1-1-2013

Aluminum Alloy AA-6061 and RSA-6061 Heat Treatment for Large Mirror Applications

T. Newsander

B. Crowther

G. Gubbels

R. Senden

Recommended Citation

Newsander, T.; Crowther, B.; Gubbels, G.; and Senden, R., "Aluminum Alloy AA-6061 and RSA-6061 Heat Treatment for Large Mirror Applications" (2013). *Space Dynamics Lab Publications.* Paper 102.
https://digitalcommons.usu.edu/sdl_pubs/102

Aluminum alloy AA-6061 and RSA-6061 heat treatment for large mirror applications

T. Newswander[a], B. Crowther[a], G. Gubbels[b], R. Senden[b]
[a]Space Dynamics Laboratory, 1695 North Research Park Way, North Logan, UT 84341;[b]RSP Technology, Metaalpark 2, 9936 BV, Delfzijl, The Netherlands

ABSTRACT

Aluminum mirrors and telescopes can be built to perform well if the material is processed correctly and can be relatively low cost and short schedule. However, the difficulty of making high quality aluminum telescopes increases as the size increases, starting with uniform heat treatment through the thickness of large mirror substrates. A risk reduction effort was started to build and test a ½ meter diameter super polished aluminum mirror. Material selection, the heat treatment process and stabilization are the first critical steps to building a successful mirror. In this study, large aluminum blanks of both conventional AA-6061 per AMS-A-22771 and RSA AA-6061 were built, heat treated and stress relieved. Both blanks were destructively tested with a cut through the thickness. Hardness measurements and tensile tests were completed. We present our results in this paper and make suggestions for modification of procedures and future work.

Keywords: aluminum, mirror, RSA-6061, AA-6061, heat treat, rapid solidification aluminum

1. INTRODUCTION: ALUMINUM OPTICAL SYSTEMS

Aluminum is a well-used and understood material. Its ease of fabrication, diversity of form, corrosion resistance, low cost, and availability make it a good material for many applications. Aluminum alloys are easily fabricated and relatively inexpensive for mirrors and telescope structures. Metallic optics, like aluminum, have an advantage in athermal telescope design, mounting and alignment registration. In addition, aluminum has an advantage of high thermal conductivity. It has an intermediate specific stiffness, approximately equivalent to glass, steel, and titanium. Specific stiffness is defined as the material's stiffness divided by its density. One disadvantage of aluminum is its high thermal coefficient of expansion, which reduces the material's dimensional stability in an unstable thermal environment. Another disadvantage is the difficulty of attaining visible quality super-polished surface finishes.

Aluminum alloy 6061 is a common alloy used in aerospace optical systems and is a precipitation hardening aluminum alloy with relatively low alloying. The major alloying elements are magnesium and silicon specified 0.8%-1.2% and 0.4%-0.8% respectively[1]. When artificially hardened to T6, it has high strength and can have good dimensional stability. It can be wrought, machined, diamond turned, and polished. Aluminum 6061 is less sensitive to solution heat treatment and quench variation than 7000 and 2000 series aluminum though it is lower strength. Typically stiffness, not strength, is a driving material property for telescope design. This makes 6061 T6 a good solution for the telescope structure and mirror substrate material. Mono-material, all-reflective, telescopes are advantageous for passive athermal soak performance. This is accomplished for isothermal temperature excursions where the structure lengths change to compensate for mirror radius of curvature changes maintaining optical performance.

Small infrared applications have proven to be popular for aluminum mirror and structural components. Conventional aluminum is easily single point diamond turned to better than a fringe of visible light surface irregularity and surface roughness of 50-100 Å Rq. Large half meter class aluminum precision mirrors are much harder to build successfully and therefore much less commonly built. Some successful large aluminum optical systems include the Raytheon Higher Energy Laser experiment[2] and the WISE instrument built at the Space Dynamics Laboratory (SDL) at Utah State University[3,4].

1.1. Aluminum space telescope heritage

SDL has flown a number of electro-optical missions that use aluminum alloy elements for both the reflective elements and the structural elements. SDL has had these elements fabricated by at least two different optical fabricators and has used both nickel-clad aluminum and bare-polished aluminum substrates. The telescopes for many, but not all, of these

Approved for Public Release 13-MDA-7396 (7 August 13)

Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems,
edited by Joseph L. Robichaud, Matthias Krödel, William A. Goodman, Proc. of SPIE Vol. 8837,
883704 · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2024369

missions have been high off-axis rejection telescopes and have been highly polished. Some of SDL's previous flight missions using aluminum telescopes are listed in Table 1 along with the approximate mirror surface area, substrate material, operational temperature, surface figure, and surface roughness of the primary mirror.

Table 1. Previous SDL space missions using aluminum telescopes.

Mission/Instrument	**Primary Mirror Area [cm^2]**	**Substrate Material**	**Operational Temperature [K]**	**P-V Surface Figure [μm]**	**RMS Surface Roughness [Angstroms]**
Cirrus 1A[5]	345	Ni:Al 6061	20		10
MSX/SPIRIT III[6]	1065	Ni:Al 6061	10	1.3	10
TIMED/SABER[7, 8]	53	Al 6061	220	0.25	20
AURA/TES FPOMA[9]	37	Ni:Al 6061	180	0.1	20
AIM/SOFIE[10]	121	Al 6061	275	1.3	100
WISE[3, 4]	1250	Al 6061	10	0.32	30

Each of the telescopes listed flew and successfully performed the intended mission. The aluminum telescopes performed as intended at the nominal operational temperatures listed. This list of successful missions based on aluminum telescopes clearly indicates the successful heritage of aluminum telescopes. While aluminum may not be suitable for all missions, it must be considered a candidate material, especially when cost and schedule are drivers.

1.2. High stability with aluminum

Building dimensionally stable aluminum mirrors is possible. History has shown successes such as the WISE telescope and other telescopes discussed previously in this paper. History has also indicated major failures when the material is processed improperly or used beyond its material limits. Vukobratovich gives the example of the 1.5m diameter case Tenzalloy mirrors. These mirrors showed a change between 160nm and 630nm over a period of twenty five years[2].

SDL's experience and heritage with aluminum mirrors and telescopes in space and terrestrial applications prove that aluminum can be successfully stabilized and formed into both structural and mirror elements. Three material characteristics are necessary for dimensionally stable aluminum optics. First, the residual stress must be low throughout the part. Residual stress over time will relax and become manifest as dimensional changes. Environmental temperature changes will speed this residual stress relaxation. Second, the material should have near homogeneous and isotropic thermal expansion properties. A mirror substrate with spatially varying or directionally varying thermal expansion will become distorted and thermal elastically stressed when the temperature changes. Third, strength or hardness spatial variation may result in increased machining induced stress non-uniformity. Higher stress non-uniformities will result in higher distortion in parts when relieved.

1.3. Advancing technology in super polishing bare aluminum

Single Point Diamond Turning (SPDT) of conventional aluminum can produce surface finishes of 50-100 Å Rq. In addition to the relatively high surface roughness, SPDT leaves small turning patterns on the surface which can produce both diffractively and randomly scattered light. These surface finishes may be good enough for mid to long infrared applications. Shorter wavelength applications and some stray light sensitive applications often require better surface finishes. Over the last several years, new technologies have emerged to address this aluminum shortcoming.

Post-polishing aluminum mirrors has produced good finishes in the past but deterministic polishing is presently producing surface finishes better than 20 Å Rq. These processes are now available due to advances in polishing and advances in the aluminum itself. Multiple companies offer super polishing capabilities for plano optics as well as powered and aspheric surfaces. The old axiom "aluminum doesn't polish, it smears" has been overcome by polishing advancements. Even with these polishing advancements, the aluminum surface finish is limited by the material itself. The grain structure orientation and size and alloying participates typically limit the surface finish. Aluminum material has to be carefully selected and processed in order to be successfully super polished.

1.3.1. Melt spun aluminum RSA-6061

Melt spinning is a rapid solidification technique for producing alloys with the highest cooling rates possible, up to 10^6 K/s, providing ultra-fine and homogeneous microstructures. Figure 1 shows the different processing steps of the rapid solidification processing. Firstly, the alloy needs to be prepared using melting and different alloying elements. Next, the melt is poured through a small nozzle onto a rotating copper wheel, creating a rapidly solidified ribbon. This ribbon is chopped to flakes and collected in a vessel. These flakes are degassed and subjected to hot isostatic pressure (HIP) processing to create a consolidated material. Principally, billet sizes of 1 m diameter can be prepared and these are available for large mirror optics. If necessary or required, the billets can be extruded or forged to different dimensions.

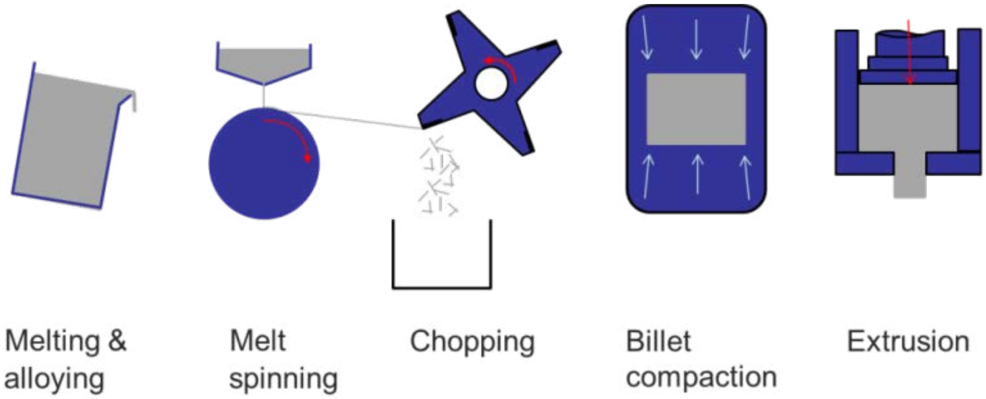


Figure 1. Processing steps in the rapid solidification processing.

Melt spinning makes it possible to achieve a very fine microstructure. For optical applications the Rapidly Solidified Aluminum (RSA) alloys RSA-6061 and RSA-905 are most commonly used. In contrast to conventional aluminum, these RSA's can be diamond turned to very low surface roughness values (Rq< 20 Å) without the need of post-polishing. For larger mirrors, post-polishing is generally required to achieve the final shape accuracies and sufficiently low surface roughness values. For polishing operations, The RSA aluminum alloys benefit from the very homogeneous microstructure, which enables increased polishing rates and super-polished surfaces[11]. Figure 2 shows that the RSA-6061 can be easily polished to the results of an optimized polishing process of conventional AA-6061, but with significantly less effort and optimization.

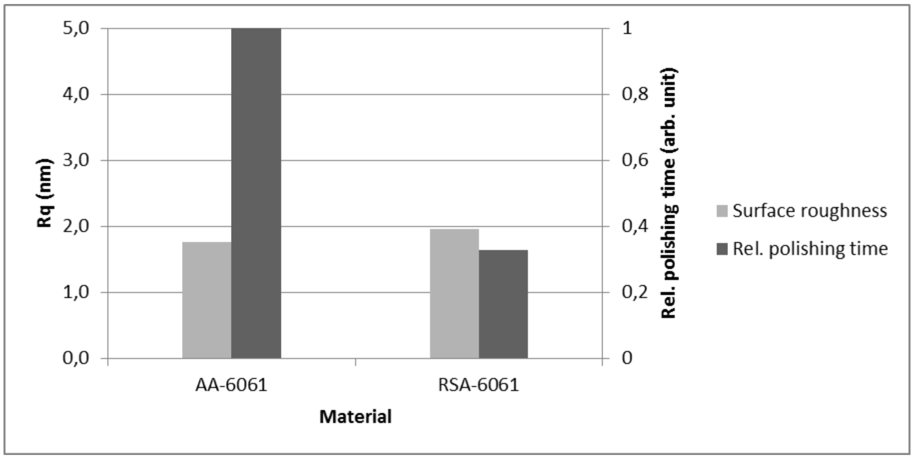


Figure 2. Polishing comparison of optimized polishing process of conventional AA-6061 with a non-optimized polishing process of melt spun RSA-6061.

2. EXPERIMENT

2.1. Material selection and blank

An effort was initiated to build and test a cryogenic, ½ meter diameter, super polished aluminum mirror. The mirror figure and surface roughness measurements are difficult for an aluminum mirror of this size.

The mirror design is an off-axis parabolic mirror with an 8:1 aspect ratio and an open-back, iso-grid, light-weighted design. The mirror is designed with a built-in pedestal for stress free mounting. The mirror light weighting design is shown in Figure 3a. Figure 3b shows the mirror in the diamond turning process.

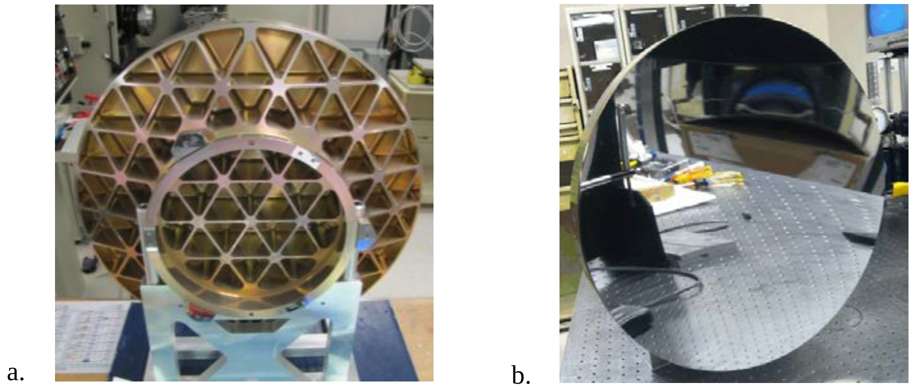


Figure 3. a) Light-weight mirror design. b) Mirror partially finished at the fabricator.

Material selection, the heat treatment process, and stabilization are the first critical steps to building a successful mirror. Due to its promise for superior surface finish, RSA-6061 T6 aluminum was chosen as the primary mirror material. Conventional AA- 6061 T6 aluminum was chosen as the secondary material.

The required billet from which the blank was to be machined is too large for standard extrusions. Therefore a forging was made from the conventional AA- 6061. The RSA-6061 billet was made through consolidation of the material with a hot iso-static pressing process.

The built-in pedestal requires a thick billet of material. Overall billet dimensions are 57 cm diameter by 15.8 cm thick weighing almost 110 kg. Uniform solution heat treating of such a thick billet of aluminum 6061 is not trivial. We were especially concerned with heat treating the RSA-6061. A slow quench could result in grain growth and precipitate growth. This would reduce its super polishing characteristics. To address these concerns, an extra blank of each material type was purchased for destructive testing after heat treatment. For conventional AA-6061, the test blank is identical to the mirror blanks shown in Figure 4a. This was possible due to its relative short lead time and low cost. For the RSA-6061 test blank, the largest available standard diameter of 26.4 cm was selected with a representable cross-sectional thickness of 15.2cm. Figure 4b shows the RSA-6061 test blank.

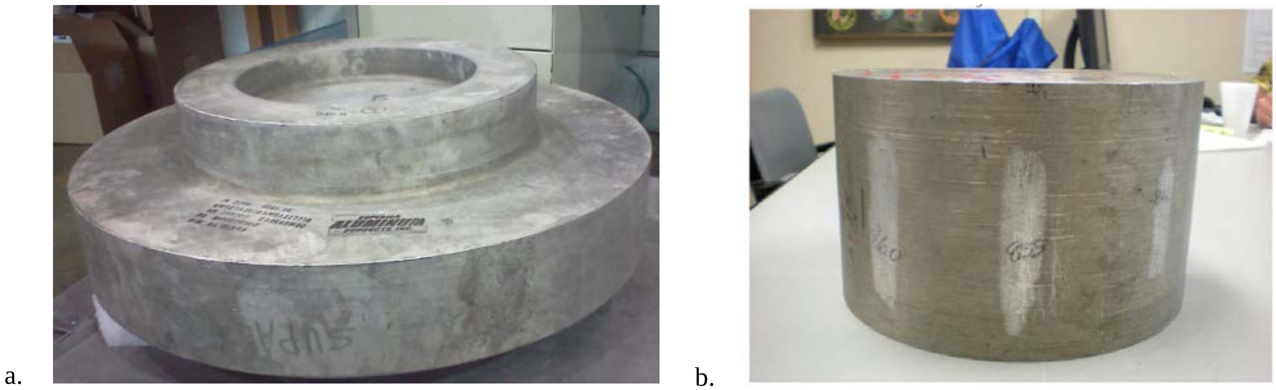


Figure 4. a) Conventional AA-6061 test blank. b) Melt spun RSA-6061 test blank.

2.2. Solution heat treatment

After the material was forged or consolidated into a billet from which the mirror blank could be machined, it was rough machined or blocked-out (Figure 5). This reduced the cross-sectional thickness of the blank to be solution heat treated and reduced its mass to 70kg.

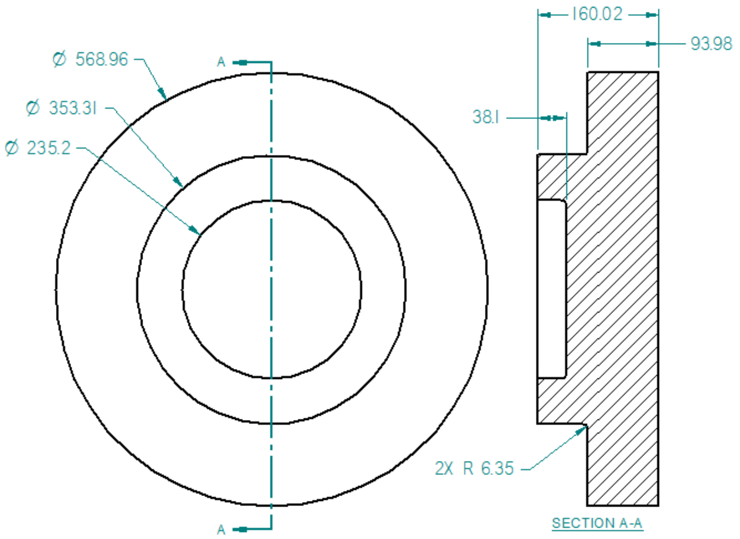


Figure 5. Blocked out mirror blank design (mm).

Solution heat treating aluminum 6061 requires heating the material above 525°C with an objective to take into solid solution the maximum amount of the soluble hardening elements in the alloy[12]. A rapid quench preserves the super saturation solid solution, minimizing precipitation of alloying materials. Precipitation of alloying materials can mean larger alloy material particles suspended in the material. On the optical surface these precipitated particles increase the attainable surface finish. They do so by pulling out and leaving a pit or may polish differently than the surrounding material. However, for thick cross-sections around 15 cm or thicker, too rapid of a quench can result in high thermal stresses that crack the billet. Even if the part does not crack, a rapid quench produces high residual stresses in the material. This occurs when the outside of the part cools and shrinks about the hot center. Prior to aging, the material has low strength and readily plastically yields. When the part is returned to room temperature a stress profile like that shown in Figure 6[13] is left in the part. The outer portion has negative or compression stress and center is under tensile stress.

Residual stress and the accompanying dimensional instability of aluminum after solution heat treat quenching is well known and understood. There are several methods for relieving and or reducing the residual stress. The most common approach is to force a relaxing strain into the part while it is still in the -W condition. The -W condition is the low strength condition of the material prior to natural and artificial aging. For extruded rod per ASTM b221 the stress is relieved by a 0.3% stretching for T651 and compression for T652. T652 can also be accomplished on larger right cylindrical billets of material. A more exotic approach to reducing the residual stress is up-hill quenching[13]. The process entails cooling the aluminum while still in the –W condition to 76.7K in a liquid nitrogen bath. After the part has fully soaked to an isothermal temperature, it is quickly moved to a hot or uphill quench. Boiling water and forced steam are both used for uphill quenching. This reverse quench flips the thermal stresses in the part compensating for the residual stress of the conventional quench. In the uphill quench the exterior warms first and stretches over the cold center. This plastically yields the material leaving a tensile stress on the exterior and a compression stress in the center as shown in Figure 6.

The high velocity steam quench provides a faster reverse quench than a boiling water quench. Early Alcoa testing showed that the steam quench relieves 80% of the residual stress versus 20% relieved by boiling water quench[13]. Boiling water quench is impeded by ice buildup on the part being quenched. However the steam quench requires special steam fixtures. If the fixtures provide non-uniform steam blasting, then the part will realize a non-uniform residual stress profile.

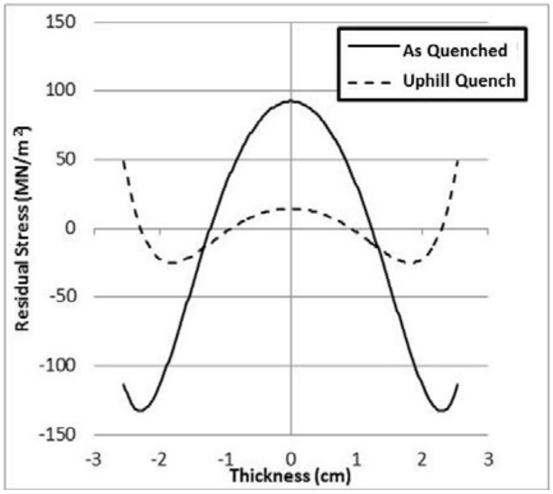


Figure 6. Up-hill quench relieves and balances the residual stress in the quenched aluminum part[14].

Another common practice is to reduce the thermal shock of the quench. Air blast, spray quench and boiling water quench are sometimes used for achieving low residual stress. However, these methods do not quench fast enough to preclude precipitation. Glycol quenchants at the right concentration can provide a moderately fast quench, minimizing precipitation and residual stresses. Figure 7[15] shows the cooling rates achieved for water and different concentrations of glycol quenchant for a 2.5 cm aluminum plate. Glycol concentrations around 20% provide a balanced quench rate reducing residual stresses but also attaining good material properties.

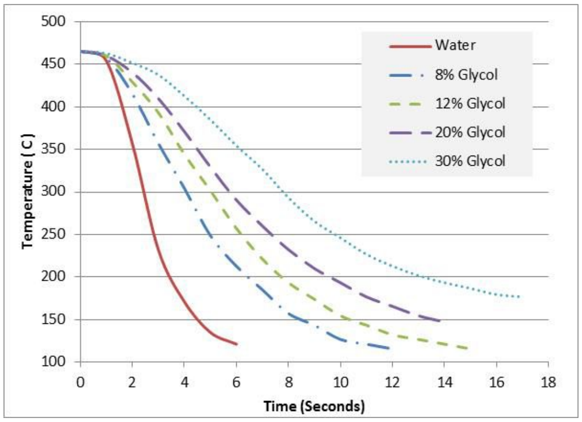
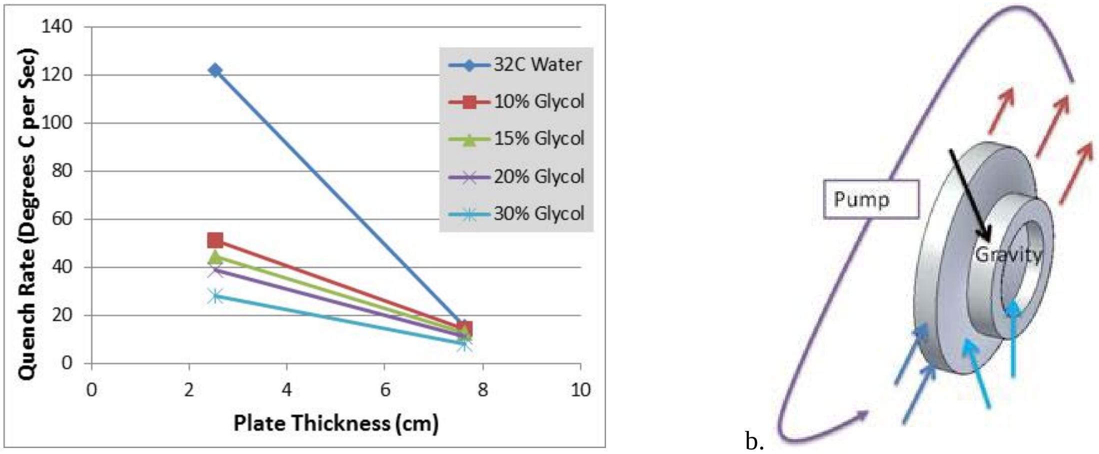


Figure 7. Quench rate curves of 2.5 cm thick Aluminum 7075 plate with the thermal couple in the center for various concentrations of Type 1 Glycol Quenchant drawn from data[15].



a. b.

Figure 8. a) Quenchant cooling rate curves derived from data[15] measured per ASTM D-6200 for 2.5 and 7.6cm aluminum plates[15]. b) Diagram showing part orientation in the quench tank with forced convection of quenchant across the part.

The blanks were treated with solution heat in accordance with the standard AMS 2772. However, additional specific requirements were levied to better preclude precipitation and minimize residual stress. It is desired to reduce the AMS 2772 specified maximum quench delay from 15 seconds to less than 10 seconds. Quench delay is the allowed transit time from the solution high temperature to full submersion in the quenchant. Minimization of this time reduces precipitation. It is also important the part is racked with space and a controlled orientation and the quench tank is agitated so that the quenchant can provide uniform forced convection on all sides of the blank as shown in Figure 8b. The quenchant was specified as 20% glycol solution (a standard bath for most heat treat houses) for the conventional AA-6061 and 10% glycol solution for the RSA-6061.

The RSA-6061 solution heat treatment temperature was specified slightly higher than the conventional AA-6061 but still within the AMS 2772 specifications. For RSA-6061, the solution treat time of 1 hour deviates from AMS 2772 on the short end. AMS 2772 specifies to soak three hours at the solution treat temperature for a 15 cm thick part. Also the quench delay of RSA-6061 was specified to be a very short 5 second maximum, well within the AMS 2772 specified maximum 15 seconds. Finally, the artificial age of the RSA-6061 was accomplished at a slightly higher temperature of 185^{o}C versus AMS 2772 specified 177^{o}C. These deviations are based on RSP Technologies past experiments and experience solution heat treating the RSA material. The general heat treatment requirements for each material type are shown in Table 2.

Table 2. Solution heat treat summarized comparison of requirements per AMS 2772 and those required in the experiment for the different materials.

Process	AMS 2772	RSA-6061	AA-6061
Solution Treat Temperature	515^{o}C to 579^{o}C	514^{o}C +/-5.6^{o}C	529^{o}F +/-5.6^{o}C
Solution Treat Time	+30 minutes per 0.5”	1 hour -0 /+15 minutes	3 hour +/- 15 minutes
Max Quench Delay	15 seconds	5 seconds	15 seconds
Quenchant Material	Water or glycol	Glycol 10% - 12%	Glycol 18% - 22%
quenchant Temperature	< 27^{o}C Start; < 54^{o} C Finish	< 27^{o}C Start; < 38^{o} C Finish	< 27^{o}C Start; < 38^{o} C Finish
Stress Stabilization	Not specified	Up-hill quench	Up-hill quench
Max Artificial Age Delay	Not specified	Not specified	Not specified
Artificial Age Temperature	177^{o}C	185^{o}C +/- 5.6^{o} C	177^{o}C +/- 5.6^{o} C
Artificial Age Time	8 hours	8-10 hours	8-10 hours

Uphill quenching was used to stress relieve the blanks, which was followed by artificial aging at 177˚C for 8-10 hours. Table 2 summarizes the process that was followed for the two material blanks. Delay between solution heat treat and artificial age followed standard heat treat practice without tight control. The parts in the -W as quenched condition were put in the freezer at below freezing temperatures to slow down natural aging.

Artificial aging was performed per ASM 2772. Artificial aging also known as precipitation heat treatment is completed at an elevated temperature. The elevated temperature raises the energy level in the material allowing precipitate formation and distribution. Some precipitate moves out of solution to the grain boundaries increasing the material strength by interfering with the slip planes.

2.2.1. Tensile Testing Results

After artificial aging, samples were taken from the heat treated parts and tested for tensile strength. For the conventional AA-6061 material a forge trimming coupon with an approximate 7.6 cm by 7.6 cm cross-section tapering up to a 13 cm by 13 cm square cross-section over a 25 cm length, accompanied the parts through heat treatment. This coupon was used for mechanical testing at room temperature. The samples were taken from the center of the coupon as per standard practice; however, documentation was not captured and delivered to us by the test laboratory to show the exact sample location in the coupon. This sample uncertainty reduces the value of the mechanical testing and requires additional testing for reduced uncertainty. Table 3 shows the mechanical tensile results from the conventional AA-6061 coupon testing. Tensile results show compliance to specification AMS-QQ-A-367B for sections up to 10 cm thick.

Table 3. Conventional AA-6061 coupon mechanical testing results per ASTM B557-10; ATLAS Testing Laboratories, Inc.

Specimen	**Conventional AA-6061**		
	Yield 0.2% Offset	**Ultimate Strength**	**Elongation**
Longitudinal (LO)	41.8 ksi (288 MPa)	49.1 ksi (339 MPa)	14%
Transverse (LT)	41.6 ksi (287 MPa)	48.7 ksi (336 MPa)	14%
6-7 inch thickness Requirements (LO)	34 ksi (234 MPa) MIN	37 ksi (255 MPa) MIN	8% MIN
6-7 inch thickness Requirements (LT)	34 ksi (234 MPa) MIN	37 ksi (255 MPa) MIN	6% MIN
0- 4 inch thickness Requirements (LO)	35 ksi (234 MPa) MIN	38 ksi (255 MPa) MIN	10% MIN
0-4 inch thickness Requirements (LT)	35 ksi (234 MPa) MIN	38 ksi (255 MPa) MIN	8% MIN

For the RSA-6061, the test piece itself was cut up for mechanical testing, and coupons were taken from the RSA-6061 test piece as shown in Figure 9. One was taken from each face and two from the center of the billet. Because this material was HIP processed, it does not have lateral and longitudinal orientations. Table 4 shows the mechanical results for coupons taken from the RSA-6061 billet. Samples 1 and 2, taken from the edge of the billet, comply in yield strength and ultimate strength. Samples 3 and 4, taken from the center of the billet are below the minimum yield strength but do meet the ultimate strength minimum requirement.

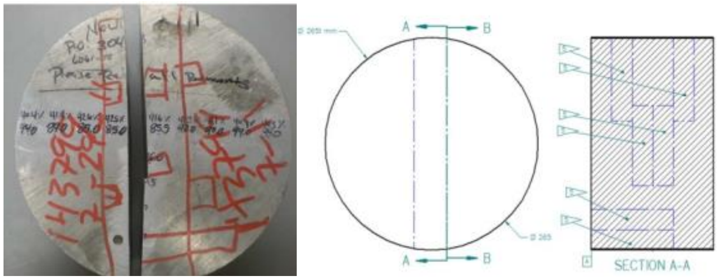


Figure 9. Mechanical test samples taken from the center of the part.

Table 4. RSA-6061 billet mechanical testing results per ASTM B557-10; ATLAS Testing Laboratories, Inc

Specimen	**RSA-6061**		
	Yield, 0.2% Offset	**Ultimate Strength**	**Elongation**
1 (edge)	40.2 ksi (277 MPa)	47.5 ksi (328 MPa)	7.1%
2 (edge)	40.3 ksi (278 MPa)	47.1 ksi (325 MPa)	6.6%
3 (center)	30.2 ksi (208 MPa)	38.7 ksi (267 MPa)	11.3%
4 (center)	30.5 ksi (210 MPa)	39.0 ksi (269 MPa)	11.2%
6-7 inch thickness Requirements	34 ksi (234 MPa) MIN	37 ksi (255 MPa) MIN	6% MIN

The table shows that the center pieces are slightly below the specification. In general, it is known that the quench result is dependent on the quench medium, workpiece geometry, cooling bath setup and quench delay. It is known[16] that for less drastic quench media (like glycol quench) shorter quench delay times are needed. For the RSA-6061 typically a cold water quench is applied to achieve maximum mechanical properties. Possibly the 10% glycol quench led to an excessively slow cooling in the center and ultimately to diminished mechanical properties.

2.3. Hardness Testing Results

Hardness tests are quick and easy. For these reasons they are often used to understand heat treated ultimate strength properties[17]. Equation 1 shows the test data derived relationship of Brinell hardness to ultimate strength in aluminum.

$$\text{UTS} = m\ (\text{Brinnell hardness}) + b \qquad (1)$$

For 6061, the linear fit coefficients m and b are 0.4173 and 6.2362 respectively. For both AA-6061 and RSA-6061 the heat treated parts were cut through the middle and hardness measurements taken on the part outside edge and in the center.

Part preparation proceeding hardness measurements is very important. Since hardness measurement instruments typically measure very fine displacements resultant from applied forces, the hardness probes interaction with the surface will affect the results. It is important that the surface being measured is perpendicular to the probe, clean and smooth. However machining the surface to be tested can alter the results by locally cold working and hardening the surface.

2.3.1. Conventional AA-6061 Hardness testing

For the AA-6061 hardness testing, a 25mm slice was cut from the center of the part with a band saw. The slice was then cut into twelve pieces (as shown in Figure 10) to better fit on the hardness anvil under the hardness measurement probe. These pieces were then trued and smoothed by taking very light cuts on an end mill. Hardness measurements were performed using a Rockwell B indenter. Measurements were taken on the front face and at approximate center across the part’s diameter as shown by the orange horizontal dashed lines in Figure 11. Figure 11 shows the hardness results on the front face (blue diamonds) and the center cut surface (red squares) across the diameter of the heat treated mirror blank. Each marker on the graph represents the average of close to 10 measurements taken in the same spatial region of the part closely grouped together. Standard deviations for these groups of measurements ranged from 0.4 to 1.2 Brinell hardness. Measured hardness variation of 87 to just over 92 HB at the center and on the face respectively was recorded. Hardness readings equal to or greater than 85 HB are recommended for Aluminum 6061 with a T6 temper in accordance with SAE-AMS-A-22771. The results are plotted over an outline of the mirror blank center section to help better understand the hardness variations. The part is the hardest furthest from center on the outside surface. The softest measurement came in the center away from outside edges, biased slightly to one side of center. This slight bias showing itself in the hardness profile asymmetry are most likely due to asymmetric quench conditions.

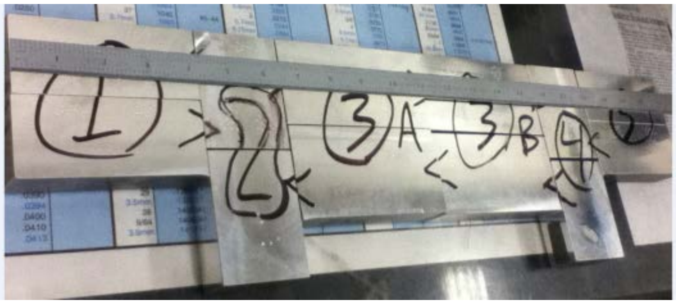


Figure 10. AA-6061 mirror blank center slice cut up into twelve smaller pieces for hardness measurements

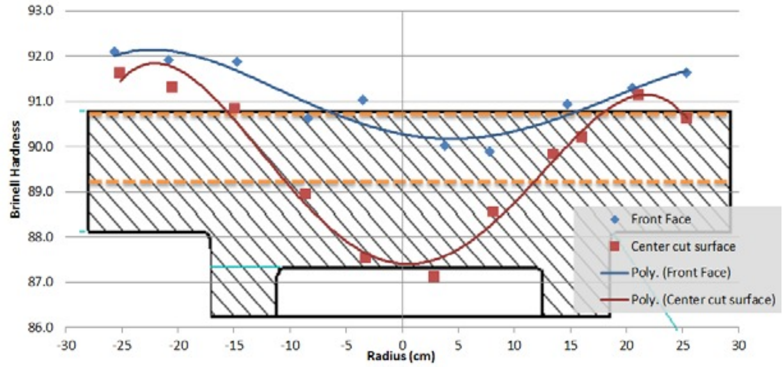


Figure 11. AA-6061 mirror blank Brinell hardness measurement results. Results are shown for measurements across the front face and measurements through the center of the blank.

2.3.2. RSA-6061 Hardness testing

Similarly, the RSA-6061 billet was sliced through the middle and hardness tested. Measurements were performed using a Brinell hardness indenter across the diameter on the top, bottom and middle of the part as shown in Figure 12. Figure 13 shows the measured hardness values over the different lines. Spread on the transverse lines is relatively large and it shows that the hardness from outer edge to center decreases from approximately 110 to 75 HB. The Transverse middle line has lower hardness values than top and bottom, which can be explained by the slower cooling rate in the center of this massive block.

The symmetry about zero on the transverse lines is quite good. However it can be seen that there is a discrepancy between the bottom and top surface. If quenching had been uniform, the hardness values should have been symmetrical between top and bottom. This indicates that quench medium was not applied equally to both sides. Mechanical properties throughout the part can be improved if the top surface were cooled as fast as the bottom surface.

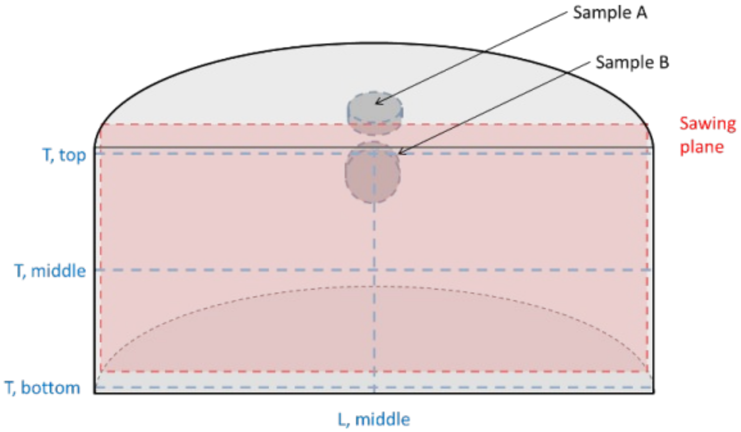


Figure 12. RSA-6061 billet diagram showing hardness measurment locations across the part in the transverse (T) direction on the top, middle and bottom. Measurements were also taken in the longitudinal (L) direction through the middle.

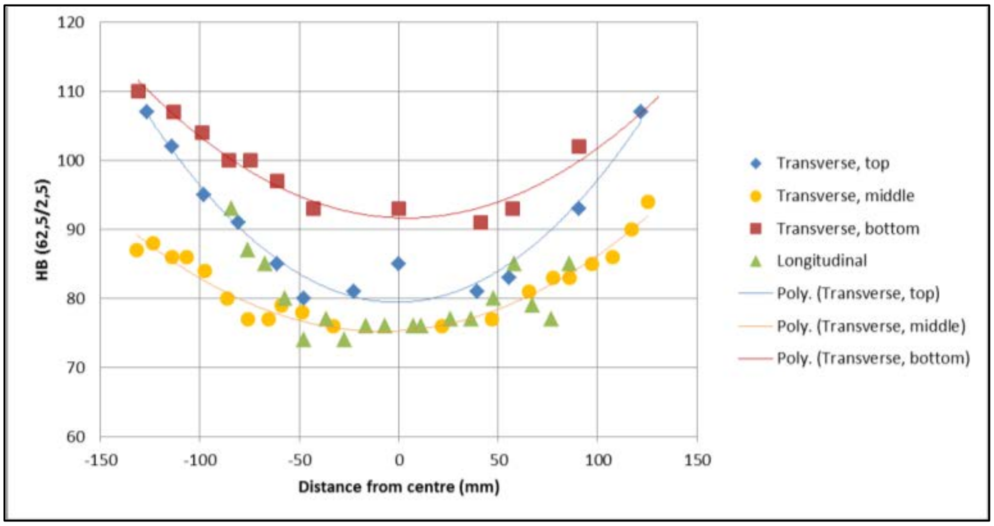


Figure 13. RSA-6061 billet measured Brinell hardness results plotted over the different cross-sections described in Figure 12.

2.3.3. Mechanical Testing results discussion

The mechanical testing results showed a great difference between the AA-6061 and the RSA-6061. The AA-6061 had minimal hardness variation of less than six points. The RSA-6061 results show a large variation of thirty five points. Many factors including material differences may have influenced this difference in results. Potential heat treat factors that may have contributed to the great differences in the results are summarized in Table 5.

Table 5. Heat treat factors that may have contributed to the hardness measurement differences.

Factor	AA-6061	RSA-6061
Cross-sectional thickness	122 mm	152 mm
Mass	70 kg	23 kg
Quenchant material	20% Glycol	10% Glycol
Quench delay	< 15 seconds	< 5 seconds

We know that hardness is very dependent on quench rate which in turn is very dependent on cross-sectional thickness as previously shown in cooling rate curves for multiple thicknesses of aluminum in Figure 8. This supports our findings that the RSA-6061 is softer in the center. The harder exterior is supported by the quenchant material of 10% glycol versus 20% glycol used on the AA-6061 and the shorter quench delay. The AA-6061 is much more massive but also has more surface area to transfer the heat out of the part during quench. From our data, it appears that heat treatment procedures should be altered when using RSA-6061. However, more tests designed to isolate individual quench factors are required to understand which contributing factors have the most influence on hardness variation as shown in these results.

2.4. RSA-6061 follow-on testing

RSP has been conducting some follow-up testing based on these results to optimize strength properties for larger sized billets. The first test worked on the optimization of the hardness values, which are indicative for the strength properties of the material. Table 6 shows the differences in the heat treatments that were applied.

Table 6. Heat treatments on RSA-6061 billet.

	Solution heat treatment			**Aging treatment**	
Exp. nr	**Temp. (°C)**	**Time (hr)**	**Aging delay (hr)**	**Temp. (°C)**	**Time (hr)**
1	525+	2	12	200	7
2	525+	2	12	170	7
3	525+	2	12	170	4
4	525+	2	0	170	4

Figure 14 shows that a time reduction between quench and aging treatment results in an increase in the hardness of the center and kernel. Furthermore, it can be seen that a reduction of aging temperature and time leads to higher hardness values. The figure also shows how the hardness can be increased by using different heat treatment approaches. The most remarkable parameter is the aging delay. This parameter has not been specified or respected in the initial billet heat treatment, but appears to be an important one. Multiple points in hardness of 5 – 10 points can be gained by minimizing the aging delay.

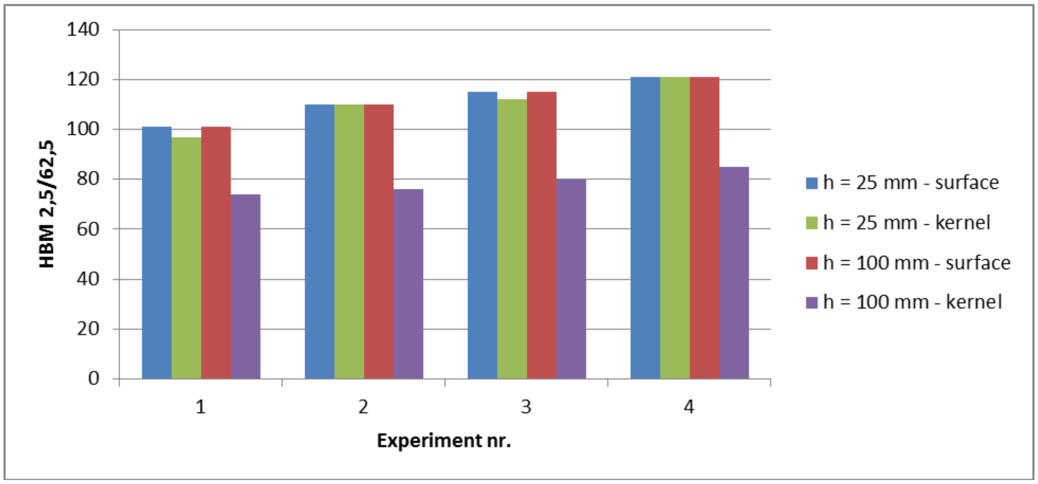


Figure 14. Influence of aging conditions and aging delays (see Table 6) on hardness values for different billet geometries.

Another interesting feature is the influence of Mg/Si ratio. The stochiometric value for Mg/Si=1.7. Changing this leads to differences in mechanical behavior and response to heat treatment properties. Figure 15 shows the different hardness values of different 6061 compositions and the difference in response to the applied heat treatments. It can be seen that a short 15 minute 100˚C soak treatment after quench can improve the hardness values. It can also be seen that an excess of silicon increases hardness too.

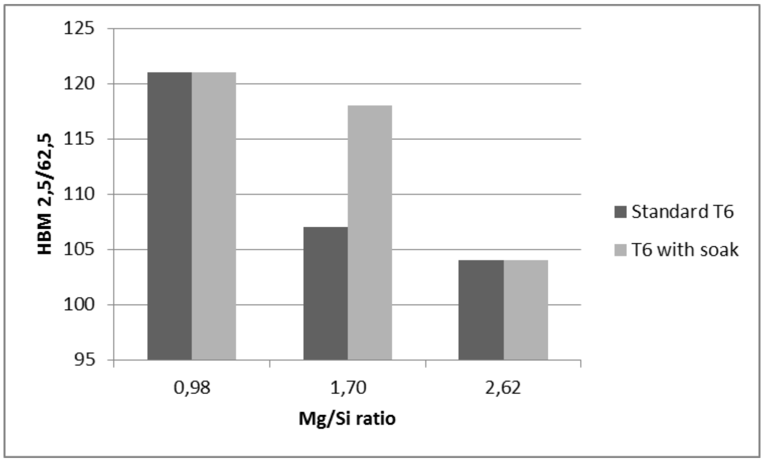


Figure 15. Influence of Mg/Si ratio for hardness values of different RSA-6061 batches. Difference in heat treatment response.

2.4.1. RSA-6061 coupon testing

Applying the parameter controls of reducing age delay to less than five minutes and reduced age time and temperature of 4 hours at 175˚C an additional RSA-6061 coupon was prepared and heat treated. This coupon was sized to be very similar size to the heat treated and tested AA-6061 forge trimming referenced in Section 2.2.1. This new coupon is an extruded cylinder with a diameter of Ø11 cm and 20 cm long. Deformation is close to a forged blank due to the low 4.2 extrusion ratio. Post heat treat tensile tests were performed and the results are shown in Table 7. The strength results meet T6 specifications in accordance with ASTM B557-10 and compare very well with the similarly sized AA-6061 forge trimming tensile results reported in Table 3.

Table 7. RSA-6061 Ø11 cm diameter cylindrical coupon mechanical testing results per ASTM B557-10; Incotest.

Specimen	**RSA-6061 T6**		
	Yield 0.2% Offset	**Ultimate Strength**	**Elongation**
Longitudinal (LO)	42.5 ksi (293 MPa)	46.1 ksi (318 MPa)	22%
Transverse (LT)	42.6 ksi (294 MPa)	49.6 ksi (342 MPa)	10%

3. DISCUSSION

3.1. Revised processes for RSA-6061

During this research, the team has developed a revised process for large RSA-6061 mirrors. First, the cross-sectional thickness and mass need to be reduced as much as possible. Rough machining leaving a minimum of excess material on all surfaces of the mirror including pockets prior to heat treat is advisable. This will increase the quench rate and will improve the mechanical properties. With a reduced cross-section, 20% glycol quenchant material can be used providing better mechanical property uniformity and reduced residual stress through the part.

A decrease of age delay was shown to be beneficial for the final properties of the heat treatment of the RSA-6061. For larger mirrors, a selection for low Mg/Si ratio can be chosen to maximize the potential for hardness and mechanical properties.

If the cross-sectional thickness cannot be reduced by rough machining and the center or billet kernel strength must meet T6 mechanical property specifications, then a cold water quench process maximizing the cooling rate may be advantageous. However, such an approach will result in high residual stresses and possible significant part distortion. Another alternative would be to use an aluminum material that does not require heat treating such as RSA-443 and RSA-905.

3.2. Non-heat treated aluminum alloys avoid the difficulties of heat treating

RSP Technology offers other alloys that make it possible to omit the difficult heat treatment practice:

1. RSA-443, which is an AlSi alloy with 40% silicon to match the coefficient of thermal expansion of NiP plating. The latter needs to be applied to diamond turn to low surface roughness values. Polishing of NiP platings is more common than polishing aluminum.
2. RSA-905, which is a dispersion-hardened alloy that can only be made by the rapid quenching of the melt spinning process. RSA-905 can be diamond turned to < 30 Å surface roughness, and without application of NiP plating just like the RSA-6061.

The material properties of these two alloys are shown in Table 8.

Table 8. Melt spun aluminum alloys for optical applications compared to conventional AA-6061.

Material	**Main composition (wt%)**	**E/ρ (GPa/g/cm^3)**	**α (10^{-6}/K)**	**σ (MPa)**
AA-6061	AlMgSi	26	23	275
RSA-6061	AlMgSi	26	23	295
RSA-905	Al Fe2,5 Ni5 Cu2,5 Mn1	31	19	475
RSA-443	AlSi40	40	13,5	150

3.3. Follow-On Testing

To better understand and further optimize aluminum 6061 for large cross-section mirrors, additional testing is needed. First, additional mechanical test data from the AA-6061 sliced up billet will improve our understanding of the heat treat results through the thickness. Hardness measurements could be taken from all outside surfaces and from differing depths toward the center of the part providing a hardness map of the cross-section. We would also like to take some tensile samples from the slice for tensile testing. Second, we would like to heat treat and test billets with varying cross-sectional thicknesses of RSA-6061. Third, such optimized approach should be related to shape stability of the substrate, in particular it is of interest how the substrate behaves during the finishing steps.

4. CONCLUSIONS

The solution heat treat of the large AA-6061 mirror blank was successful. Mechanical properties were realized with minimal variation through the thickness. Residual stresses were minimized by using 20% glycol quenchant material. Further residual stresses were relieved using an up-hill quench thermal stabilization process.

Solution heat treat of the RSA-6061 test piece was different from the conventional AA-6061. Mechanical properties showed significant variation through the thickness of the part and were below T6 specification in the center. A significant contributor is the very thick cross-section of 152mm, thicker than the AA-6061 cross-section of 125mm. A revised process has been developed during this research. For RSA-6061, age delays should be minimized and a low Mg/Si ratio is recommended for optimum kernel properties. It can be concluded that a controlled heat treatment practice is essential for meeting good mechanical properties and a symmetrical distribution of properties.

5. ACKNOWLEDGEMENTS

We would like to acknowledge Tom Croucher of Tom Croucher & Associates for his willingness and expertise providing technical information pertaining to aluminum solution heat treating, quenching and residual stress control.

6. REFERENCES

[1] Mil-A-22771d, Military Specification: Aluminum Alloy Forgings, Heat Treated (30 Jan 1984) [S/S By SAE-AMS-A-22771]

[2] Vukobratovich, D., Schaefer J. P., "Large stable aluminum optics for aerospace applications," Proc. SPIE 8125, (2011)

[3] Schwalm, M., Barry, M., Perron, G., Sampath, D., LaMalva, F., Guregian, J., and Crowther, B., "Cryogenic telescope, scanner, and imaging optics for the wide-field survery explorer (WISE)," Proc. SPIE 5904, (2005).

[4] Sampath, D., Akerstrom, A., Barry, M., Guregian, J., Schwalm, M., and Ugolini, V., "The WISE telescope and scanner: design choices and hardware results," Proc. SPIE 7796, (2010).

[5] Bartschi, B., Steed, A., Blakeley, J., Ahmadjian, M.,Griffin, J., and Nadile, R., "Cryogenic infrared radiance instrumentation for shuttle (CIRRIS 1A) instrumentation and flight performance," Proc. SPIE 1765, (1993).

[6] Bartschi, B., Morse, D., and Woolston, T., "The spatial infrared imaging telescope III," Johns Hopkins APL Tech. Dig. 17(2), 215-225, 1996.

[7] Esplin, R., Batty, C., Jensen, M., McLain, D., Stauder, J., Jensen, S., Stump, C., Robinson, D., Dodgen, J., "Sounding of the atmosphere using broadband emission radiometer (SABER): instrument overview," Proc. SPIE 2268, (1994).

[8] Brown, S., Jensen, M., Jensen, S., Hansen, G., Zollinger, L., Esplin, R., and Miller, J., "Souding of the atmosphere using broadband emission radiometry (SABER): sensor design, performance, and lessons learned," Proc. SPIE 6297, (2006).

[9] Crowther, B., Elwell, J., and Anderson, R., "Cryogenic optical design and testing of the focal plane optomechanical assembly for the tropospheric emission spectrometer," Proc. SPIE 4093, (2000).

[10] Shumway, A., Fish, C., Peterson, J., Mace, P., Cook, J., Nelsen, J., Hooper, D., Young, Q., Wassom, S., Hansen, S., Kemp, J., Gordley, L., and Hervig, M., "SOFIE instrument overview," Proc. SPIE 6297, (2006).

[11] Horst R.T., de Haan, M., Gubbels, G., Senden, R., van Venrooy, B., Hoogstrate, A., "Diamond turning and polishing tests on new RSP aluminum alloys", Proc. SPIE 8450, (2012).

[12] Chandler, H., [Heat Treater's Guide: Practices and Procedures for Nonferrous Alloys], ASM International, Materials Park, Ohio, 129-144 (1996).

[13] Croucher, T., "Minimizing Machining Distortion In Aluminum Alloys Thru Successful Application Of Uphill Quenching -A Process Overview," Journal of ASTM International (JAI) (2009).

[14] Marschall, C. W., Maringer, R. E., [Dimensional Instability an Introduction], Maxwell House, Fairview Park, Elmsford, New York, 145-150 (1977).

[15] T. Croucher, T., "Polymer Quenchants: Their Advantages for Aluminum Alloys," Heat Treating, 18 – 19 (1982).

[16] Hatch, J.E., [Aluminium: Properties and Physical Metallurgy], ASM International, Materials Park, Ohio, p. 169 (1984).

[17] Karabin, L., Tech Q&A, Aluminum Association website
http://www.aluminum.org/Content/ContentFolders/TechQandA/February2008/Hardness_Ultimate_T.htm