Study on the surface quality of a diamond-turned oxygen-free high-conductance copper reflector used in a high-power CO_2 laser

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Abstract. When using the single-point diamond-turning (SPDT) technique to produce oxygen-free high-conductance (OFHC) copper reflector, it is found that surface quality, in terms of microroughness, reflectivity, laser damage threshold, residual stress, etc., has a close relation with the microstructure and the processing sequence of the material. In addition, the uniformity of the crystal grains and the heat-treatment processes largely affect the microroughness and the residual stress of the finished surface. Finally, an optimized processing method before diamond turning is given to obtain the best surface quality. © *1997 Society of Photo-Optical Instrumentation Engineers.*

Subject terms: diamond turning; heat treatment; surface quality; microstructure.

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1 Introduction

Oxygen-free high-conductance (OFHC) copper has been widely used to produce laser relectors because of its superior electric and thermal conductivity as well as its ultraprecision machinability. Compared to other materials such as coated glass, OFHC copper is of much higher laser damage threshold and has excellent performance when used in a high-power CO_2 laser as the reflector material.

Single-point diamond turning (SPDT) is a precise and efficient method to produce optical components. This technique has been extensively used for the fabrication of aspherical surfaces, high-precision relecting mirrors, etc. When compared to conventional fabrication methods such as grinding and polishing, SPDT is more deterministic, saves time, and is particularly suitable for shaping soft metals such as OFHC copper.[1–3]

Microroughness, laser damage threshold, reflectivity, and residual stress are important parameters for the preliminary evaluation of surface quality.[4] Conventional factors affecting surface quality in the SPDT process, such as tool shape, depth of cut, and feed rate, have been reported by others. Decker and Hurt,[5] Decker,[6] and Porteus and Decker[7] have extensively studied the microstructure on diamond turning of aluminum.

The purpose of this paper is to study in depth the important role played by the heat-treatment process in diamond turning of OFHC copper and to better understand the relationship between the microstructure and the surface quality. In addition, the mechanism of laser damage is discussed. The results presented show that crystal uniformity and processing sequence largely affect surface roughness, laser damage threshold, and residual stress status. In addition, the OFHC samples subjected to cold-deformation recrystallization annealing (CDRA) have excellent surface quality after diamond turning.

2 Theory Basis

Diamond-turned materials present problems that are not encountered in the conventional machining process. In the SPDT process, the depth of cut can be much less than the average grain size. When cutting is performed within an individual grain, the microstructure of the crystal boundary, the crystal uniformity, and the average grain size greatly influence the surface quality.[8] According to metallic theory, one can improve the machinability of soft metal by annealing. The improvement in the machinability is explained by the formation of a fine grain structure as a result of phase recrystallization.

When a metal is cold worked (by cold deformation), its properties change because of the change in its structure, elongation, and reduction of its grains, which result in a decrease in ductility. The ductility of metals can be restored through an ordinary phase-annealing operation, but the ductility of a cold-worked metal is restored more often by special recrystallization annealing. In this operation, new equiaxial grains gradually grow from the fragments of the original elongated grains, forming centers. These new grains progressively become equiaxial. Metals with fine and equiaxial grains exhibit good machinability.[9]

3 Experimental Procedure

Two heat-treatment processes, CDRA and normal annealing were employed to obtain different structure states. Thirteen OFHC samples in different states are listed in Table 1.

Mirror turning was performed on an MSG-325 (Pneumo Precision, Inc.) two-axis, numerically computer-controlled lathe with a single-point diamond tool. The rake angle, relief angle, and edge radius of the tool are 20 deg, 6 deg, and 0.7 μm, respectively. The lathe had an air-bearing spindle in which axial and radial runouts were maintained at less than 0.01 μm. (peak to valley). After turning was performed, the surface roughness and the reflectivity of all samples were measured. An MSF-2M (Hitachi) (x-ray)

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stress measurer and an HSS-2X scanning electron microscope (Hitachi) were used to measure the surface residual stress, and the finished surface structure was observed. The average size of the crystal grains and the surface microhardness of the OFHC samples were also measured.

4 Experimental Results and Analyses

4.1 *Crystal Size and Uniformity of the OFHC Samples in Different States*

Figure 1 is a microphotograph (200×) of the structure for OFHC samples in different states. The change of the average crystal size with the deformation rate and annealing temperature is shown in Fig. 2.

In the case of the CDRA state, the average crystal grain size becomes smaller with an increase in the deformation rate, and it becomes smallest when the deformation rate is 60%. When the deformation rate is 80%, huge crystal cores form with the disappearance of texture caused by intensive deformation.[10] The average crystal size of the samples in the hot-rolled state and the annealing state is slightly smaller than that of the samples in the CDRA state. However, as shown in Fig. 1, the degree of nonuniformity in the crystal shape of the former is obviously higher than that of the latter, and the crystal of the latter has a uniform and equiaxial shape.

4.2 *Surface Roughness, Reflectivity, and Laser Damage Threshold*

After the samples had been diamond turned, surface roughness, reflectivity (Lambda-9 spectrometer, 3.2 μm), and laser damage threshold were measured.

Figure 3 illustrates the surface roughness of the samples in different states. In the case of CDRA, where the crystals have equiaxial shapes and are uniform in size, the surface roughness reduces as the deformation rate increases. In other word, the sample with fine grains has finer surface roughness than that with rough grains. The grains in the sample with 60% deformation are the finest, and the surface roughness is the best. The sample with 80% deformation has a rougher surface because of the huge crystal caused by the intensive deformation. What is interesting, however, is that the average grain size of the samples in the hot-rolling and annealing states is the same or in some cases even finer than that in the CDRA state, but the surface is rougher than that of the samples subjected to CDRA under identical diamond-cutting conditions. This is so because the degree of crystal nonuniformity in the samples in the hot-rolling

Table 1 OFHC samples in different states and their heat-treatment parameters.

Sample Number	Heat-Treatment Process	Parameters—Deformation Rate (%) or Annealing Temperature (°C)
108	CDRA (210 °C×1.5 h)	8%
120	CDRA (210 °C×1.5 h)	20%
130	CDRA (210 °C×1.5 h)	30%
140	CDRA (210 °C×1.5 h)	40%
160	CDRA (210 °C×1.5 h)	60%
180	CDRA (210 °C×1.5 h)	80%
220	Annealing (1.5 h)	210 °C
230	Annealing (1.5 h)	300 °C
240	Annealing (1.5 h)	400 °C
250	Annealing (1.5 h)	500 °C
260	Annealing (1.5 h)	600 °C
270	Annealing (1.5 h)	700 °C
200	Hot rolling[a]	—

[a]Sample 200 was in a primary hot-rolled state, not subjected to heat treatment.

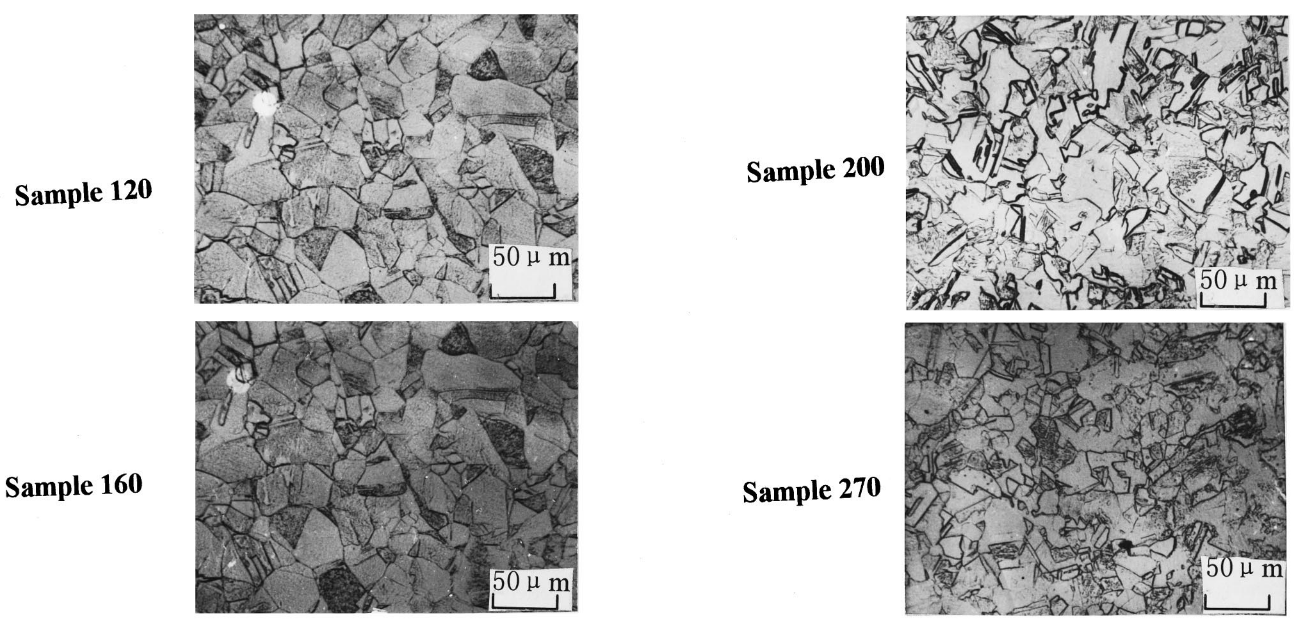

Fig. 1 Microphotograph (200×) of the structure for OFHC samples in different states.

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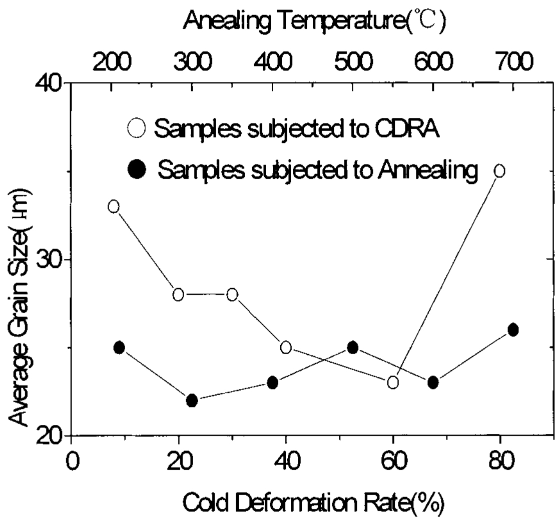

Fig. 2 Average grain size of the samples in different states.

and annealing states is obviously higher than that of the samples in the CDRA state.

In polycrystalline materials,[11] each crystal is randomly oriented. The modals of elasticity among grain boundaries are different; they vary[12] from 5 to 20%. Under the effect of the cutting force, the surface elastic deformation is different. Therefore a small difference in height levels among the boundaries of the grains is produced, as shown in Fig. 4; this difference affects the surface quality.

In the case of OFHC diamond turning, the higher the degree of crystal nonuniformity, the greater the difference in Young's modulus along the grain boundaries. Thus, after diamond turning is performed, the differences in the height levels of the grain boundaries become large, and the surface roughness of the samples are not improved even though the samples have fine grains.

Table 2 lists the reflectivities (Lambda-9 spectrometer, 3.2 μm) and laser damage thresholds of some samples. One

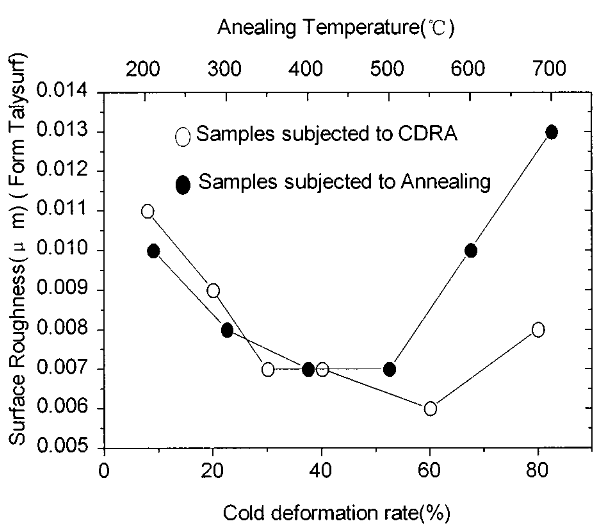

Fig. 3 Surface roughness of the samples in different states. Cutoff was 8 mm, an ISO fiter was used, the reference was straight, and the style was diamond.

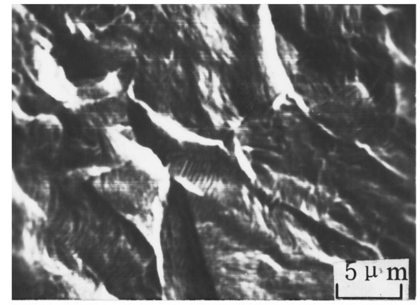

Fig. 4 Difference in height levels on crystal boundaries [scanning electron microscope (SEM) image ×2000].

can see that the reflectivity and the laser damage threshold increase with a decrease in surface roughness. The sample in the CDRA (60%) state, which has the finest surface roughness, is of the highest reflectivity and laser damage threshold.

Figure 5 is the microphotograph of sample 200 after being laser damaged. This experiment was carried out using a PRF (300 Hz) CO_2 laser. The laser pulse duration was 100 ns, the wavelength was 10.6 μm, and the focused spot size was 3.3×10^{-3} cm^2. The laser was operated in the Gaussian TEM_{00} mode. The uncertainty was less than 1%. A scanning tunneling microscope (STM) supplied by the Beijing Laboratory of Electron Microscope was employed to detect the laser damage. A tungsten scanning tip was prepared by the electrochemical etching method; the tunnel current was 1.04 nA. Typically, a site was considered damaged if it exhibited permanent changes detectable with the

Table 2 Effect of heat treatment on surface quality of OFHC samples after diamond turning.

Sample Number	Average Grain Size (μm)	Surface Roughness (Form Talysurf; μm)	Reflectivity* (%)	Laser Damage Threshold (10^7 W/cm^2)
108	33	0.011	—	—
120	28	0.009	—	—
130	28	0.007	—	—
140	25	0.007	—	—
160	23	0.006	99.62	51
180	35	0.008	—	—
220	25	0.010	—	—
230	22	0.008	—	—
240	23	0.007	—	—
250	25	0.007	—	—
260	23	0.010	98.44	47
270	26	0.013	97.84	45
200	23	0.008	99.30	47

*The reflectivity was measured using Lambda-9 UV/VIS/NIR spectrometer at the wavelength of 3.2 μm, with an aluminum sample mirror as the reference. However, the OFHC reflector will be used at the wavelength of 10.6 μm, the results presented here were obtained by a conversion (please refer to the Lambda-9 operation manual for details).

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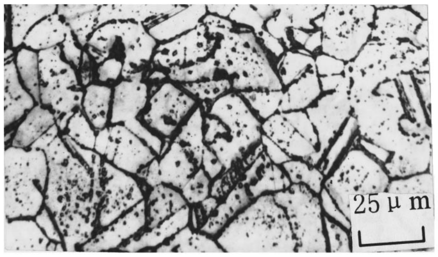

Fig. 5 Microstructure after laser damage (×400).

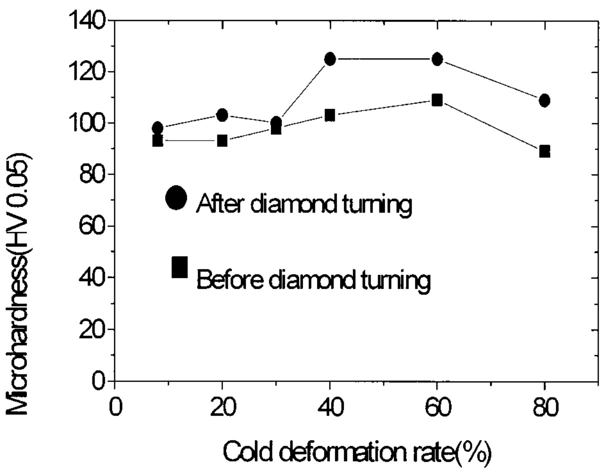

Fig. 6 Microhardness of the samples subjected to CDRA.

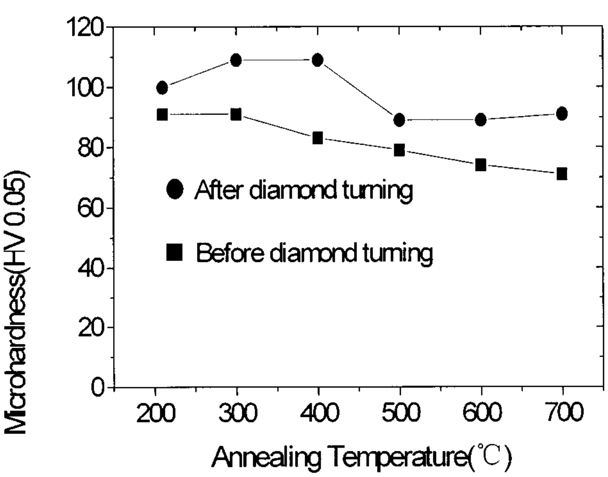

Fig. 7 Microhardness of the samples in the annealing state.

Table 3 Cutting conditions.

Turning Sequence	Spindle Revolution (rpm)	Depth of Cut (μm)	Feed Rate (μm/rev)
Rough turning	750	200–400	100
Precision Turning	1000	10–20	15
Diamond turning	1000	3	2.5

STM within an area of 100×100 nm. Obviously, the damage starts from the grain boundaries and the cracks spread along the boundaries. In addition, the microhardness increases from 125 to 132 HV0.05 (kg/mm^2). When the samples are subjected to CDRA, they have uniform crystal grains and sound boundaries (without defects, cracks, or impurities). When used in a high-power laser, these samples absorb less energy and present higher laser damage threshold.

4.3 *Surface Microhardness and Surface Residual Stress*

Surface microhardnesses of the OFHC samples in 12 states were measured either before or after diamond turning. As shown in Figs. 6 and 7, the microhardness of all samples increases after the samples have been diamond turned. This shows that in diamond turning, the cutting edge of the tool has a continuous squeezing action on the finished surface while it is turning, and that causes the surface microhardness to increase. This squeezing action can put the finished surface in a compressive stress state and improve surface quality.

We measured the given-point residual stresses (0.5 μm under the surface) of the samples mentioned after rough turning, stress relief annealing, and diamond turning. Cutting and heat-treatment conditions are listed in Tables 3 and 4. The values of the residual stress were measured at points 7.5 mm away from the workpiece's center by the MSF-2M stress measurer. The results are listed in Table 5. After the samples were rough turned, the value of the surface residual stress was relatively large and some tensile stress resulted from hot rolling. After the samples were stress relief annealed, the stress became insignificant, and when the samples were subjected to ultraprecision turning, the stress was found to be less than when they were rough turned. The residual stress in the samples in the CDRA state was compressive stress. Some tensile stress was observed among the samples in the annealing state.

Table 4 Technical conditions for stress Relief annealing and recrystallization annealing.

Processing Sequence	Furnace Type	Heating Time (h)	Temperature (°C)	Cooling Rate (°C/h)
Stress relief annealing	HL-76	1.5	210	50
Recrystallization annealing	HL-76	1.5	210	50

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Table 5 Process sequence and residual stress.

Sample Number	Residual Stress (MPa)		
	After Rough Turning	After Stress Relief Annealing	After Diamond Turning
108	19.482	9.248	−17.326
120	−33.839	7.737	−44.169
130	−111.132	−4.142	−88.318
140	−99.274	26.500	−31.517
160	−86.740	−0.451	−19.179
180	−54.498	14.308	−35.427
200	−45.707	9.354	12.172
220	4.106	1.331	−16.768
230	−21.178	11.819	24.216
240	−23.226	−1.620	12.407
250	−78.763	−3.577	−15.278
260	20.012	2.249	−27.607
270	20.266	−2.715	55.899
161	−30.430	—	−45.080
261	−21.637	—	−28.135
271	−55.621	—	−60.310

The last three samples in the table have been ultraprecisely turned directly after being rough turned without going through the stress relief annealing. The values of the residual stress measured after ultraprecision turning was performed are obviously larger than those measured after rough turning occurred. This fact shows that the stress relief annealing that occurs between rough turning and diamond turning is effective in eliminating residual stress. Residual stress is almost eliminated after stress relief annealing is performed.

5 Discussion and Conclusions

On the basis of our experiments, we came to the following conclusions:

1. Samples subjected to CDRA have finer surface roughness and higher reflectivity after diamond turning. They also present higher laser damage thresholds. The sample with 60% deformation rate shows the best result: surface roughness, reflectivity, and laser damage threshold can reach 0.006 μm rms, 99.62%, and 51×10^7 W/cm^2.
2. The degree of crystal nonuniformity has a great influence on the finished surface quality. The higher the degree of crystal nonuniformity, the worse the finished surface quality is. Samples subjected to CDRA are of fine and uniform crystals and show excellent surface quality.
3. One can obtain a relatively small surface residual stress value by stress relief annealing between rough turning and diamond turning.

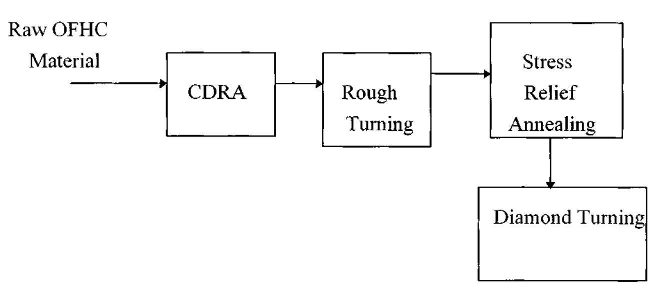

Fig. 8 Optimized process sequence for producing an OFHC copper reflector.

The optimized process sequence is illustrated by Fig. 8. When using SPDT to produce an OFHC copper reflector, we suggest that the material be subjected to CDRA and the deformation rate should vary from 40 to 60%. In addition, stress relief annealing between rough turning and diamond turning should be employed to eliminate the surface residual stress.

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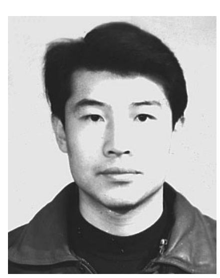

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