ASPEN

Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-14-0060

Magnetic field dependent machinability in ultra-precision machining of single-crystal copper

Yunfa Guo and Hao Wang#

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore
Corresponding Author / Email: mpewhao@nus.edu.sg, TEL: +65-65162207

KEYWORDS: magnetic field, machinability, ultra-precision machining, copper

The unsteady plastic flow during machining of ductile materials significantly limits their machinability. The magnetic field has shown a positive influence to alter the material deformation behaviour by promoting the dislocation movement in micro-cutting. In this work, the effect of a weak magnetic field and its directions on the machinability of single-crystal copper is investigated through magnetic field-assisted micro-cutting tests. Seven different magnetic field directions (0°, 30°, 60°, 90°, 120°, 150°, and 180°) relative to a constant cutting direction are applied in the micro-cutting tests. As a result, the application of magnetic field confirms the benefits to enhance the machinability of single-crystal copper, illustrated by a reduced cutting force, improved surface roughness, and suppressed subsurface damage. Moreover, the improvement in machinability of single-crystal copper closely depends on the magnetic field directions, and the 90° magnetic field shows the optimal cutting performance. The findings offer general guidance to enhance the machinability of ductile metals by introducing suitable magnetic fields with favourable directions.

1. Introduction

Cutting-induced plastic deformation at micro scale is controlled by the movement of dislocations. A mass of dislocations is created in the contact region between tooltip and workpiece due to the motivation of cutting loading and they tend to move along activated slip systems in the deformation zone. However, cutting-induced defects in the deformation zone would limit the displacement of dislocations and foster the formation of dislocation pile-up when the leading dislocation is stopped by these barriers and then the subsequent dislocations continuously accumulation here [1]. Accordingly, increased dislocation density owing to dislocation pile-up gives rise to the stress concentration on the barriers, and cutting loading must increase to induce enough stress to make the dislocations detach from the barriers in micro-cutting. Moreover, the dislocation pile-up effect would expand the area of the chip-free surface driving the excessive plastic deformation on the surface and lengthening the chip thickness, which further boosts the cutting force and inhomogeneous deformation in the cutting process [2,3]. The excessive plastic deformation and unsteady plastic deformation quash considerably the machinability of ductile materials. Positive efforts have been contributed to enhance the excessive plastic deformation in cutting of ductile materials, which includes the Rehbinder effect [4,5], microstructural modulation [6], and external constraints [7]. Magnetic field assistance is another potential technology to facilitate the machinability of ductile metals. Compared to other technologies, magnetic field assistance is easier to implant into the existing machines and more eco-friendly.

In the past few years, magnetic field has been successfully used in the field of ultra-precision manufacture to improve the machinability of difficult-to-machine materials, e.g., brittle ceramics [8], titanium alloys [9,10], and 316L stainless steel [11,12]. In addition, magnetic field also has shown the positive feasibility to promote the dislocation detachment from the barriers and advance the plastic deformation of ductile materials [13]. The magnetic effect on the micro-cutting of single-crystal copper was reported by Guo et al. [13], which reveals that the machinability of ductile metals is significantly improved by stabilizing the plastic deformation under a magnetic field, and the magnetic field directions dominant the advancement compared to the intensity and polarity. However, the prior research is confined to a small number of magnetic field directions. In the paper, we will investigate comprehensively the directional feature of magnetic field in micro-cutting of ductile metals by applying seven different magnetic field directions.

2. Experiments

To estimate the contribution of magnetic field and its orientations on the machinability of ductile metals, orthogonal micro-cutting tests

(Fig. 1) were conducted on an ultra-precision diamond turning machine (Toshiba ULG-100), equipped with a self-built electromagnetic setup. Single-crystal copper, a non-magnetic ductile metal, was chosen as the work material. The cutting tool used in the experiments is a single-crystal diamond tool with a 0° rake angle and nose radius of 0.8 mm. The cutting direction was fixed along $(111)[\bar{1}10]$. The intensity of the magnetic field was set as 20 mT, and the magnetic field orientations were arranged at 30° intervals from 0° to 180° relative to the fixed cutting direction $(111)[\bar{1}10]$, where 0° magnetic field represents the magnetic field orientation in line with the cutting direction, and 180° magnetic field is along the opposite direction of the cutting direction, as shown in Fig. 1. The cutting speed, undeformed chip thickness, and cutting length were respectively set as 20 mm/min, 10 μm, and 3.5 mm. The cutting force was recorded using a dynamometer (Kistler 9256C1) and amplifier (type 5051A) during the cutting process. The machined surface quality was assessed by a laser confocal microscope (Olympus LEXT OLS5500) after cutting. In addition, transmission electron microscopic (TEM) analyses using the equipment of Talos 200FX FEI USA were conducted to observe the evolution of subsurface microstructure.

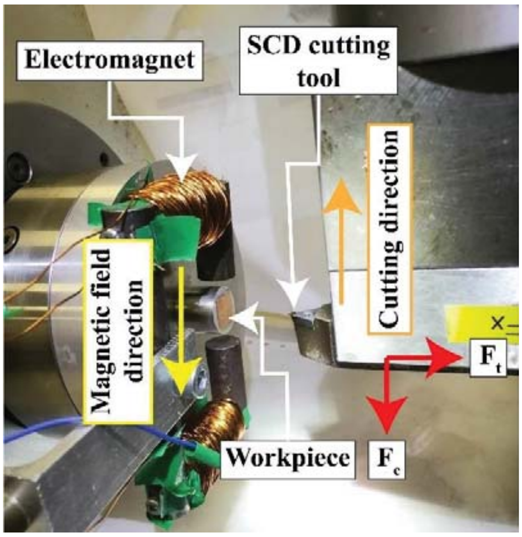

Fig. 1 Ultra-precision micro-cutting setup with assistance of magnetic field.

3. Results and discussion

Fig. 2 illustrates the recorded curves and average values of cutting force during micro-cutting under no magnetic field and different magnetic field directions, from which the magnetic field effect on the reduction in cutting force can be observed clearly from 3.19 N to 2.945-1.325 N. With increasing magnetic field angles, the magnetic field-induced force reduction is gradually more significant from 0° to 90° magnetic field, and the cutting force reaches a minimum at 90° magnetic field, after which, the extent of force reduction diminishes. In addition, the magnetic field-induced force reduction exhibits a symmetric relation relative to the minimal value at 90° magnetic field where similar force reduction is observed for the 0° and 180°, 30° and 150°, 60° and 120° magnetic field directions.

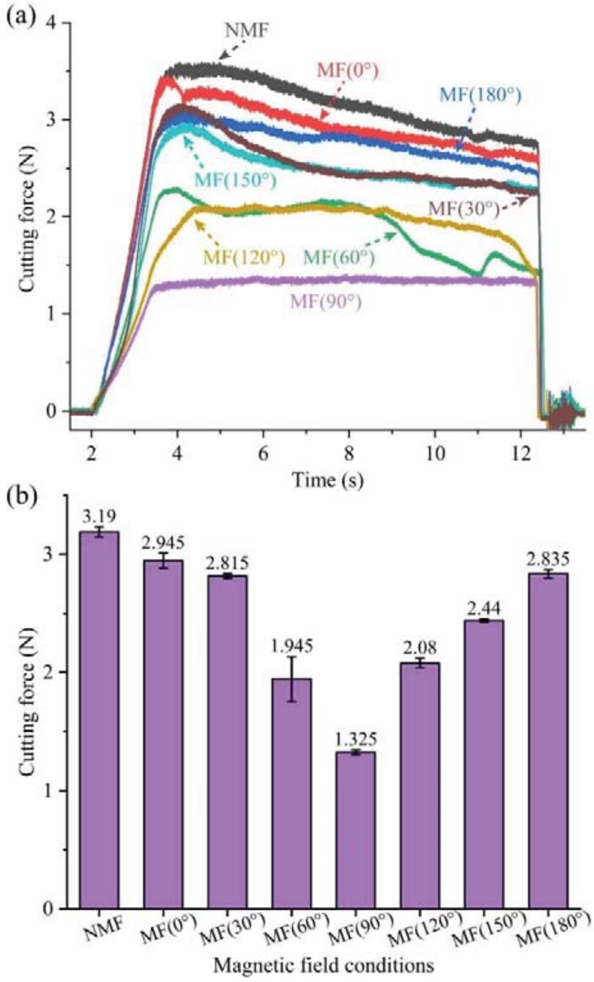

Fig. 2 Cutting force measurements under different magnetic field conditions: (a) recorded cutting force curves; (b) average values of cutting force. NMF: no magnetic field. MF: magnetic field.

Fig. 3 shows the optical images of machined surface under different magnetic field conditions. As seen in Fig. 3, transverse micro-stripes and two obvious folding including mushroom-shape folds and diagonal folds have been introduced during magnetic field-free cutting. According to Wang et al. [14], the damping effect induced by the elastic recovery on the machined surface results in the formation of transverse micro-stripes. The cutting-induced stress triggers an excessive plastic deformation and unsteady plastic flow, which contributes to the generation of mushroom-shape and diagonal folds on the machined surface [15]. After applying the magnetic field, the surface folding is suppressed to a varying extent with magnetic field directions, and the folding disappears completely at 90° magnetic field. However, we cannot find the apparent difference in the transverse micro-stripes after employing the magnetic field. This indicates that the applied magnetic field can significantly enhance the plastic deformation and has a negligible influence on the elastic deformation in micro-cutting of single-crystal copper.

To quantize the improvement of machined surface quality under the influence of magnetic field, the areal surface roughness Sa and Sz were measured, and the results are shown in Fig. 4. The change in surface roughness agrees with the evolution of surface morphology in

Fig. 3, which presents the orientational reduction from 47 nm to 43-29 nm for Sa, and from 1.258 μm to 1.135-0.836 μm for Sz with magnetic field directions. Furthermore, a symmetric relation at the two sides of 90° magnetic field is also observed in the surface folding suppression and roughness reduction, which is consistent with the directional reduction of cutting forces from 0° to 180° magnetic field in Fig. 2.

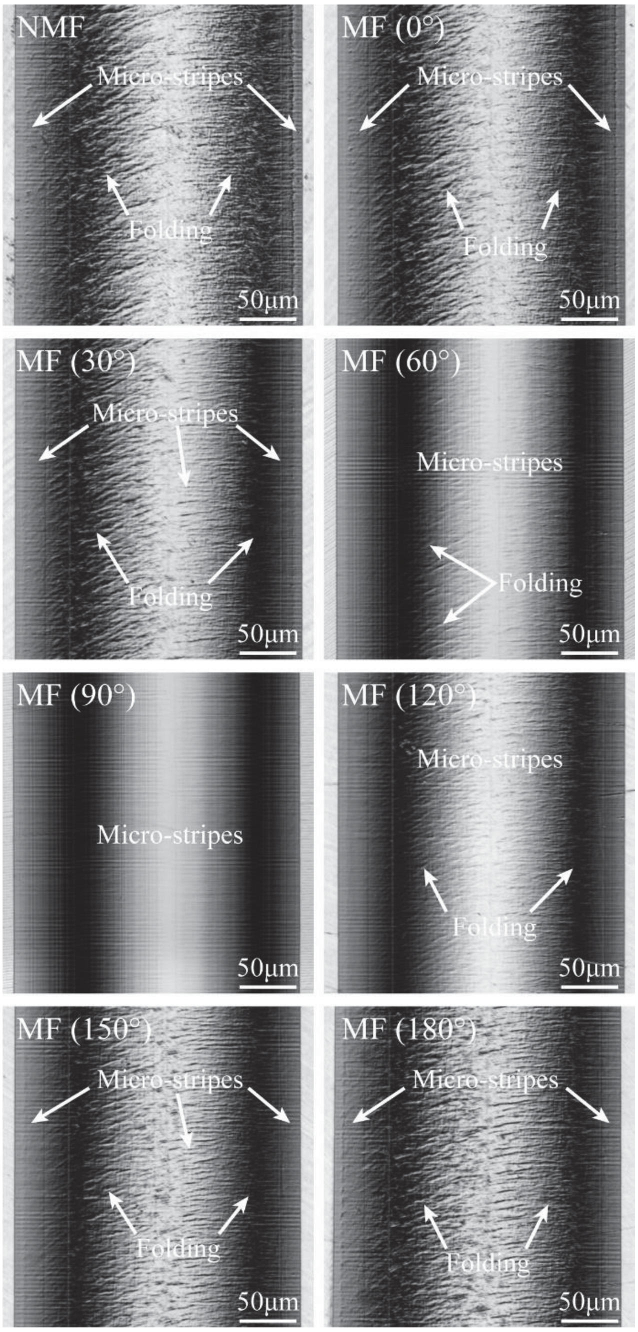

Fig. 3 Optical morphology of machined surface under different magnetic field conditions.

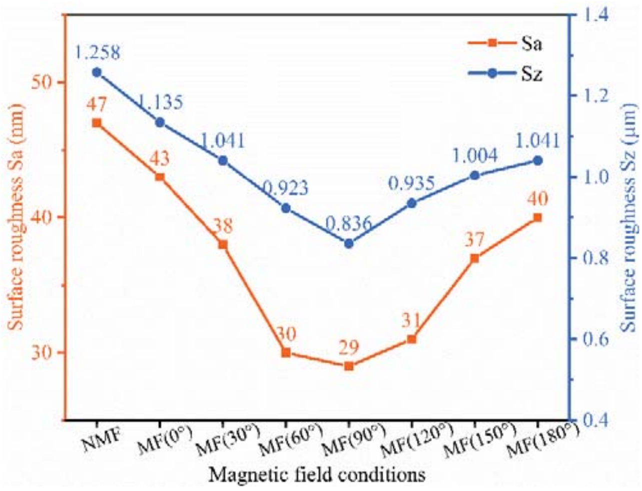

Fig. 4 Machined surface roughness (Sa: areal arithmetical mean height; Sz: areal maximum height) under different magnetic field conditions.

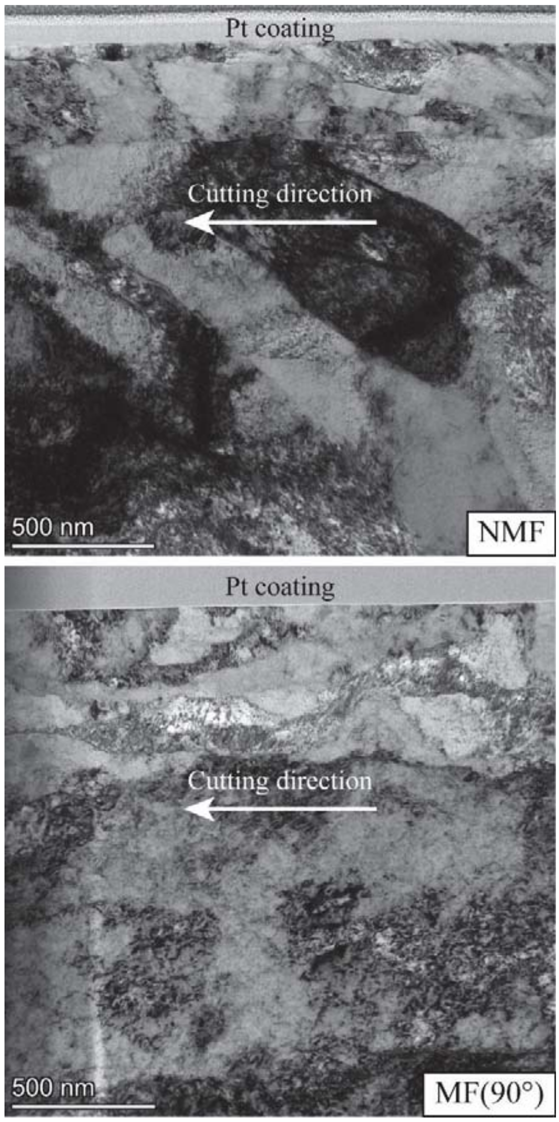

Fig. 5. Cross-sectional transmission electron microscopy (XTEM) images of subsurface microstructure under no magnetic field and 90° magnetic field.

In the study, we also evaluated the magnetic field-induced changes in subsurface microstructure formed below the machined surface during the cutting process. Fig. 5 shows the cross-sectional transmission electron microscopy (XTEM) morphology of subsurface microstructure under no magnetic field and 90° magnetic field. The cutting process instigates the generation of sub-grains below the machined surface, and the sub-grains are believed to be an accumulation area of dislocations, which would cause serious dislocation pile-up and then restrict the dislocation motion and plastic deformation [16]. With magnetic-field assisted cutting, the sub-grains are obviously suppressed with a smaller size and more coherent boundary orientation with cutting direction. The enhanced sub-grains under a magnetic field would be beneficial to the displacement of dislocations and reduce the stress concentration, leading to more steady plastic flow and attenuation of surface folds in micro-cutting.

4. Conclusions

The investigation successfully verified the positive impact of magnetic field on the machinability of ductile metals in magnetic field-assisted micro-cutting of single-crystal copper. The cutting results illustrate a significant decrease in cutting force from 3.19 N to 2.945-1.325 N, and surface roughness from 47 nm to 43-29 nm for Sa and from 1.258 μm to 1.135-0.836 μm for Sz after adding the external magnetic field. In addition, the surface and subsurface defects are also clearly suppressed with the magnetic field. It is also noticeable that the magnetic field-dependent machinability is closely decided by the magnetic field directions, and the 90° magnetic field exhibits the optimal cutting performance among all magnetic field directions. The results shown in the study offer a great understanding of the magnetic effect in ultra-precision machining of ductile materials and push the development of magnetic field assistance technique in manufacturing science.

ACKNOWLEDGEMENT

This research was conducted by National University of Singapore. We thank the support of the Singapore Ministry of Education Academic Research Funds (Grant No.: MOE-T2EP50120-0010, MOE-T2EP50220-0010, and A-0005236-01-00).

REFERENCES

[1] D. Hull, D.J. Bacon, Introduction to dislocations, 5. ed, Butterworth Heinemann, Elsevier, 2011.

[2] A. Chaudhari, H. Wang, Effect of surface-active media on chip formation in micromachining, J. Mater. Process. Technol. 271 (2019) 325–335. https://doi.org/10.1016/j.jmatprotec.2019.04.011.

[3] A. Udupa, T. Sugihara, K. Viswanathan, S. Chandrasekar, Altering the Stability of Surface Plastic Flow via Mechanochemical Effects, Phys. Rev. Appl. 11 (2019) 1. https://doi.org/10.1103/PhysRevApplied.11.014021.

[4] A. Chaudhari, Z.Y. Soh, H. Wang, A.S. Kumar, Rehbinder effect in ultraprecision machining of ductile materials, Int. J. Mach. Tools Manuf. 133 (2018) 47–60. https://doi.org/10.1016/j.ijmachtools.2018.05.009.

[5] Y.J. Lee, H. Wang, Current understanding of surface effects in microcutting, Mater. Des. 192 (2020) 108688. https://doi.org/10.1016/j.matdes.2020.108688.

[6] H. Zhang, X. Zhang, Factors affecting surface quality in diamond turning of oxygen-free high-conductance copper, Appl. Opt. 33 (1994) 2039. https://doi.org/10.1364/AO.33.002039.

[7] A. Udupa, A.S. Vandana, M. Saei, D. Gupta, J.B. Mann, K. Viswanathan, N.K. Sundaram, Sinuous plastic flow: Mechanics, microstructural basis, and control, Int. J. Mach. Tools Manuf. (2021) 103728. https://doi.org/10.1016/j.ijmachtools.2021.103728.

[8] Y. Guo, Y.J. Lee, Y. Zhang, A. Sorkin, S. Manzhos, H. Wang, Effect of a weak magnetic field on ductile–brittle transition in micro-cutting of single-crystal calcium fluoride, J. Mater. Sci. Technol. 112 (2022) 96–113. https://doi.org/10.1016/j.jmst.2021.09.049.

[9] W.S. Yip, S. To, Tool life enhancement in dry diamond turning of titanium alloys using an eddy current damping and a magnetic field for sustainable manufacturing, J. Clean. Prod. 168 (2017) 929–939. https://doi.org/10.1016/j.jclepro.2017.09.100.

[10] W.S. Yip, S. To, An application of eddy current damping effect on single point diamond turning of titanium alloys, J. Phys. D. Appl. Phys. 50 (2017) 435002. https://doi.org/10.1088/1361-6463/aa86fc.

[11] J. Zhang, H. Wang, A. Senthil Kumar, M. Jin, Experimental and theoretical study of internal finishing by a novel magnetically driven polishing tool, Int. J. Mach. Tools Manuf. 153 (2020) 103552. https://doi.org/10.1016/j.ijmachtools.2020.103552.

[12] J. Zhang, A. Chaudhari, H. Wang, Surface quality and material removal in magnetic abrasive finishing of selective laser melted 316L stainless steel, J. Manuf. Process. 45 (2019) 710–719. https://doi.org/10.1016/j.jmapro.2019.07.044.

[13] Y. Guo, Y.J. Lee, Y. Zhang, H. Wang, Magneto-plasticity in micro-cutting of single-crystal copper, J. Mater. Sci. Technol. 124 (2022) 121–134. https://doi.org/10.1016/j.jmst.2022.03.003.

[14] H. Wang, S. To, C.Y. Chan, C.F. Cheung, W.B. Lee, A theoretical and experimental investigation of the tool-tip vibration and its influence upon surface generation in single-point diamond turning, Int. J. Mach. Tools Manuf. 50 (2010) 241–252. https://doi.org/10.1016/j.ijmachtools.2009.12.003.

[15] D. Sagapuram, H. Yeung, Y. Guo, A. Mahato, R. M'Saoubi, W.D. Compton, K.P. Trumble, S. Chandrasekar, On control of flow instabilities in cutting of metals, CIRP Ann. 64 (2015) 49–52. https://doi.org/10.1016/j.cirp.2015.04.059.

[16] S.Y. Tarasov, A. V. Chumaevskii, D. V. Lychagin, A.Y. Nikonov, A.I. Dmitriev, Subsurface structural evolution and wear lip formation on copper single crystals under unlubricated sliding conditions, Wear. 410–411 (2018) 210–221. https://doi.org/10.1016/j.wear.2018.07.004.