Effects of forged stock and pure aluminum coating on cryogenic performance of heat treated aluminum mirrors

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Abstract

We present the results of an on-going test program designed to empirically determine the effects of different stress relief procedures for aluminum mirrors. Earlier test results identified a preferred heat treatment for flat and spherical mirrors diamond turned from blanks cut out of Al 6061-T651 plate stock[1]. Further tests have been performed on mirrors from forged stock and one set from plate stock coated with Alumiplate™ aluminum coating to measure the effect of these variables on cryogenic performance. The mirrors are tested for figure error and radius of curvature at room temperature and at 80 K for three thermal cycles. We correlate the results of our optical testing with heat treatment and metallographic data.

KEYWORDS: mirrors, cryogenic, aluminum, heat treatment, stress relief

INTRODUCTION

The *Infrared Multi-Object Spectrograph (IRMOS)* is a facility instrument for the Kitt Peak National Observatory (KPNO) Mayall Telescope (3.8 meter) that will see first light in the spring of 2003. The project is a collaboration of NASA/Goddard Space Flight Center (GSFC), the Space Telescope Science Institute (STScI), and KPNO. *IRMOS* is a low- to mid-resolution (R = _/__ = 300—3000), near-IR (0.8—2.5 _m) spectrograph which produces simultaneous spectra of ~100 objects in its 2.8 · 2.0 arcmin field of view. The instrument uses a Texas Instruments, Inc. micro-electromechanical system (MEMS) multi-mirror array (MMA) device as a real-time programmable slit mask. The spectrograph operating temperature is ~80 K and the design is athermal: The optical bench and mirrors are machined from aluminum (Al) 6061-T651.

The optics for IRMOS are single-point diamond turned (SPDT) from Al 6061-T651 plate stock with figure error requirements of $< 0.1\lambda$ RMS ($\lambda = 632.8$ nm and microroughness of <100 Angstroms RMS. These numbers are at the limits of what can currently be achieved by SPDT. To ensure good performance at operating temperature of the IRMOS mirrors, we first ran a set of tests to find a heat treatment process which could relieve the residual stress in Al 6061-T651 and thus produce a mirror which underwent minimal distortion from 293K to 80K[1].

However, to meet the microroughness requirements, the IRMOS mirrors will be coated with Alumniplate™ high-purity aluminum. Also, the mirrors as originally tested were all from plate stock; none were from forged or extruded Al stock. Thus the first part of our testing program had no data on how these variables might affect cryogenic performance.

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forged stock and one set from plate stock coated with Alumiplate™ aluminum coating to measure the effect of these variables on cryogenic performance. The mirrors are tested for figure error and radius of curvature at room temperature and at 80 K for three thermal cycles. We correlate the results of our optical testing with heat treatment and metallographic data.

PREVIOUS WORK

Previously we reported the results of a mirror testing program designed to select the best heat treatment process for the IRMOS mirrors. We tested 6 pairs of mirrors—flats and spheres—representing 6 different heat treatment procedures. Evidence from the cryogenic testing led us to choose process 'SR5' for the IRMOS mirrors, based on the repeatably small figure error distortion of its two representative mirrors.

However, these tests were performed on mirrors all taken from plate stock. Al6061-T651 is available in forged and extruded stock, as well, and it is not obvious that each type should behave identically under cryogenic conditions, even after having undergone similar heat treating. In addition, at a later date we decided to add a coating of Alumniplate™ to the IRMOS mirrors to reduce the overall microroughness of the mirror surfaces, a factor not present in our previous tests.

MIRROR MANUFACTURE

To measure the effects of these variables, we cryogenically tested two new sets of mirrors. Mirrors 008 and 008A were cut from Al6061-T651 forged stock and underwent our SR4 heat treatment process prior to cryogenic testing. We sent mirrors 004 and 004A, made from plate stock and treated with SR4[1], to be coated with Alumniplate™. Mirrors 004 and 004A were tested as part of our previous investigations, and thus could provide a direct comparison of cryogenic performance with and without the Alumniplate™ coating.

As with the previous test mirrors[1], each has a 94 × 100 mm aperture. The flat mirrors are 17.3 mm thick. The spherical mirrors have a radius of 400 mm (concave) and are cut such that they would be 22.9 mm thick at the corners of the aperture, were the corners "sharp" and not "racetrack." The mirrors do not have mounting features. Janos Technology, Inc. single point diamond turned the mirror figures to $< 0.1\ \lambda$ RMS ($\lambda = 632.8$ nm), with a radius tolerance of ±1% for the spheres.

Alumniplate™ is a nearly (99.9%) pure aluminum coating developed by Alumniplate, Inc. to improve the surface finish of diamond turned aluminum optics. Electroless nickel plating, a more traditional method, leads to CTE mismatch at cryogenic temperatures, causing unwanted figure distortion. Alumniplating has been used successfully to reduce microroughness in aluminum diamond turned optics to between 30 and 40 angstroms—well below the IRMOS requirements[2]. However, cryogenic performance for these coated mirrors has not been rigorously demonstrated.

TESTING PROCEDURE

These tests are part of a general investigation of the effect of various heat treatment procedures on aluminum mirror performance at 80K. As such, we used the same method to test the mirrors described herein as in our previous work. This procedure is described in detail elsewhere.

To summarize, each mirror is free-mounted inside a cryogenic chamber with a 6" fused silica window to allow optical testing through the chamber wall. We use a Fizeau-type phase-shifting interferometer to obtain figure data on the mirror both at ambient and 80K through the chamber window. For the spheres, the dewar is mounted on a rail for radius of curvature measurements. Moving the dewar from the best focus position for interferometric testing to the "cat's eye" position and measuring the distance traveled gives the current radius of curvature of the mirror. We compare the radius of curvature as measured at ambient to that measured at cryogenic temperatures to further characterize the changes in the mirror from warm to cold.

Mirror 008A was tested in a slightly different manner than described above. To help us characterize the effects of the window on our measurements, we placed diodes on the center and edge of the window while testing 008A. This blocked certain portions of the mirror from being seen by the interferometer. As a result, Peak-to-Valley data for the mirror may be exaggeratedly large. We do not believe RMS data on 008A is affected.

For mirror 008, problems with test execution and data collection obliged us to test the mirror through five cold cycles instead of the usual three. Each of the five tests, however, was conducted normally.

TESTING RESULTS

Data acquired from the interferometer is reduced via custom routines in Interactive Data Language (IDL). The phase maps taken at 293K and 80K are carefully registered to avoid subtraction errors. We then subtract the warm data from the cold data. Piston and tilt are fitted to this delta and subtracted out. The results in Tables1 and 2 are based on this delta wavefront error map, which is displayed in Figure 1. The power term listed is twice the Zernike power coefficient, for reasons explained earlier[1].

Window effects are assumed to be minimal due to the use of a shutter to screen off the window from the interior of the dewar[1].

It should be noted that the scale for the contour maps shown is not constant. That is, identical grayscale tones do not correspond to identical heights from map to map. The various scales have been chosen to highlight certain features of delta wavefront error map.

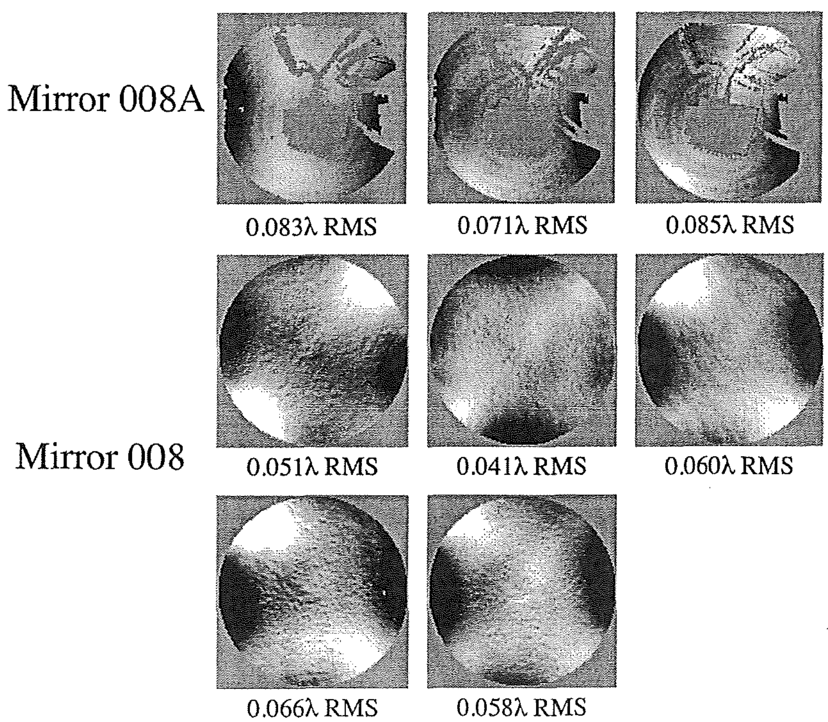

Figure 1: Contour maps of change in mirror figure error from warm to cold. Each map represents one cold cycle. λ=632.8 nm

Mirror 008A	1st Cycle	2nd Cycle	3rd Cycle	Avg	Stnd Dev
PV	0.449	0.960	0.655	0.688	0.257
RMS	0.083	0.071	0.085	0.080	0.008
Power	-0.5274	-0.4454	-0.2876		
Astig 45	-0.1323	-0.0718	-0.0460		
Astig 0/90	0.0251	0.0256	0.0439		

Table 1: Data for 3 cold cycles of mirror 008A. All values given in waves.

Mirror 008	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle	Avg	Stnd Dev
PV	0.333	0.262	0.397	0.426	0.345	0.353	0.063
RMS	0.051	0.041	0.060	0.066	0.058	0.055	0.010
Power	-0.1082	-0.0790	-0.1926	-0.2054	-0.1684		
Astig 45	0.0048	-0.0376	-0.0238	-0.0283	-0.0458		
Astig 0/90	-0.0080	-0.0101	-0.0020	0.0070	-0.0127		
Δ %Radius							

Table 2: Data for 5 cold cycles of mirror 008. All values given in waves (radius change given as percentage of radius as measured at ambient).

MICROROUGHNESS TESTING

We used an ADE Phase Shift MicroXAM white light interferometer to measure the microroughness at 3 locations on the aperture of each test mirror. The interferometer has a spatial resolution of 0.3 nm and an amplitude sensitivity of 0.01 nm over a 0.30 × 0.41 mm field of view. Its software uses a fringe-fitting algorithm to calculate surface error. For powered mirrors, low order, spherical and cylindrical terms are removed by subtraction of a least squares fit to the surface error array.

For completeness, we present the data for all mirrors used in this test program. The microroughness of the SR 1—6 plate stock test mirrors is virtually identical in amplitude (≤10 nm RMS) and character. The data appear to be dominated by the interaction of the SPDT tool with the impurities associated with Al 6061. The grain structure and tool marks give the roughness a well-defined orientation for various spatial periods. The microroughness of the mirrors cut from forging stock is about the same amplitude, but much more random in character. Table 3 gives the Microroughness data for each mirror.

Mirror	RMS @ Point A	RMS @ Point B	RMS @ Point C
Sphere 001	14.178	10.098	10.118
Sphere 002	7.867	6.898	12.713
Sphere 003	9.906	8.461	7.304
Sphere 004	------	------	------
Sphere 005	7.605	10.666	11.436
Sphere 006	9.419	8.675	14.565
Sphere 007	6.155	4.940	5.690
Sphere 008	5.235	5.515	6.094
Sphere 009	15.741	12.366	21.776
Sphere-3	17.496	43.333	11.051
Sphere-1	22.334	31.859	22.267
Flat 001A	7.340	7.729	5.710
Flat 002A	8.893	6.996	8.038
Flat 003A	5.468	6.367	7.109
Flat 004A	------	------	------
Flat 005A	7.663	7.230	8.138
Flat 006A	3.451	8.006	4.451
Flat 007A	4.043	5.702	4.227
Flat 008A	8.794	5.663	5.688
Flat-1	9.279	8.075	5.679
Flat-3	15.267	14.676	11.411

Table 3: Microroughness data for the mirrors under test. Tilt, Sphere, and Cylinder have been removed. All values given in nanometers.

CONCLUSIONS

The test results lead to slightly ambiguous conclusions. The average distortion of the plate stock SR4 mirrors was: PV 0.477 λ , RMS 0.064 λ , for the flat and PV 0.703 λ , RMS 0.120 λ for the sphere. The forged stock flat thus performed noticeably worse than its plate stock equivalent, while the forged sphere did better. However, operator error when testing mirror 004 (without the Alumniplate^{TM} coating) could have exaggerated the figure error present[1], making the forged spherical mirror's improved performance somewhat dubious. We can tentatively say that our results support the thesis that similar heat treatment processes will produce similar mirrors for different types of Al6061 stock.

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