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The role of diagnostic testing in identifying and resolving dimensional stability problems in electroplated laser mirrors
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INTRODUCTION

New technology in directed energy systems introduces requirements for optical mirrors that are uniquely met by electroplated metals. Thermal conductivity, optical efficiency, and economy make electroplated metals the first choice in many mirror applications. However, control of electroplating process variables becomes more important as surface finish and optical figure specifications become more stringent. The morphology and mechanical properties of electrodeposits are being recognized for their effect upon the overall optical quality of mirrors.

The metal mirrors which are the subject of this discussion are to be used in the Antares inertial fusion laser system. Antares is a high-power (40 TW), high-energy (35-40 kJ), pulsed CO₂ laser system for the investigation of inertial confinement fusion. The system contains more than four hundred small and large diamond-turned and conventionally polished mirrors. The largest mirrors are trapezoidal in shape with the longest dimension being 16 to 18 inches. The substrates are type 2124 aluminum for most large mirrors, and aluminum bronze, oxygen-free copper or a copper-zirconium alloy for most of the smaller mirrors. The optical surface is electro-deposited copper 20 to 40 mils thick. After nondestructive testing and rough machining, the electroplated surface is single-point diamond machined or conventionally polished.

The finished mirrors are interferometrically tested before shipment to and upon arrival at Los Alamos to be certain that they meet optical specifications. The equipment used for all the optical testing consists of a Zygo interferometer, a Twyman-Green or Lupi, and a tooling laser. The first indication of a problem with the mirrors emerged when a change in the interferometric figure was noticed during comparison of the first and second test results. The change in figure was seen to accelerate with time until some mirrors were completely out of tolerance. In addition, a slight "orange peel" degrades the reflectance measurement and tends to scatter the laser beam.

The most frequent figure change has been associated with flat mirrors becoming slightly convex. However, some of the mirrors have long radii. Since the figure changes have been quite symmetrical, the optical technician can change focus on the radiused mirrors and obtain straight line fringes. A remeasurement of the radius of the mirror at this time shows the operator that this orange-peel effect, although hard to define by eye, can be shown by optical measurements to be quite significant.

Metallographic analysis shows the electroplated copper to be typically characterized by one or more layers of a fibrous or needle-like texture. This type of deposit is associated with a very fine grain, typically too small to resolve with a light microscope, and an extreme amount of internal stress. This layer frequently will have a hardness of 170-180 DPH, while the electrodeposit both above and below the stressed layer will average between 30-100 DPH. With the addition of energy from machining and diamond turning, the copper begins to recrystallize. After recrystallization, the grains are quite large and stress free with a typical hardness of 50-55 DPH. In some of the accompanying photomicrographs, these large stress-free grains can be seen adjacent to unrecrystallized islands of the highly-stressed, fibrous deposit. The actual time necessary to complete recrystallization varies from mirror to mirror and is a function of the stress of the deposit, the amount of mechanical energy stored, and the temperature. We can accelerate the recrystallization to provide a stable deposit by thermally treating the mirrors prior to diamond turning.

Increasing the defect density of a metal increases the free energy. The defects may be the result of deformation, or they may result from electroplating. In either case, the effect is the same; the free energy is increased by an amount approximately equal to the stored strain energy. Under certain circumstances, a metal with a high free energy may begin to soften spontaneously. This softening, or releasing of the stored energy, does not usually occur by a single, simple reaction. There are more likely a number of different reactions, most involving some sort of atom or vacancy movement. The realignment of atoms into crystals with a lower free energy is called recrystallization. An entirely new set of essentially defect-free crystals grows at the expense of the original crystals.²

The amount of time necessary, as well as the temperature at which recrystallization will occur, both vary with the amount of stored energy³. In the case of deformation-induced defects in copper, recrystallization will not normally occur below 90°C to 100°C. However, in this case, the mirrors were shipped and stored at temperatures that never exceeded 30°C. The difference in recrystallization temperature is related to the higher density of defects in the electrodeposit than is normally found in cold worked copper. In electroplating, these defects may be produced by the speed with which the ions are deposited. In general, an increase in the depositional rate also increases the defect density. Another way to increase the number of defects is to add something to the electrolyte which interferes with the ionic deposition. This may be done to increase strength, hardness, add brightness, or refine the grain size.⁴

In this case, we believe that the highly-stressed layer is the result of bulk additions of brightening agent to the electrolyte. Large additions were made at widely spaced intervals. Thus, the bath saw extremes of insufficient, as well as excessive amounts of brightening agent while the mirrors were in residence. Continuous addition of the brightener would alleviate this problem.

In the case of a highly-polished or diamond-turned surface, recrystallization is accompanied by a shifting of the surface along the individual grain boundaries. This shifting, which in extreme cases is visible to the eye as an orange-peel effect, may be the result of slight volumetric changes in the deposit. However, it also may be due to the unbalancing of stresses that were previously in equilibrium.

Our approach to solving this problem has been to develop a thermal treatment to force completion of the recrystallization process. Once the mirrors are stable, they can be polished or diamond turned again. After trying samples at various temperatures, we found that heating the mirrors to 140°C for one and one half to two hours produced a stable, homogeneous microstructure which polished or diamond turned readily.

Figure 1. A typical substrate that has been plated and trimmed, and is ready for diamond turning.

Figure 2. A photomicrograph taken of a cross section of the copper plating showing the grain structure.

Figure 3. An interferogram of the optical surface immediately after diamond machining. Note that the fringes are generally in a straight-line pattern except for the high frequency due to the tooling marks.

Figure 4. The same mirror after sitting on a shelf for four months. This time period is arbitrary as we have not done a complete time study. The figure changes began within days of diamond turning and continued for several months.

Figure 5. A photomicrograph of the cross section of the plating after the first diamond turning effort. The hardness of the microstructure varies inversely with the size of the microhardness indentations.

Figure 6. Orange peel effect. Aside from the obvious figure change of the optical surface which is measured by optical evaluation methods, we also notice some physical changes to the surface. Generally there is only a very slight change that is visible to the trained eye. The visible reflection from the mirrored surface is quite clear and sharp to the eye, but an optical test utilizing a HeNe laser beam clearly shows the diffraction effects of a half-inch beam centered on the mirror (Fig. 7).

Figure 7. Diffraction of half-inch beam.

Figure 8. Half-inch beam reflected by a good mirror.

Figure 9A. The effects of heating on the copper microstructure.

Figure 9B. The fibrous structure has been completely recrystallized.

The Results

Figure 10. Final interferogram after annealing. Diamond turning now takes place after the thermal cycle, and the resultant interferogram clearly shows that the fringes are straight. The results of retest on diffraction reflectance and focus were also satisfactory.

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