Agrawal, J. Wadhwa, A. Pitroda, C.I. Pruncu, M. Sarikaya and N. Khanna, "Comprehensive analysis of tool wear, tool life, surface roughness, costing and carbon emissions in turning Ti-6Al-4V titanium alloy: Cryogenic versus wet machining," Tribol. Int., Vol. 153, pp. 106597, 2021.
9. R.A. Rahman Rashid, S. Sun, G. Wang and M.S. Dargusch, "An investigation of cutting forces and cutting temperatures during

laser-assisted machining of the Ti-6Cr-5Mo-5V-4Al beta titanium alloy," Int J Mach Tool Manufact., Vol. 63, pp. 58-69, 2012.

10. Y. Zheng, C. Wang, J. Ma, H. Li, Y. Li and C. Luo, "Gradient Characteristics of Surface Metamorphic Layer Microstructure Induced by Longitudinal Torsional Ultrasonic-Assisted Milling Ti-6Al-4 V Alloy," J. Mater. Eng. Perform., Vol. 32, No. 22, pp. 510141-10157, 2023.
11. W.S. Yip and S. To, "Reduction of material swelling and recovery of titanium alloys in diamond cutting by magnetic field assistance," J. Alloys Compd., Vol. 722, pp. 525-531, 2017.
12. M.S. Dargusch, T. Sivarupan, M. Bermingham, R.A.R. Rashid, S. Palanisamy and S. Sun, "Challenges in laser-assisted milling of titanium alloys," Int. J. Extreme Manuf., Vol. 3, No. 1, pp. 015001, 2020.
13. S. Sun, M. Brandt and M.S. Dargusch, "Thermally enhanced machining of hard-to-machine materials-A review," Int J Mach Tool Manufact., Vol. 50, No. 8, pp. 663-680, 2010.
14. M.J. Bermingham, S. Palanisamy and M.S. Dargusch, "Understanding the tool wear mechanism during thermally assisted machining Ti-6Al-4V," Int J Mach Tool Manufact., Vol. 62, pp. 76-87, 2012.
15. J. Dominguez-Caballero, S. Ayvar-Soberanis, J. Kim, A. Roy, L. Li and D. Curtis, "Hybrid simultaneous laser- and ultrasonic-assisted machining of Ti-6Al-4V alloy," Int. J. Adv. Manuf. Technol., Vol. 125, No. 3-4, pp. 1903-1916, 2023.
16. Z. Fan, Y. Tian, Z. Liu, C. Shi and Y. Zhao, "Investigation of a novel finishing tool in magnetic field assisted finishing for titanium alloy Ti-6Al-4V," J. Manuf. Process., Vol. 43, pp. 74-82, 2019.
17. C. Tang, D. Zhang, F. Wang, F. Yin, D. Qian, K. Li, Z. Cai, T. Huang, X. Zhang, J. Wang, C. Ye and H. Ding, "Effects of magnetic intensity on the machining quality and tool damage in nickel-based superalloys subjected to magnetic-assisted cutting," J. Mater. Res. Technol., Vol. 331, pp. 118494, 2024.
18. H. Du, C. Wu, D. Li, W.S. Yip, Z. Wang and S. To, "Feasibility study on ultraprecision micro-milling of the additively manufactured NiTi alloy for generating microstructure arrays," J. Mater. Res. Technol., Vol. 25, pp. 55-67, 2023.
19. C. Ni, L. Zhu, Z. Zheng, J. Zhang, Y. Yang, J. Yang, Y. Bai, C. Weng, W.F. Lu and H. Wang, "Effect of material anisotropy on ultra-precision machining of Ti-6Al-4V alloy fabricated by selective laser melting," J. Alloys Compd., Vol. 848, pp. 156457, 2020.