Fabrication of groove-with-protrusion structures by ultrasonic vibration-assisted burnishing using a laser-grooved tool

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Micro-textured surfaces, such as groove and protrusion structures, are attracting considerable interests due to their anchor effect in direct bonding of metals and polymers, where the interfacial texture enhances the bonding strength of dissimilar materials. Especially the protrusion shape allows the metal to puncture the polymer side of the interface, thereby providing higher bonding strength against external shear forces. However, for the processing of such microstructures, powder additive manufacturing has difficulty in local processing and the protrusions may delaminate due to external forces, while material removal processing also has many restrictions on the shapes of texture available for machining and has relatively low machining efficiency. Therefore, an alternative technique for producing micro-protrusion textures in a local area with high efficiency is required.

In this study, an ultrasonic vibration-assisted burnishing method with a tool that has pre-formed micro-grooves at the tip was established to fabricate groove-with-protrusion structures on metal surface by plastic deformation. Before the burnishing experiment, the tip of ball-shaped polycrystalline diamond (PCD) burnishing tool was irradiated with a femtosecond pulsed laser to generate multiple trapezoid grooves which were approximately 42 μm in depth. Then the burnishing with and without ultrasonic vibration was conducted on a copper surface to investigate the characteristics and mechanism of plastic flow process.

The results showed that the protrusions and grooves were simultaneously produced along the tool path on the material surface, which were several tens of micrometers in height and depth. Cross-sectional observation also revealed that dislocation movement at the top surface was increasingly activated as the burnishing depth increased, causing significant grain elongation and refinement. This indicates that shear stress applied by burnishing produced refined grains, which flowed and formed the protrusion shape. Furthermore, ultrasonic vibration-assisted burnishing enhanced the plastic flow of refined grains, which was more concentrated on the topmost surface, leading to an increase in the height of the protrusions. This research demonstrates the feasibility of a highly efficient method for the simultaneous generation of groove-with-protrusion structures with enhanced surface properties.

1. Introduction

Reducing the weight of products has attracted much attention, particularly in the automotive and aeronautical industries, when increasing driving range and considering environmental issues. To minimize the weight, a combination of different materials has often been adopted, thus the methods of bonding materials with different properties are of significant importance. Among several jointing methods, direct bonding, in which metal and plastic can be bonded by utilizing the textures of the interface, is known as the anchor effect. In this method, the metal side is machined to generate microstructures on the surface so that plastic is allowed to flow into the gaps to form a bond. A protrusion structure on the metal surface can puncture the plastic side and show higher strength against the forces applied to the bonding interface.

Protrusions can be processed using additive powder processing or removal machining. However, in additive manufacturing, powder particles may detach under shear forces, and it is challenging to process curved surfaces or work locally. The removal machining process has limitations in shape and lower efficiency. Hence, an alternative method is needed to efficiently deform the base material for protrusions and enable localized processing. The new method proposed in this study is to use a tool with multiple micro-grooves in burnishing. By pre-grooving the tool with a number of micro-grooves, the workpiece flows into the grooves during burnishing, resulting in the continuous formation of a number of protrusion shapes along the tool path. The

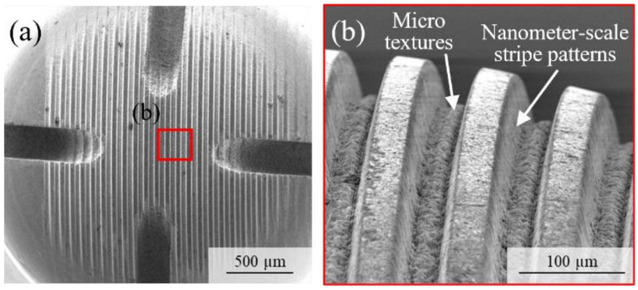

Fig. 1 SEM images of (a) overall view of a laser-grooved PCD tool; (b) close-up view of the tool tip.

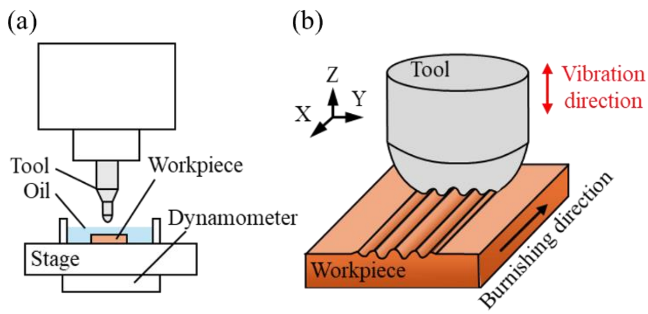

Fig. 2 Schematic diagram of (a) the burnishing system and (b) the burnishing experiment.

area compressed by the tool surface becomes a groove, which allows protrusion shapes and groove shapes to be alternately aligned. In addition, multiple shapes can be produced in a single tool pass, simplifying the process and reducing machining time compared to conventional methods. Furthermore, attaching the burnishing tool to a lathe allows for NC-programmed processing on curved surfaces and localized areas. From the above, the proposed processing method has the potential for novel microfabrication techniques.

In this plastic deformation process, one problem exists regarding form accuracy[1]. That is, since the workpiece material is being deformed instead of removed, the deformation resistance is higher than that in material removal machining, which can affect the precision of the tool's movement and may result in insufficient shape accuracy of the workpiece. The magnitude of this deformation resistance strongly depends on the processing conditions and the material properties of the workpiece, so appropriate modifications are required. One approach to address this issue is to apply ultrasonic vibration to the tool. Ultrasonic vibration has been reported to activate plastic flow and reduce deformation resistance by repeatedly applying pressure[2]. Utilizing vibration is expected to facilitate the flow of material into the tool, resulting in a more accurate transfer of the groove geometry of the tool.

In this study, micro-grooves were fabricated on the tip of a polycrystalline diamond (PCD) tool by ultrashort pulsed laser irradiation and then burnishing was conducted with the tool. Surface observation, profile measurement, and observation of the internal structural deformation were performed to investigate the fundamental processing characteristics. Then, the effectiveness of ultrasonic vibration was examined by applying vibration to the tool and by studying the changes in the microstructures of the workpiece.

2. Experimental method

For laser-grooved tool fabrication, a femtosecond pulsed laser was irradiated onto the tip of a PCD tool with a hemispherical shape (diameter 3.0 mm). 26 trapezoidal grooves of 42 µm height, 50 µm width and 80 µm pitch in cross-section were generated by the process. Fig. 1 shows the PCD tool tip after laser irradiation. As shown in Fig. 1(a), micro-groove shapes were fabricated on the entire area (500 µm diameter) of the tool surface that contacts the workpiece in the burnishing process. From Fig. 1(b), surface textures were observed at the bottom of the micro-groove, and nanometer-scale stripe patterns were observed on the sides in the direction parallel to the groove due to the influence of laser processing.

Table 1 Experimental parameters.

Parameters	Values
Burnishing parameters	
Burnishing depth [µm]	9, 15, 23
Speed [mm/s]	2.0
Lubrication condition	oil
Ultrasonic vibration parameters	
Vibration ampritude [µm]	2
Vibration frequency [kHz]	27

Fig. 2 shows a diagram of the burnishing system and the experimental method. As shown in Fig. 2(a), the tool was attached perpendicular to the workpiece which was fixed on the stage and the tool groove was adjusted to be parallel to the X direction. The workpiece was oxygen-free copper (15 mm × 15 mm × 3 mm), which was flattened on an ultra-precision cutting machine and tilt-corrected on the stage before the burnishing experiment. As shown in Figure 2(b), in the experiment the tool was first moved in the -Z direction to a constant burnishing depth and then moved forward 6 mm at a constant speed of 2.0 mm/s in the -X direction. Table 1 shows the experimental parameters. To investigate the fundamental characteristics of the process, the burnishing depth h_0 was varied. Furthermore, ultrasonic vibrations were applied to the tool in the Z direction. After the burnishing experiments, the burnished groove-with-protrusion structures were observed using a field emission scanning electron microscope (FE-SEM). The cross-sectional profiles were measured by scanning white light interferometry, and microstructural changes in subsurface layers were characterized using EBSD analysis.

3. Results and discussion

3.1 Surface morphology under conventional burnishing

Fig. 3 shows an overall image of the workpiece surface and a magnified image of protrusions when burnishing was performed at three different burnishing depths. At every burnishing depth, grooves compressed by normal directional forces and protrusions raised by the plastic flow of the workpiece were formed alternately and continuously along the tool trajectory; the groove and protrusions were uniformly spaced in line with the groove gap on the tool, and the grooves were smoothed on their sides by frictional contact with the tool. In contrast, on the protrusion surface, pile-ups containing shear zones were randomly observed at both ends of the protrusions. The pre-processed surface remained at the center of the protrusion, indicating no contact with the tool. Based on the above results, it can be deduced that during burnishing, the grooved tool initially glides over the workpiece,

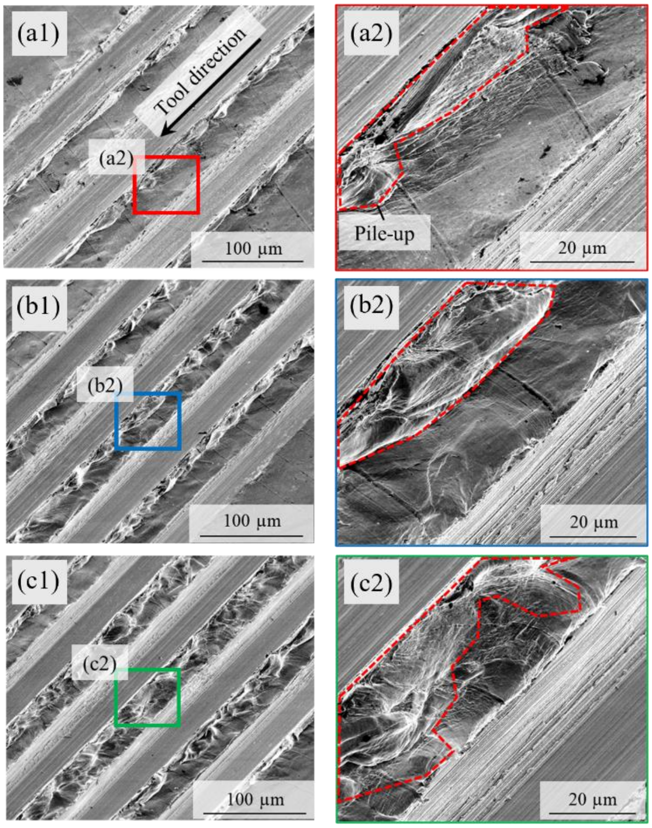

Fig. 3 SEM images of burnished grooves under the burnishing depth of (a) 9 μm, (b) 15 μm, and (c) 23 μm.

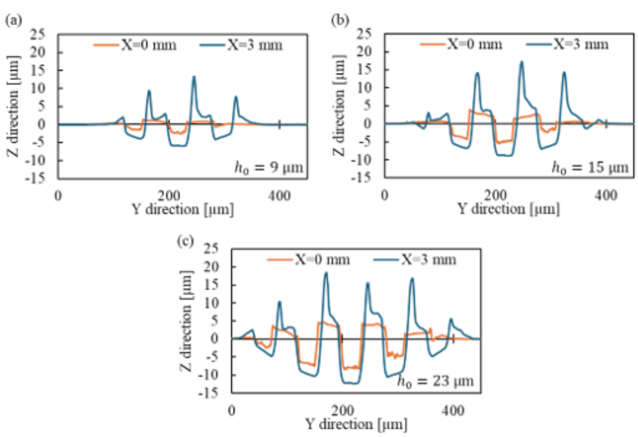

Fig. 4 Cross-sectional profiles of the burnished grooves at X = 0 mm and 3 mm under the burnishing depth of (a) 9 μm, (b) 15 μm, and (c) 23 μm.

effectively smoothing the central region of the grooves. Then, work material flowed into the tool groove by plastic flow and was deposited, leading to pile-ups at both ends of the protrusion. The variation of the protrusion shape is a result of the polycrystalline nature of the copper used in this experiment and the non-uniform deformation behavior caused by the differences in the crystallographic orientation of the individual grains.

Fig. 4 shows the cross-sectional profiles of the workpiece at positions X=0 mm (the start of burnishing) and X=3 mm (the middle of burnishing) at each burnishing depth: at X=0 mm, only the compressive effect on the workpiece was applied, while at X=3 mm the tangential force was applied as the tool moved in the X direction.

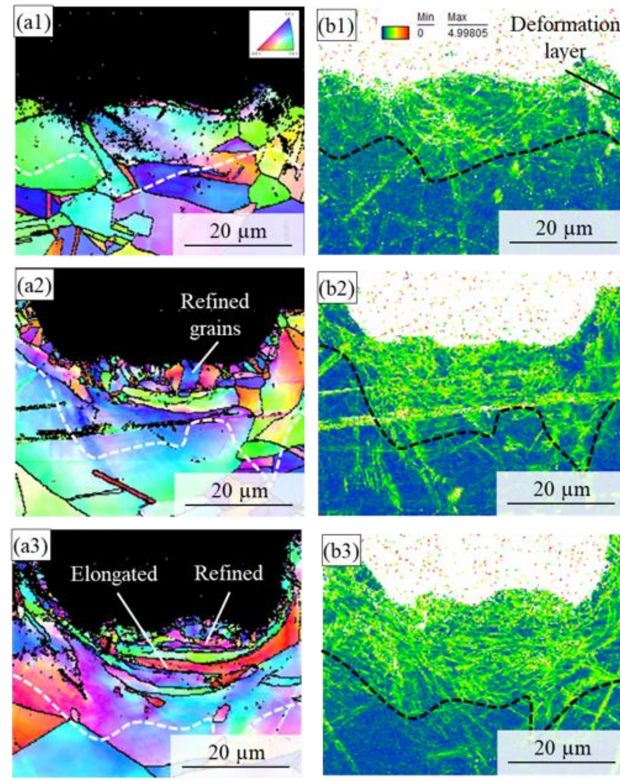

Fig. 5 IPF and KAM maps of the bottom of burnished grooves conducted at the burnishing depth of (a) 9 μm, (b) 15 μm, and (c) 23 μm.

For all the burnishing depths in Fig. 4, both the groove depth and the height of the protrusions were larger at X = 3 mm, while the width of the protrusions decreased. The reason for this could be that, with the tool movement, the tangential force as well as normal force was generated, which changed the direction of the total force towards the front of the tool, resulting in a plowing effect. This activated plastic flow and caused the workpiece to move more from groove to protrusion. Therefore, it can be said that in this process, the groove-with-protrusion structures were formed by two types of material deformation: the workpiece material extruded by compression in the normal direction and the workpiece material that flowed laterally from the front of the tool due to shear stresses. To calculate the proportion of the workpiece material that was compressed inwards and the proportion that flowed upwards, we define A as the cross-sectional area that protrudes above the original surface of the workpiece and B as the cross-sectional area that is void at the bottom; A/B represents the proportion of the workpiece that is raised from below to above by plastic flow. Calculations showed that at X = 3 mm, A/B was 99.6% at $h_0 = 9$ μm, 99.1% at $h_0 = 15$ μm, and 73.2% at $h_0 = 23$ μm. The results indicate that at $h_0 = 9$ and 15 μm, almost all of the workpiece material flowed, while around 27% of the Cu was compressed into the groove rather than flowing into the protrusion at $h_0 = 23$ μm. Thus, depending on the tool motion and burnishing depth, the plastic flow behavior of the workpiece was characterized by the action of plastic flow and the compression effect.

3.2 Subsurface microstructural changes

For further investigation on the plastic flow of the workpiece from grooves to protrusions, cross-sectional observations and local strain

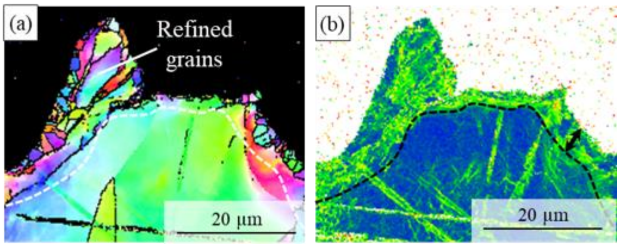

Fig. 6 (a) IPF and (b) KAM maps of the top of the burnished protrusion conducted at the burnishing depth of 15 μm.

distribution measurements were conducted. Fig. 5 shows the IPF and KAM maps of the groove cross-sections at different burnishing depths. With an increase in burnishing depth, Fig. 5(a1) -(a3) indicates that the grain refinement near the top surface was significant, with the average grain size on the surface decreasing from 9.2 μm (before the experiment) to 1.3 μm at $h_0 = 23$ μm. Furthermore, in Fig. 5(a3), elongated grains perpendicular to the tool motion were observed beneath the refined grains. Therefore, grains in the subsurface layers were likely elongated by tool loading and then divided into fine grains. From Figs. 5(b1) -(b3), it can also be seen that the dislocations inside the deformation layer increased in both density and depth with increasing burnishing depth. This indicates that the dislocations were composited by the shear stresses generated by the tangential forces, and as the workpiece was polycrystalline, the dislocations were accumulated near the grain boundaries. And since sub-crystalline grain boundaries are formed when the dislocation density reaches a certain degree, it can be assumed that the grain elongation and refinement occurred due to dislocation movement[3].

Fig. 6 shows the IPF and KAM maps of the protrusion at a burnishing depth of 15 μm. The inner part of the pile-up observed at both ends of the protrusion in Fig. 3 was composed of fine grains, the amount of which decreased towards the center. This indicates that protrusion was formed due to the flow of grains into the tool groove, which was elongated and refined by the motion of dislocations. From the above, it was found that in burnishing with a grooved tool, the shear stress generated by the tool motion activated the motion of dislocations, which led to grain refinement and the formation of a groove-with-protrusion structure.

3.3 Effect of ultrasonic vibration on deformation behavior

The clarification of the fundamental characteristics of this process indicates that the application of high strain to the workpiece through ultrasonic vibration enhances plastic deformation and shape formation. Fig. 7 shows the cross-sectional profile and the IPF map and KAM map of the subsurface layer when ultrasonic vibration was applied to the tool. From Fig. 7(a), it can be seen that the center of the protrusion was raised higher with vibration. It can be inferred that the repetitive application of compressive and tensile stresses inside the workpiece by vibration has accelerated plastic flow in the XY plane[4], thus introducing high strains in a very short period. The strain distribution was concentrated in the very near surface, which resulted in fine grains covering the groove. Therefore, it is assumed that dislocation movement was more activated, concentrating grain refinement in the subsurface layer, which raised fine grains into the tool groove during plastic flow, forming the central part of the protrusion. From the above, the application of vibration to burnishing is effective in introducing

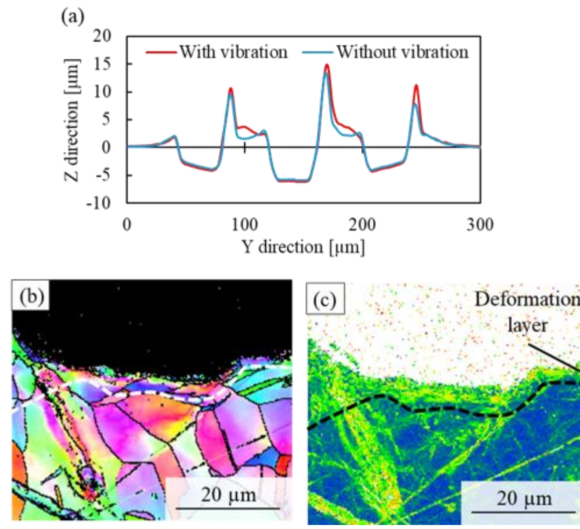

Fig. 7 (a) Comparison of the cross-sectional profiles with/without ultrasonic vibration assistance; (b) IPF and (c) KAM map of the bottom of the burnished groove when ultrasonic vibration was applied

local strain into the workpiece and is expected to stabilize the protrusion shape.

4. Conclusion

Ultrasonic vibration-assisted burnishing was conducted on oxygen-free copper using a micro laser-grooved tool, and the conclusions were summarized as follows:

(1) Protrusions and grooves were alternately and simultaneously formed on the workpiece due to the plastic flow of the material.

(2) The compressive stress induced by the normal force and the shear stress induced by the tangential force promoted plastic flow, increasing the groove depth and protrusion height.

(3) Crystal grains were elongated and refined by the motion of dislocations activated by shear stress on the groove surface and flowed to form a protrusion.

(4) With the application of ultrasonic vibration, high strain was repeatedly imposed on the workpiece, enhancing plastic flow in the X and Y directions and increasing the central part of the protrusion shape.

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