APPLICATION OF RAPID INFRARED HEATING FOR PROCESSING OF ALUMINUM FORGINGS

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Abstract

Rapid infrared (IR) heating has the potential to be used for solutionizing of aluminum forgings with benefits of reduced energy consumption, increased productivity, and improved microstructure and mechanical properties. Standard procedures to take advantage of rapid IR heating for solutionizing are not currently available. Thus, a primary objective of this work was to determine optimum solutionizing cycles for two aluminum alloys; AA2618 and AA6061. Laboratory experiments on aluminum coupons were performed to establish time/temperature solutionizing data for each alloy. Electrical conductivity and hardness measurements were used to evaluate the degree to which samples were solutionized. Grain structure in the solutionized and aged condition was also evaluated for select thermal cycles. The solution data presented herein is the basis for future production tests using rapid IR equipment.

Introduction

The benefits of rapid infrared (IR) heating, including short heat-up times, good temperature control, and energy efficiency have yet to be fully exploited in the processing of wrought aluminum parts. Significantly higher heating rates and better temperature control is possible than in conventional convection furnaces. Since heating is on a demand basis, reduced energy consumption is a major advantage, in addition to the shorter production times. For solution treating of forged aluminum alloy parts, the improved control at higher heating rates provides the flexibility to solutionize at temperatures closer to the solidus, and for shorter soak times.

The projected savings from IR heating for this application due to reductions in energy consumptions and lead times are about 50%. In addition, it has been shown that enhanced mechanical properties can be obtained by using infrared heating for processing of aluminum forgings [1]. The absence of standard solutionizing procedures using IR furnaces prevents industry from implementing and taking full advantage of this process. Short soak solution treatment [2], and fluidized bed solution treatment [3-5] of aluminum alloy castings are some of the current related work exploring improvements in thermal processing. Improvements in microstructure and mechanical properties using rapid heating have also been explored for other alloy system [6-8].

The objective of this work is to determine improved solution thermal cycles for aluminum alloys AA2618 and AA6061. An array of rapid solutionizing cycles was performed on coupons of these alloys using a laboratory furnace, and the effects on electrical conductivity, microhardness

and grain size were measured and compared. Based on these results, improved solution cycles for AA2618 and AA6061 forgings are proposed using rapid IR heating.

Materials

The coupons used for laboratory solutionizing experiments were taken from AA6061-F and AA2618-F round bars in the as-extruded condition. The extruded bars were 57 mm (2¼ inches) in diameter and were extruded on a 58.7 MN (6600 US ton) indirect press. The scalped extrusion billets were 15 inches in diameter and 89 inches in length, and extruded through a 5-hole die, providing an extrusion ratio of 9.2. The microstructure of both alloys was un-recrystallized and fibrous with fragmented and redistributed second phases.

The chemical compositions of the alloys were determined by atomic emission spectroscopy. Table 1 gives the chemical compositions of the two alloys used in this work.

Table 1: Compositions of AA2618 and AA6061 test specimens in weight %, via atomic emission spectroscopy. The balance is Al.

Alloy	Elements by weight percent								
	Cu	Fe	Si	Mn	Mg	Zn	Cr	Ni	Ti
AA 2618	1.97	1.07	0.24	0.02	1.52	0.01	-----	1.17	0.07
AA 6061	0.16	0.28	0.63	0.09	0.82	0.06	0.10	-----	0.02

Experimental Procedures

Disks (or coupons) approximately 4.8 mm thick and 19 mm in diameter were machined from the mid-radius of the extruded bar. One surface of each disk sample was metallurgically polished to 6μm diamond media prior to the solutionizing tests. Fine (30 AWG) K-type thermocouple wires were welded to the center of the opposite surface of each disk in order to monitor, control and record sample temperature during solutionizing and quenching. The relatively thin disks can be heated at essentially the same rate as IR heated forged parts that are significantly thicker.

Two types of solutionizing cycles were employed. Conventional solution temperatures and times were utilized to establish baseline information, while shorter, rapid solution cycles at higher temperatures were performed to assess their effects on physical properties.

The test temperatures for rapid solution cycles of AA6061 were 532 C, 552 C and 572 C. Note that 532 C is the standard solutionizing temperature for AA6061. The published solidus for this alloy is 582 C. The test temperatures for AA2618 were 530 C, 535 C, 540 C and 545 C. The published solidus temperature for this alloy is 549 C. Samples were individually heated to the test temperature in a small natural-convection lab furnace (Thermalyne 1300). Thermocouple wires were connected to a computer data acquisition system which was activated just prior to insertion of the specimen into the furnace. Temperature data were sampled at 4 Hz. A typical heating cycle for 532 C with a hold time of 1200 s is shown in Figure 1. Heating times were generally about 10 minutes. Once the sample reached the test temperature, it was held at that temperature for the specific test time.

Test times were originally planned at 60 s, 300 s, 600 s, 900 s and 1200 s, however several tests were performed for 1 hour and 8 hours, and a non-isothermal test was performed for each test temperature. The non-isothermal tests essentially involved heating the sample to the test temperature and immediately quenching once the test temperature had been reached. Analysis of

the thermal cycle indicated that these samples were actually at temperature for approximately 20 s; therefore these data were plotted as such, for expediency. In fact, the relatively long heating time introduces a considerable non-isothermal aspect to the overall thermal cycle; however this will also be experienced in actual production heat treating.

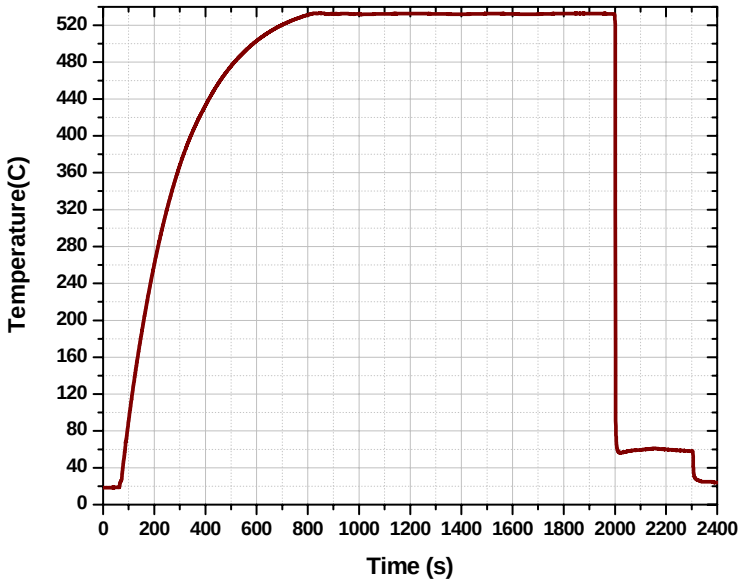


Figure 1: Thermal cycle data for AA6061 sample that was solutionized for 1200 s at 532 C and then quenched. K-type, 30 AWG thermocouple wires were attached to the specimen surface to measure temperature during heating and quenching.

Quenching was performed by rapidly removing the sample from the furnace and placing the sample in a water bath maintained at approximately 65 C, the standard quench temperature for AA6061, and at 100 C, the standard quench temperature for AA2618. The sample was held at that temperature for 5 minutes before cooling to room temperature. A portion of a typical quench cycle from a test temperature of 532 C is shown in Figure 2. The time from when specimen removal from the furnace commenced until it entered the quench bath was typically within 3 seconds. This is well within the maximum quench delay time of 15 seconds as specified as standard practice [9]. The temperature decreased approximately 10 C during this time.

Immediately following quenching and subsequent cooling to room temperature, samples were tested for electrical conductivity and hardness. Conductivity tests were performed with a Foerster Sigmatest® 2.068 eddy current tester with a standard 14 mm probe and at a frequency of 120 kHz. Five sequential measurements were made on each sample. Samples were then tested for hardness on the Vickers scale using a LECO LM300AT microhardness tester with a 1 kgf load. Eight hardness measurements were taken across the face of the polished side of each sample. After testing on a sample was complete, the sample was placed in a lab freezer at approximately -25 C. All tests were performed within ½ hour, which is within the maximum delay time between quench and refrigeration [9]. All samples of AA6061 were aged in one batch at 175 C for 8 hours after all tests on solutionized samples were complete. This is the standard T6 aging thermal treatment for AA6061 alloy. All AA2618 samples were T61 aged at 199 C for 20 hours. After aging, samples were once again tested for electrical conductivity and hardness.

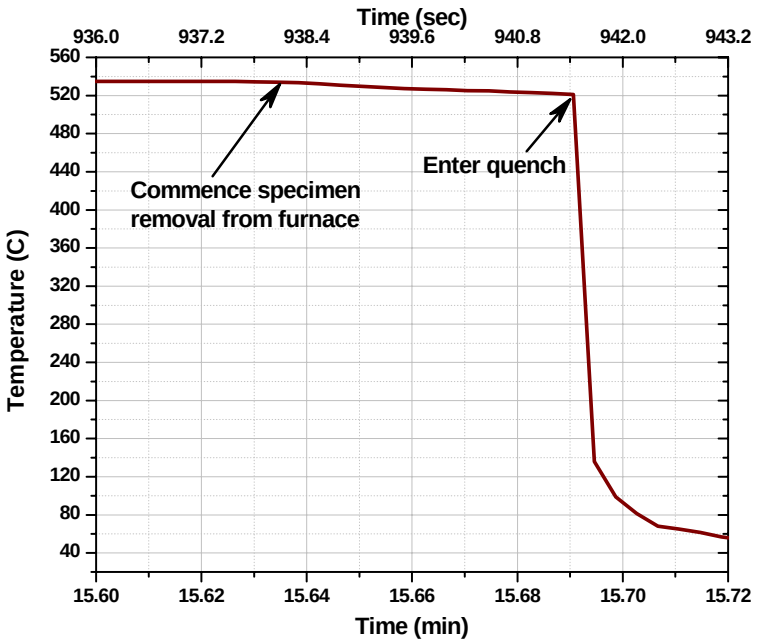


Figure 2: Typical quenching cycle for AA6061 samples heated to 532 C.

The next step was to perform metallurgical analyses. Since mechanical and physical properties were essentially constant after 900 seconds, samples that underwent solutionizing for 20 and 900 seconds at each of the solutionizing temperatures were used for metallurgical analysis. In addition, metallurgical analyses were performed on AA6061 and AA2618 coupons that were solutionized at 532 C and 530 C, respectively for 8 hours with a subsequent conventional age. Two disks for each of the temperatures were selected for the evaluation; one sample was perpendicular to the extrusion direction and one was parallel to it. Axial and longitudinal sections were also evaluated in the as-extruded condition.

Electrolytic etching ensued, with a solution of 5ml fluoroboric acid (HBF_4) and 200ml distilled water. The aluminum samples were the anode, and a strip of stainless steel was used as the cathode. A 22V DC power supply was used. The etchant was continuously stirred using a magnetic stirrer during the electrolytic etching process. Etching was performed on each solutionized/aged piece for 3 ¾ minutes. Immediately after etching, samples were washed with water and dried with compressed air.

Grain size measurements were made by the ASTM line intercept method [10]. The specification defines intersect as a segment of test line overlaying one grain. Since the microstructure differs in planes parallel and transverse to the extrusion direction, grain size measurements were treated separately for each plane.

Results

AA 6061

Electrical conductivity and hardness values of AA6061, respectively, are presented as functions of solutionizing time and temperature in Figures 3 and 4. These measurements were taken prior to the aging cycles.

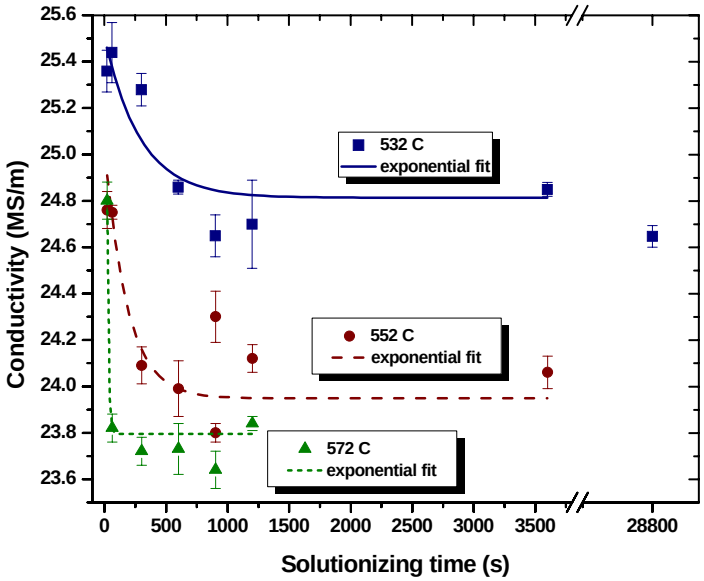


Figure 3: Average conductivity of AA6061 as a function of solutionizing time and test temperature. Error bars represent ±1 standard deviation. Each data point is an average of 5 measurements on the sample. This graph only includes measurements on "solutionized" samples. The conductivity of as-extruded/un-solutionized material was 29.8 MS/m.

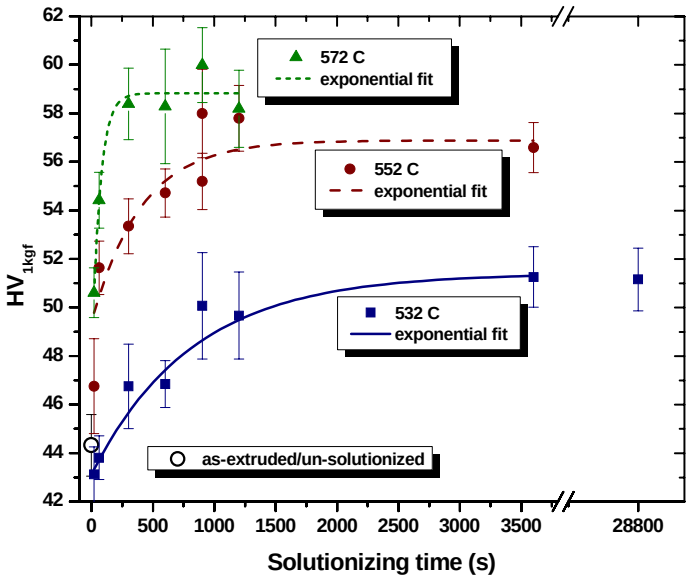


Figure 4: Average hardness of AA6061 as a function solutionizing time. Error bars represent ±1 standard deviation. Each data point is an average of 8 measurements on the sample.

Figures 5 and 6 show the variation of electrical conductivity and hardness after aging the AA6061 solutionized samples to the T6 condition.

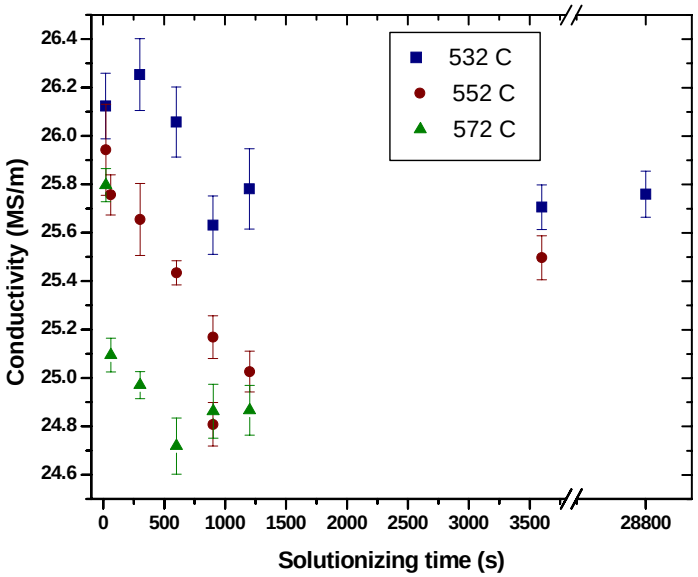


Figure 5: Average conductivity of AA 6061 as a function time and solutionizing test temperature for samples aged at 175 C for 8 hours. Error bars represent ±1 standard deviation. Each data point is an average of 5 measurements on the sample.

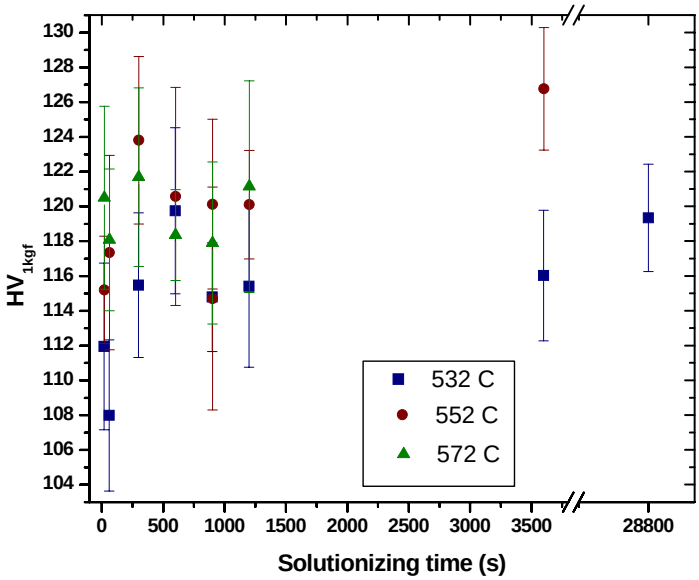


Figure 6: Average hardness of AA6061 as a function solutionizing time for samples aged at 175 C for 8 hours. Error bars represent ±1 standard deviation. Each data point is an average of 8 measurements on the same sample.

As solutionizing temperature increased, the conductivity and hardness tended to decrease and increase, respectively, in the T6 aged condition. The higher hardness may be due to an increase in coherent precipitates after aging. However during solutionizing at 572C, the properties do not seem to change after 300s.

AA 2618

The variation of electrical conductivity and hardness values of AA2618 are presented as functions of solutionizing temperature and time in Figure 7 and Figure 8. These measurements were taken before and after the aging cycles.

AA2618 did not experience the same distinct solutionizing trends as seen with AA6061, in which significant differences in electrical conductivity and microhardness could be resolved at different test temperatures. Nevertheless, it is evident that regardless of the test temperature, solutionizing appears to occur very rapidly.

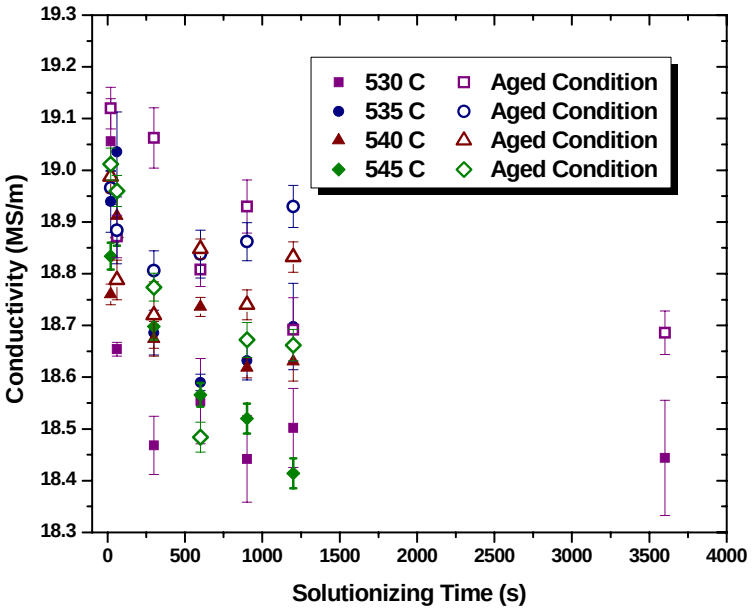


Figure 7: Average conductivity of AA 2618 after solutionizing and after aging, as a function of solutionizing time and test temperature. Error bars represent ±1 standard deviation. Each data point is an average of 5 measurements on the sample.

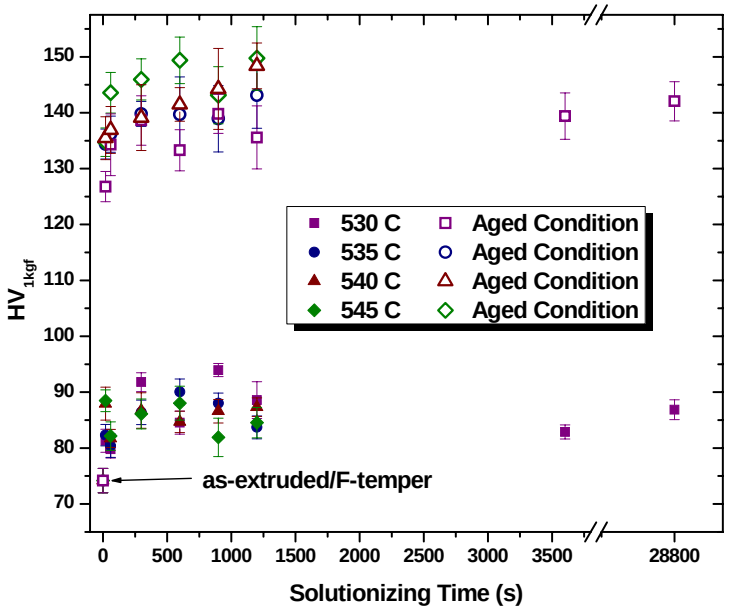
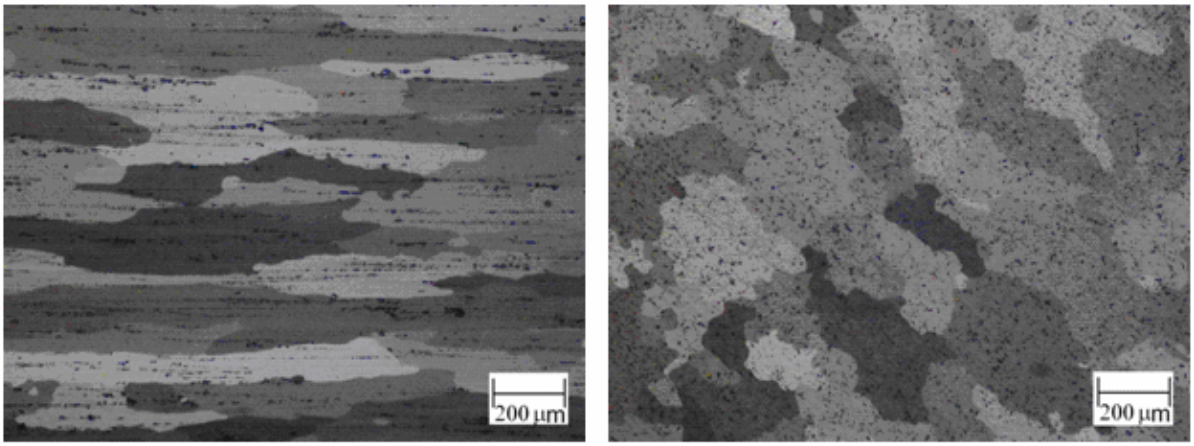


Figure 8: Average hardness of AA2618 after solutionizing and after aging, as a function solutionizing time. Error bars represent ±1 standard deviation. Each data point is an average of 8 measurements on the sample.

Metallurgical Analysis

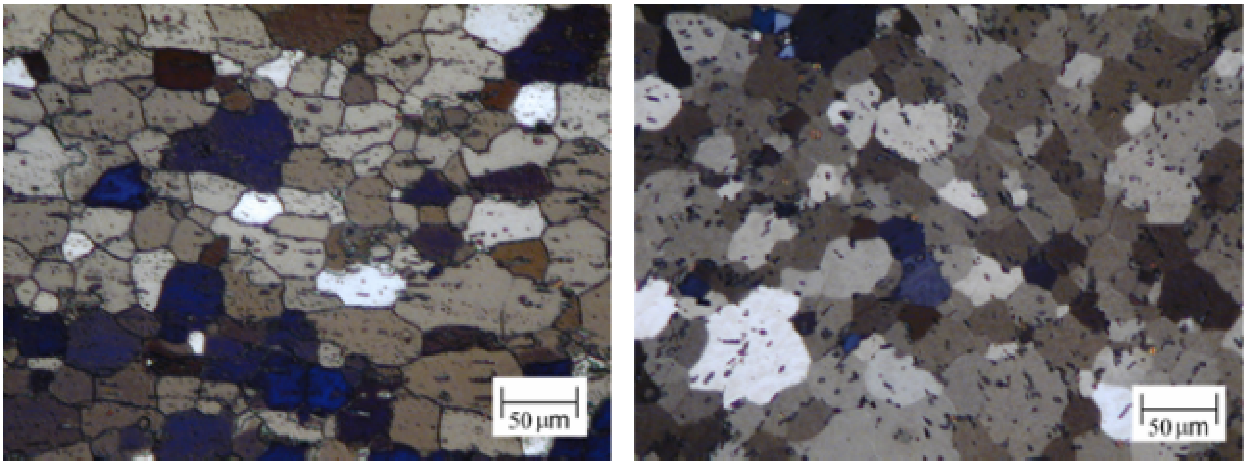
Metallurgical analyses were performed on as-extruded and selected solution/aged samples. The as-extruded material (both AA6061 and AA2618) exhibited a fibrous, un-recrystallized grain structure indicative of warm working. For AA6061, this structure coarsened during solutionizing, however elongated grains in the direction of extrusion were retained. Grain coarsening increased with increasing time and temperature. This was also the evident in AA6061 samples solutionized to 8 hours at 532 C. Figure 9 shows photomicrographs from axial and transverse planes of a solution treated and aged AA6061 coupon. Grain coarsening was modest from about 180 μm at 20 s to 225 μm at 900 s.

The fibrous grain structure of the as-extruded AA2618 recrystallized to an equiaxed grain structure, even after solutionizing at 530 C for 20 seconds. Photomicrographs for this condition are shown in Figure 10. For AA2618, average grain sizes for 20 s solutionizing cycles were all less 30 μm (22-29 μm) while at 900 C, the maximum grain size was 38 μm at 540 C.



(a) (b)

Figure 9: AA6061 samples were solutionized at 572 C for 900 seconds, and conventionally aged. (a) shows the section parallel to the extrusion direction (horizontal to page). (b) shows a section perpendicular to the extrusion direction



(a) (b)

Figure 10: AA2618 samples were solutionized at 530 C for 20 seconds, and conventionally aged. (a) shows the section parallel to the extrusion direction (horizontal to page). (b) shows a section perpendicular to the extrusion direction

Conclusions

For two wrought aluminum alloys, AA6061 and AA2618, time and temperature has been correlated to the degree the alloy has been solutionized. AA6061 exhibited a distinct trend in that higher solutionizing temperatures significantly reduced the solutionizing time. The data suggest that higher dissolution of second phases occurred at the higher temperatures. This level of dissolution could not be achieved at the conventional solutionizing temperature of 532 C, even at much longer times. This in turn, may have led to the modest increase in hardness after conventional aging. AA6061 samples exhibited grain coarsening of the fibrous as-extruded structure during solutionizing, which increased with time and temperature. AA2618 also exhibited relatively rapid solutionizing, however a similar trend to AA6061 was not observed. AA2618 fully recrystallized from its fibrous as-extruded structure, even at the shortest time and lowest temperature. It is apparent that shorter solutionizing time at lower temperature will provide the minimum grain size.

In the next phase of this work, an array of AA6061 and AA2618 forgings will be processed with a production IR furnace using "optimized" and conventional solution cycles. A complete characterization of the microsturcture and mechanical properties will be performed to evaluate potential benefits. Additional testing will include AA2014 and AA7075.

Acknowledgement

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References:

1. H. Lu, P.B. Kadolkar, T. Ando, C.A. Blue, R. Mayer, "Control of Grain Size and Age Hardening in AA2618 Forgings Processed by Infrared Radiant Heating", *TMS Letters*, 2004
2. D.L. Zhang, L.H. Zheng, D.H. St. John, "Effect of a Short Solution Treatment Time on Microstructure and Mechanical Properties of Modified Al–7wt.%Si–0.3wt.%Mg Alloy", *Journal of Light Metals*, 2002, pp. 27-36
3. J. Keist, "The Development of a Fluidized Bed Process for the Heat Treatment of Aluminum Alloys", *JOM*, April 2005, pp. 34-39
4. S. Chaudhury, S. Shankar, D. Apelian, J. VanWert, "Short Cycle Heat Treating with Fluidized Beds: Microstructure Evolution", *Transactions of the American Foundry Society*, 2003
5. J. Keist, C. Bergman, "Short Cycle Heat Treating with Fluidized Beds: Optimizing Mechanical Properties", *Transactions of the American Foundry Society*, 2003
6. J.A. Scot, J.E. Spruiell, "Grain Refinement of Wrought Austenitic Stainless Steel by Rapid Heating", *Metallurgical Transactions*, Vol. 5, January 1974, pp. 255-259
7. L.A. Elagina, A.I. Gordienko, M.Ya. Brun, V.V. Ivashko, "Possibilities for Using Rapid Heating to Improve the Mechanical Properties of Titanium Alloys", *Metal Science and Heat Treatment*, Vol.26, No. 10-11, Nov-Dec 1984, pp. 905-910
8. O.M. Ivasishin, R.V. Teliovich, "Potential of Rapid Heat Treatment of Titanium Alloys and Steels", *Journal of Materials Science and Engineering*, 1999, pp. 142–154
9. Aerospace Material Specification (AMS) 2770E, SAE International, p.10
10. Standard Test Methods for Determining Average Grain Size Designation: E 112-96, Annual Book of ASTM Standards, 2004, Volume 03.01, pp.267-292