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# Study on the ultra-precision machining of polycrystalline tin

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*Metallic tin finds wide applications in the high-tech fields of atomic power industry, extreme ultraviolet light source, etc. Thus, high surface finishing and form accuracy of the tin components are in great demand. However, the low melting point and low stiffness of the metallic tin induce strong plastic deformation easily in micro- and nano-scale machining process, resulting in side-flow, burr formation and stick-slip phenomenon of materials on machined surface, which cause the deterioration of surface roughness. In this study, the polycrystalline tin is processed by single point diamond turning, and the factors contributing to the machined surface roughness are analyzed. It is found that the grain boundary steps are the major influence factors for the surface roughness with optimized processing parameters. Based on this knowledge, the surface modification methods to improve the machined surface roughness of polycrystalline tin are proposed. The first approach is using the thermal effect generated by the continuous wave laser, to achieve the grain refinement and case hardening of polycrystalline tin. Then single point diamond turning experiments are carried out on the modified workpiece and the machined surface roughness (Sa) reaches 2 nm, while the unmodified polycrystalline tin has a machined surface roughness of around 10 nm. Another way is to use the large thermal gradient treatment by induction discharge plasma, to achieve the grain expanding and fusion. Thus the amount of grain boundaries on the surface is decreased. After single point diamond turning, the surface roughness (Sa) of tin can achieve less than 1 nm.*

## 1. Introduction

Soft polycrystalline tin (Sn) has wide applications in various fields including atomic power industry, extreme ultraviolet light source, etc. [1, 2] The high shape accuracy and surface integrity, as well as low material damage are required in these micro- and nano-scale structures and components. Single point diamond turning (SPDT) is a promising manufacturing technology for the high surface quality machining of various materials [3]. However, the strong plasticity of soft metal materials induces plastic deformation easily in the micro- and nano-scale machining process, resulting in a stick-slip phenomenon with friction between the tool interface and soft metal materials. It was found that the elastic-plastic recovery of each grain was varied after cutting and the resulting grain boundary steps deteriorated the surface quality of polycrystalline copper (Cu) and lead brass ($CuZn_{39}Pb_3$) [4, 5]. Huang *et al.* [6] discovered that the minimal surface roughness when turning zinc selenide was dominated by grain boundary steps, which formed when the cutting tool crossed twin boundaries at a large angle. Yan *et al.* [7] reported that grain dislodgement was a major reason for the surface roughness of reaction-bonded silicon carbide during diamond turning. Therefore, the grain boundaries and orientations also affect the machined surface quality significantly in the SPDT of polycrystalline metals. As for soft polycrystalline tin, the negative effects of strong plasticity and grain boundaries on the machined surface roughness during SPDT are predictable. Therefore, improving the machinability by surface modification plays an important role in improving the deformation resistance and processing accuracy of soft metal materials.

In this study, the polycrystalline tin is processed by SPDT experiments, and the factors contributing to the machined surface roughness are firstly analyzed. Then, the surface modification methods to improve the machined surface roughness are proposed. The first approach is using the thermal effect generated by the continuous wave laser, to achieve the grain refinement and case hardening of polycrystalline tin. Another way is to use the large thermal gradient treatment by induction discharge plasma, to achieve the grain expanding and fusion. Finally, the SPDT experiments are carried out on the modified surface and the lower surface roughness is achieved.

## 2. Factors contributing to the machined surface roughness

In SPDT process, the arc form of tool nose will imprint on the surface of workpiece and the unremoved material will induce the theoretical nanoscale surface roughness, as indicated as $R_z$ in Fig. 1. The theoretical scallop height of this part $R_z$ is a function of tool nose radius ($R_{nose}$) and feed rate ($f$) as follows:

$$R_z = R_{nose} - \sqrt{R_{nose}^2 - \frac{f^2}{4}} \quad (1)$$

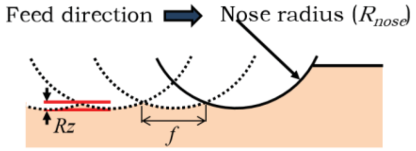


Fig. 1 Schematic of theoretical scallop height

In nanometric cutting, because of the effects from the tool edge radius, there must be a critical depth of cut, less than which the material cannot be removed, bringing more scallop height on the machined surface [8]. Another factor affects the machined surface roughness of soft metal tin is the side-flow in processing because of the strong plasticity, which will also bring negative effects on machined surface finishing.

SPDT experiments are carried out on polycrystalline tin, and the surface micro topography is measured by the white light interferometer (WLI), as show in Fig. 2. It can be seen that the measured surface roughness (Sa) and micro topography of individual grain is different from each other. Grain 1 has a smooth surface with roughness Sa of 1.76 nm, and the regular turning patterns are observed. The surface roughness of Grain 2 is 5.20 nm and the surface folds are observed. The difference can be explained by the anisotropy of crystal tin in surface formation and sub-surface deformation in nanometric cutting, since the crystal orientation of each grain is different. When cutting along different orientations of crystal tin, the sub-surface defects such as dislocations and stacking faults would extend along different directions, resulting in the difference in surface formation. In addition, the machined surface recovery would also be different when cutting on different lattice planes.

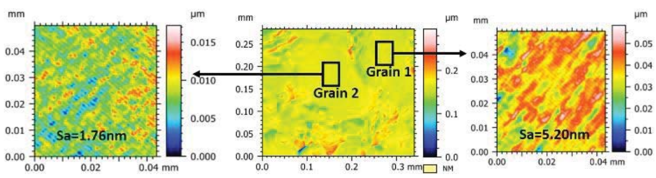


Fig. 2 Surface topography of polycrystalline tin after SPDT

Fig. 3 shows the grain boundary steps on machined surface. It can be seen that the step could be as high as more than 60 nm, which is much higher than the theoretical scallop height with specific processing parameters in SPDT. This phenomenon shows that the grain boundary steps dominants the minimal surface roughness of polycrystalline tin in SPDT machining. Thus, adjusting the grain boundary condition could be an effective way to improve the surface finishing of polycrystalline tin in SPDT.

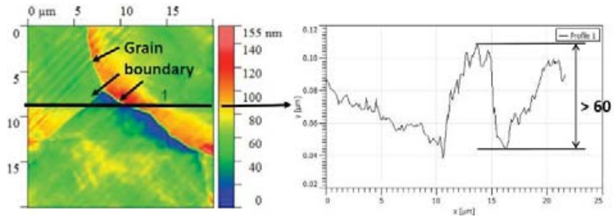


Fig. 3 Grain boundary steps of polycrystalline tin after SPDT

## 3. Surface modification methods to improve the machined surface quality

### 3.1 Laser-based surface modification

In recent decades, lasers have been widely used in the fields of electronic industry and machinery manufacturing. The principle of laser surface modification technology is to use the energy of the laser beam to change the chemical composition or structure of the material surface, so as to improve the performance of the material in some aspects [9]. Thus, a method of surface modification assisted ultra-precision machining of polycrystalline tin by using the thermal effect generated by the continuous wave (CW) laser is proposed. The surface of polycrystalline tin is irradiated by the laser, and the surface material is melted by endothermic heat and then recrystallized to form a modified layer of a certain thickness. SPDT experiments is then performed on the modified surface. Fig. 4(a) shows the surface morphology of unmodified polycrystalline tin obtained by SPDT. Grain boundaries can be identified easily because of the large height difference. Therefore, the surface roughness is seriously affected by the existence of grain boundary steps. The machined surface roughness (Sa) of the unmodified polycrystalline tin is 11.71 nm. After laser modification, the machined surface roughness of polycrystalline tin decreases to 2.16 nm with the same turning parameters, as show in Fig. 4(b). The turning marks are obvious and no grain boundary steps are observed.

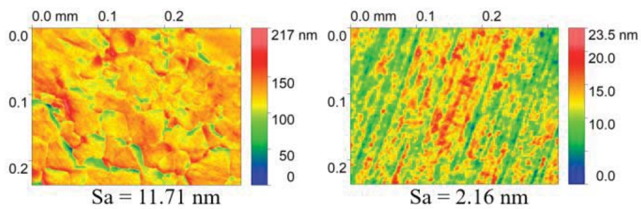


Fig. 4 Surface topography of polycrystalline tin after SPDT. (a) Unmodified surface; (b) Laser-based modified surface.

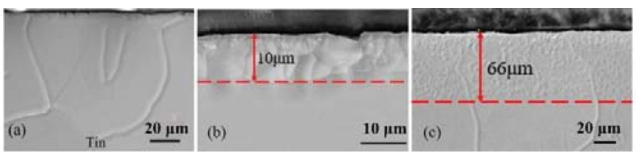


Fig. 5 SEM images of cross-sectional samples. (a) Unmodified subsurface; (b) Modified subsurface with laser beam with low power density ($2.1 \times 10^4$ W/mm$^2$); (c) Modified subsurface with laser beam with high power density ($3.9 \times 10^4$ W/mm$^2$).

Cross-sectional samples are prepared for both modified and unmodified samples. Then SEM is used for subsurface morphology observation, as shown in Fig. 5. The unmodified subsurface of polycrystalline tin presents the grain size of 100-200 μm, as shown in Fig. 5(a). After the laser surface modification, the grain size decrease to less than 10 μm. When the laser power density is $2.1 \times 10^4$ W/mm$^2$, the thickness of the modified layer is about 10 μm (Fig. 5(b)), and when the laser power density increases to $3.9 \times 10^4$ W/mm$^2$, the thickness of the modified layer is about 66 μm (Fig. 5(c)), which means the thickness of modified layer increases with the higher laser power density.

### 2.2 Plasma-based surface modification

It was reported that several metals can obtain the effect of grain size amplification by large thermal gradient treatment. Maruyama et al. [10] found that after heating ceria with a large thermal gradient of 0.3-0.5℃/μm, the grain size of ceria increased from 8 μm increased to 37 μm. In this study, an induction discharge plasma-assisted cutting (PaC) method is proposed to reduce the influence of grain boundary steps on the surface roughness in the SPDT of polycrystalline tin. Through the large thermal gradient of induction discharge plasma, the polycrystalline tin grains in the area are expanded, which decrease the number of grain boundaries on the surface of polycrystalline tin. Then, the influence of a large number of grain boundary steps on the surface roughness in SPDT is eliminated.

The inductively coupled plasma (ICP) thermal treatment is carried out and the equipment is shown in Fig. 6. The PaC treatment for polycrystalline tin can be divided into two steps: plasma thermal treatment and ultra-precision SPDT which are optimized respectively. The magnitude of the thermal gradient is the key parameter that modifies the solidification microstructures. Different temperature gradients are obtained by changing the plasma power, and the feasibility of PaC is verified by SPDT experiments with the optimized parameters. Through the comparison of surface roughness in Sa, the appropriate plasma thermal treatment power is selected.

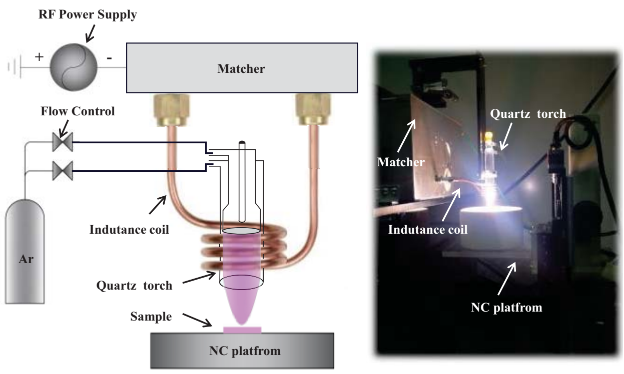


Fig. 6. Schematic diagram and photograph of ICP setup.

The unmodified polycrystalline tin and plasma modified polycrystalline tin with power of 0.9 kW are selected for the SPDT experiment, and the results are shown in Fig 7. The machined polycrystalline tin surface quality with the PaC method is less than 1 nm, and the turning patterns can be observed in the inner region of the polycrystalline tin grain, and the surface roughness is 0.80 nm, as shown in Fig. 7(a). There are grain boundary steps at the junction of two polycrystalline tin grains, but the height of grain boundary steps is only 4.12 nm, which has little effect on the surface roughness of the measurement area, as shown in Fig. 7(b). However, as shown in Fig. 7(c), it can be observed that a large number of grains boundaries appear on the surface of unmodified polycrystalline tin. Due to the different orientation and size of each grain, the types of grain boundaries between different grains are also different, resulting in significant differences in the microstructure deformation of the machined surface grain and the elastic-plastic recovery of each grain is also different after SPDT. The disparity of grain boundary step height between different grains is obvious so the surface quality is seriously affected. The surface roughness is 8.53 nm in Sa, and the grain boundary step height is 48.23 nm. The above characterization results show that the surface quality of polycrystalline tin modified by ICP can be improved greatly after optimized SPDT processing, and the surface roughness of Sa less than 1 nm can be achieved, which proves the progressiveness of PaC treatment.

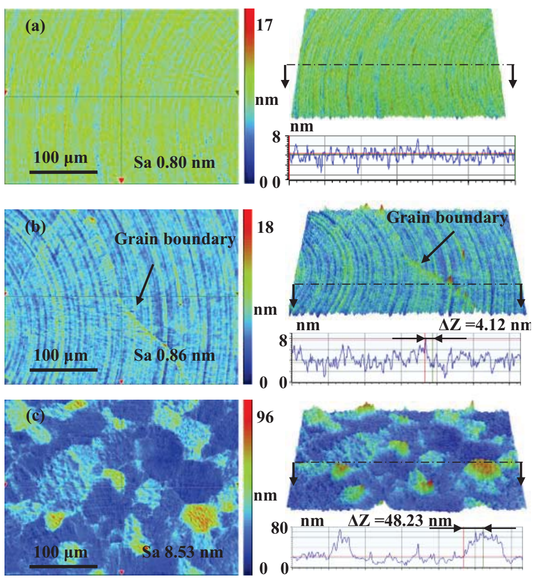


Fig. 7. Surface roughness in Sa under orthogonal optimal parameters. (a) After plasma treatment and in one of grain; (b) After plasma treatment and at the junction of two grains; (c) Without plasma treatment.

The surface grain distribution of the unmodified and modified polycrystalline after SPDT are characterized, and the results are shown in Fig. 8. Fig. 8(a) and (b) show that the unmodified polycrystalline tin remaines a large number of grain boundaries after SPDT, and the grain size is distributed between 20 μm and 200 μm. After modification, the grain size increases significantly, and the grain size is greater than 500 μm, as shown in Fig. 8(c) and (d). The comparison results show that the grain size increases significantly after ICP modification.

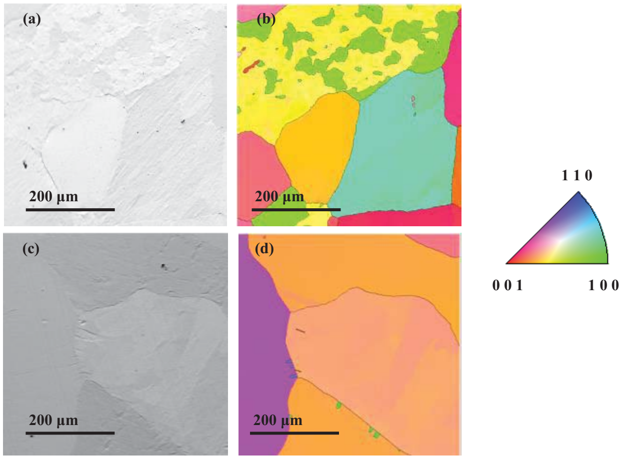


Fig. 8. Characterization of polycrystalline tin surface. (a) SEM image of the 500 ×500 μm area in unmodified sample; (b) EBSD IPF map of the same surface in (a); (c) SEM image of the 500 ×500 μm area in modified sample; (d) EBSD IPF map of the same surface in (c).

## 3. Conclusions

The methods of surface modification assisted ultra-precision machining of polycrystalline tin using laser and plasma are proposed. The conclusions are summarized as follows.

(1) Laser-based surface modification assisted ultra-precision machining of polycrystalline tin improves surface quality. The surface roughness after laser modification could achieve 2.16 nm in Sa while unmodified surface roughness is around 10 nm with obvious grain boundary steps.

(2) The thickness of the laser-based modified layer is different from different laser power densities. The greater laser power density induces the thicker modified layer.

(3) The irradiation of plasma provides a large temperature gradient on the surface of polycrystalline tin, and a grain fusion modified layer is obtained in a very short processing time, which greatly reduces the influence of grain boundary steps on the machined surface roughness from SPDT processing of polycrystalline tin. The grain size increases from 20 μm - 80 μm to a millimeter scale.

(4) Compared with the traditional SPDT process, the surface roughness of PaC machined surface is reduced greatly from 8.53 nm to 0.80 nm in Sa.

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