Final Report on

Improving Fatigue Performance of Aluminum Alloy Forgings using Rapid Infrared Thermal Processing

To:

Forging Industry Educational and Research Foundation

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1.0 Introduction

The goal of this project is to improve fatigue and general mechanical properties of aluminum alloy forgings through the application of rapid infrared (IR) heating to the forging pre-heat and solution treatment cycles. This involved plant and laboratory experimentation, and the development of process data to optimize the microstructure of forged parts. A high performance aluminum alloy, AA 2618, is the subject of this report; however additional alloys, including AA 6061 are under consideration.

Project objectives were to demonstrate improved or comparable fatigue performance and shortened lead times in the production of heat treatable aluminum alloy forgings using rapid IR thermal processing. This would also lead to reduced process energy use and costs. With the construction of a rapid IR furnace for solution treatment of aluminum alloy parts, commercialization of this new rapid heating technology is the ultimate objective of this effort. Thus, it is essential to develop requisite process and material data.

Initial laboratory trials indicated that applying rapid IR superheating to the solutionizing cycle can reduce heat-treating cycle times by as much as 75% with a resulting decrease in energy consumption.[1] In addition, laboratory results indicated an improvement of metallurgical properties in rapid IR prototype parts.[2,3] This effect has been measured when compared to sample forgings heat-treated using conventional commercial processing. Recently published work indicates that rapid IR heating for solution heat-treating can result in grain sizes of 27-32 micrometers, whereas conventional thermal processing produces measurably larger grains.[4,5] Recently published work also indicates that IR treated samples with reduced grain size show an improvement in fatigue properties compared to forged components produced with conventional processes.[6]

The approach presented herein was to produce forged aluminum parts or upsets, conventionally heat-treated and heat treated with an array of cycles using rapid IR heating. (Previously, systematic lab testing was undertaken to determine a range of process parameters to maximize metallurgical improvements and process capabilities.[7]) Samples were selectively machined from these forged upsets. Mechanical testing involved room-temperature low and high cycle fatigue testing, tensile testing and hardness testing. Tests were conducted to produce comprehensive data for AA 2618 alloy. The objectives were to develop sufficient data to validate the goal of this effort and guide continuing commercialization of the rapid IR solutionizing process as well as optimization of components currently under development. The following were tasks performed under this effort.

- A base-line was established by compiling existing process information and mechanical data of conventionally processed, forged and heat-treated aluminum parts/upsets.
- A prototype rapid IR solutionizing furnace that produced the parts for this project was constructed and installed at the Queen City Forging (QCF) Company.
- A sample matrix test plan was developed from a previous project's data. Two solution temperatures and times were chosen for the subject prototype tests.
- A sufficient number of forged upsets (~50% reduction) were produced at QCF to fulfill the sample matrix plan.

- Specimens from forging upsets were machined and tested, most being used to develop high and low cycle fatigue curves (S-N diagrams).
- Metallographic evaluations were performed to characterize microstructures.
- The data were analyzed and evaluated, with the results being presented in this report.

2.0 Experimental Approach

The experimental approach involved producing simple upset forged parts in a manufacturing environment such that actual production data could be developed. This section is divided into three main sub sections that:

1. describes and characterizes the alloy and processing of the forging upsets
2. presents the solutionizing heat-treatment cycles, which are the main focus of this effort
3. describes sample preparation and the various tests performed.

Based on previous work[8], three processing conditions were considered. The first was the baseline condition, which involved conventional furnace billet preheating prior to forging and a conventional furnace solution treatment (530 C for 8 hours) and ageing. The other two conditions involved IR heating of billets prior to forging and for solution treatment. The difference in the two IR process conditions was that one set of samples was solution treated at 530 C for 40 minutes and the other set was solution treated at 539 C for 20 minutes. The heat-up times for both IR solution treatments for these upsets was approximately 30 minutes, which was not included in the aforementioned times. Three forging upsets from each of the three conditions were used to make samples for tensile and fatigue testing. Forging upsets for all three conditions were given a conventional artificial ageing cycle for this alloy, 199 C (390 F) for 20 hours.

2.1 Material Processing and Characterization

This section presents the alloy that is the focus of this report, namely AA 2618, and it documents the processing of simple forged upsets from casting through hot forging.

2.1.1 Alloy and Chemistry

Aluminum Association (AA) 2618 alloy is the focus of this report. This alloy is typically used in high-performance impression-die forged parts, such as pistons and rotating aircraft engine parts that operate at elevated temperatures.[9] The material for this study was produced at Kaiser Aluminum, Newark, Ohio. The billet from which the extruded bar-stock was produced was DC (direct-chill) cast. The chemical composition of the alloy was determined by atomic emission spectroscopy. Table 1 gives the chemical composition of the material used herein and the AA standard.

Table 1: Composition of AA2618 test material in weight %, via atomic emission spectroscopy. The balance is Al.[10]

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 specification	1.9-2.7	0.9-1.3	0.10-0.25	0.05 max	1.3-1.8	0.10 max	0.05 max	0.9-1.2	0.04-0.10

2.1.2 Extrusion

The forging bar-stock was produced via hot extrusion by Kaiser Aluminum in Newark, Ohio. 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 381 mm (15 inches) in diameter and 2261 mm (89 inches) in length, and extruded through a 5-hole die, resulting in an extrusion ratio of 9.2.[11] The as-extruded grain structure was a fine recrystallized structure indicative of hot extrusion. This is shown in Figure 1. The as-cast structure was unavailable.

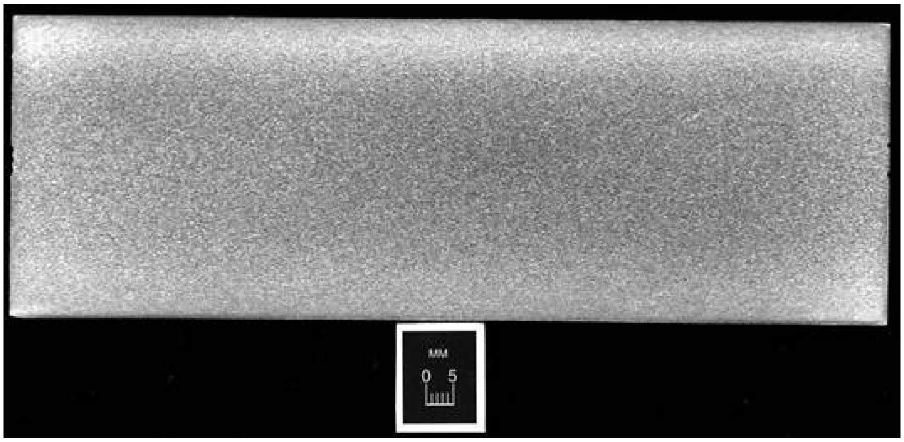


Figure 1: Longitudinal macro-structure of AA 2618 forging billet in the as-extruded condition. The photo shows a fine, recrystallized grain structure. Extrusion direction is horizontal to page. Photo was taken at ORNL.[12]

2.1.3 Forging

Forging and related preparation was undertaken at the Queen City Forging Company, Cincinnati, Ohio. The extruded bar-stock was cut into forging billets that were approximately 165 mm (6.5 inches) long. Billets were heated to forging temperatures via a conventional gas-fired furnace and via a continuous flatbed IR furnace. Conventionally heated billets served as control samples, which would also receive a conventional solution heat-treatment. Billets that were preheated via IR heating in the continuous flatbed furnace were those that were subsequently solution heat-treated via rapid IR heating.

Billets that were conventionally heated took approximately 2 hours to reach the forging temperature of 427 C (800 F). These billets were held an additional hour at this temperature before upset forging. Billets heated via rapid IR heating in a continuous furnace were first bead-blasted to produce a consistent dull finish. The billets were then heated to the same forging temperature (427 C) and upset forged immediately after reaching that temperature. Heat-up time in the IR furnace was approximately 20 minutes. A photograph showing the continuous IR flatbed furnace and process layout is shown in Figure 2.

Figure 2: Continuous flatbed IR furnace (right) and forging billet (left-foreground) at the Queen City Forging Company. The forging press with die heater is shown in the background. Photo courtesy of QCF.

Forging consisted of about a 50% reduction to 83 mm (3.25 inches) in one hit in a mechanical press. The macro-structure of one of the conventionally heated upset billets was evaluated and this is shown in Figure 3. The fine equi-axed grain structure was similar to that of the as-extruded bar, thus it was not deemed necessary to evaluate that of the IR processed upset.

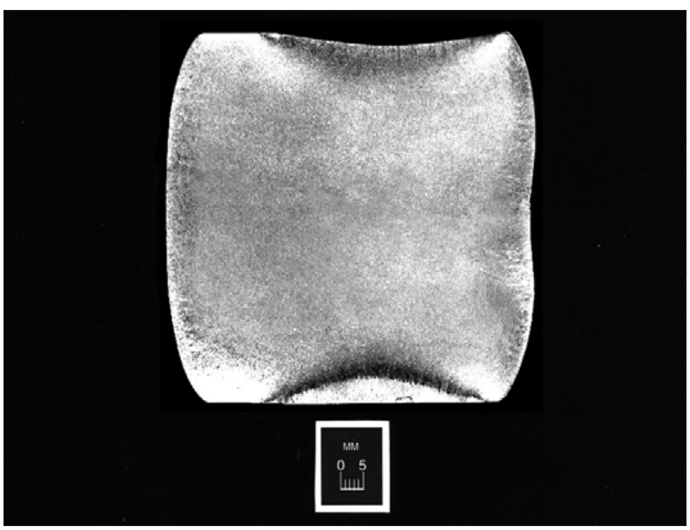


Figure 3: Longitudinal macro-structure of AA2618 billet after upsetting 50% at 427C (800F). The grain structure remained similar to that of the as-extruded condition. Pre-heating of this sample was via conventional methods. Extrusion and forging directions are vertical to the page. Photo was taken at ORNL.[13]

2.2 Solutionizing Heat-treatment

Reducing solution treatment time with IR heating is a primary objective of this work. The conventional time and temperature for solutionzing this size AA 2618 alloy work-piece is 8 hours at 530 C. The solutionzing process involves the solid-state dissolution of second phases at elevated temperatures and then a rapid quench to preserve or retain this state at room temperature. Rapid IR solution treatments were done at 530 C for 40 minutes plus a 30 minute heat-up, and at 539 C for 20 minutes plus a 30 minute heat-up time.

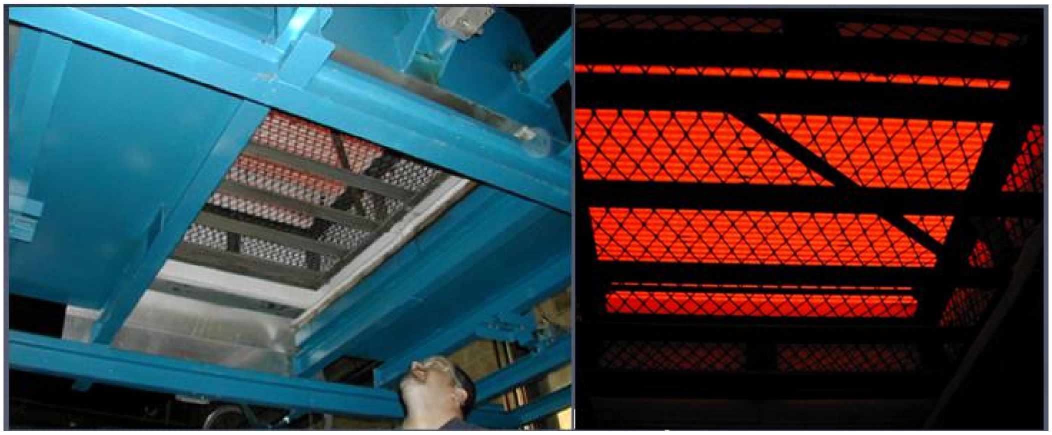
2.2.1 Conventional Processing

Conventional solution heat-treating and artificial ageing of forged upsets were performed at ORNL, Oakridge, TN. The forging upsets were loaded into a conventional solution treating furnace at 530 C (985 F) and quenched after 8 hours. Subsequent artificial aging was at 199 C for 20 hours. From this production lot, three upset billets were used for test samples.

2.2.2 IR Processing

A prototype production IR solution furnace installed at the Queen City Forging Company was used to produce samples for this work. Photographs of this special furnace are shown in Figures 4 and 5. Parts are placed in a basket measuring 33”×44” × 8” (838 mm × 1118 mm × 203 mm), see Figure 5. Upon the requisite time at temperature, the basket is dropped into the water quench tank (shown in Figure 4). The water is held at approximately 100 C.

Figure 4: Photograph of the prototype production IR drop furnace installed at the Queen City Forging Company. The IR furnace elements are located in the top-middle unit, and the quench bath (from which the steam is rising) is shown at the bottom-left. Photo courtesy of QCF.



(a) (b)

Figure 5: Photographs showing the "underside" of the prototype production IR drop furnace installed at the Queen City Forging Company. The photos show the steel-mesh basket in which the parts are place for heat-treating. The parts-basket drops into a quench tank after solution treatment. Photo courtesy of QCF.

Axial holes were drilled at the center of the forged upsets to accommodate thermocouples. These embedded thermocouples were used to monitor and record the solutionizing cycle. The IR solution treatment cycles at 530 C and 539 C are shown in Figures 6 and 7, respectively.

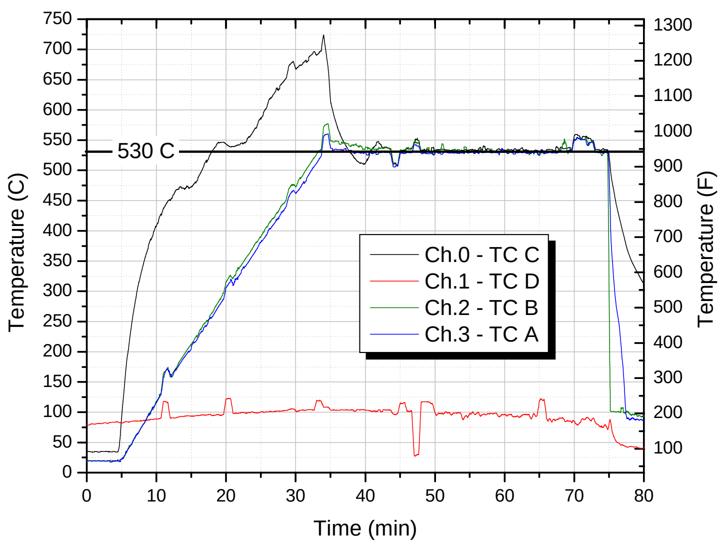


Figure 6: IR furnace solutionizing data for AA 2618 forged upsets. Thermocouples were imbedded in the center of the forged upsets. Target thermal profile was for 40 minute soak time at 530 C (985 F). Ch.0 is the furnace temperature and Ch.1 is the quench bath temperature. Sharp/fast spikes in the data are due to excessive noise that was not filtered from the data.

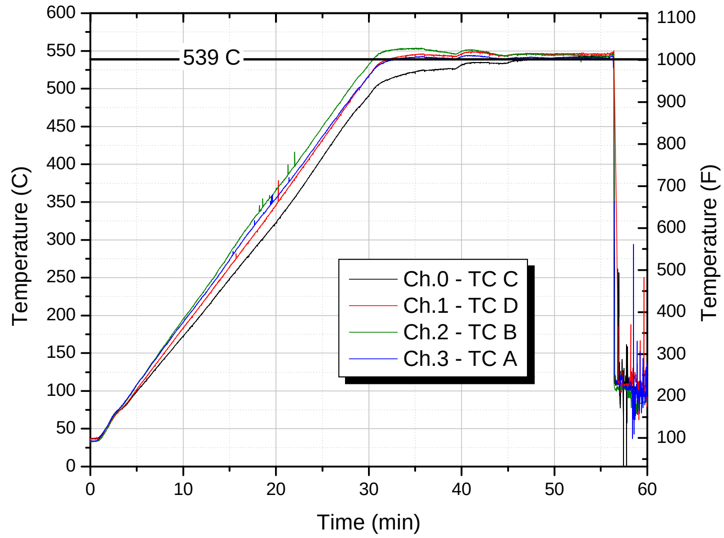


Figure 7: IR furnace solutionizing thermal cycle data for AA 2618 forged upsets. Target thermal profile was for 20 minute soak time at 539 C (1002 F). Thermocouples were imbedded in the center of the forged upsets.

Subsequent to the solution cycles, the forging upsets were given a 20 hour artificial ageing cycle at 199 C (360 F) to provide a T61 temper. Three billets per condition were used for evaluation.

2.3 Sample preparation and testing

Cylindrical rod samples for tensile testing and fatigue testing were extracted from the mid-radius of the "T61" forged upsets using wire EDM (electro discharge machining). Schematics of the forged upsets and layout of the extracted rod-specimens are shown in Figures 8 and 9. The layout in Figure 8 was (initially) used for conventionally heat-treated samples; one ½" diameter rod was used for a tensile specimen and the remaining 7/16" diameter rods were used for fatigue test specimens. For the IR heat-treated upsets, all rods extracted were ½" diameter, as depicted in Figure 9. This resulted in one less specimen per upset. Figure 10 is a photograph of an upset from which rods have been wire EDM'ed.

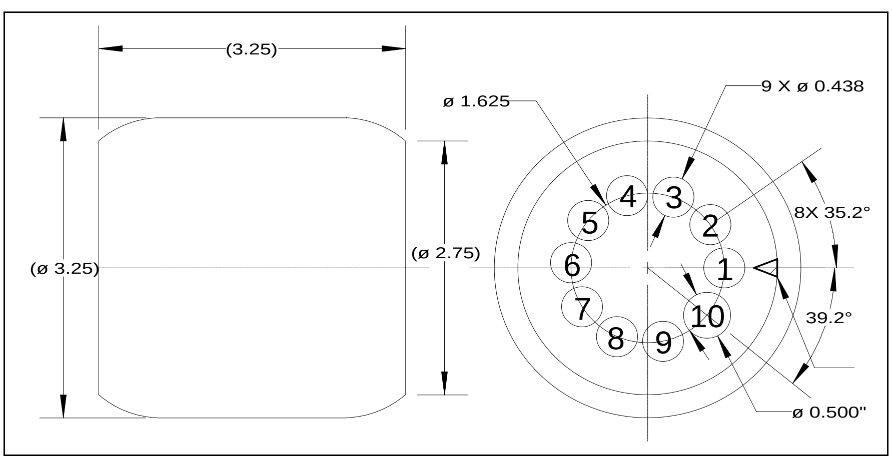


Figure 8: Sample layout with respect to forging upset. Samples from conventionally heat-treated upsets were produced in this manner.

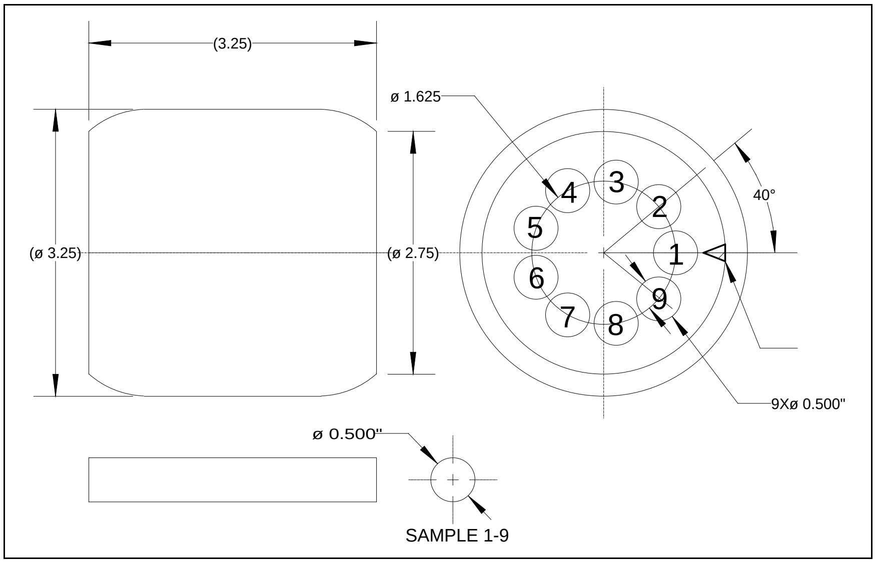


Figure 9: Sample layout with respect to forging upset. Samples from IR heat-treated upsets were produced in this manner.

Figure 10: Photo shows rods that have been wire-EDM machined from an AA 2618 forging upset that was conventionally heat treated. Rod samples were further machined into samples for tensile testing, and low and high cycle fatigue testing.

2.3.1 Tensile testing

Standard ASTM tensile test specimens were machined from the 0.5 inch (12.7 mm) diameter rods, depicted in Figures 8, 9 and 10. These samples had a gauge section of 1 inch (25.4 mm) with a diameter of 0.25 inch (6.35 mm). Tensile tests were conducted with a servo hydraulic MTS machine. Tensile stress, 0.2% yield stress and elongation were obtained. One sample for each forging upset was tested; with the remainder being for fatigue testing. Specimens that were machined from rods extracted from heat-treated forged upsets are shown in Figure 11. The same general type of specimens was used for low cycle fatigue testing.

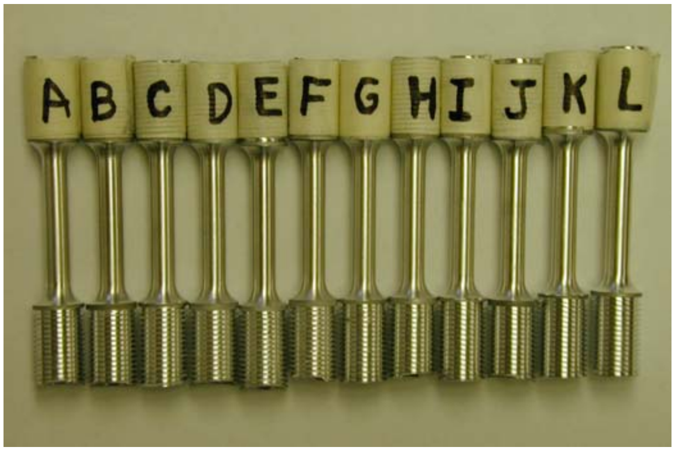


Figure 11: Tensile test specimens CNC machined from ½" diameter rods. One specimen from each forging upset was produced.

2.3.2 Hardness testing

Hardness tests were performed with a Wilson tester using the Rockwell B scale. Five tests were performed on the flat portion of each upset. These flat areas were polished with SiC paper prior to hardness testing.

2.3.3 High Cycle Fatigue Testing

High cycle fatigue (HCF) tests were performed with the Instron tester seen in Figure 12. The test was an R.R. Moore, rotating beam test with a stress ratio, $R = -1$ (fully reversed bending). Tests were performed in accordance with ISO 1143-1975 (E).[14] All tests were at approximately 9000 rpm, or 150 Hz. Prior to testing, samples were measured with a special gauge that was made to measure the diameter of the samples in the neck region. This device is shown in Figure 13.

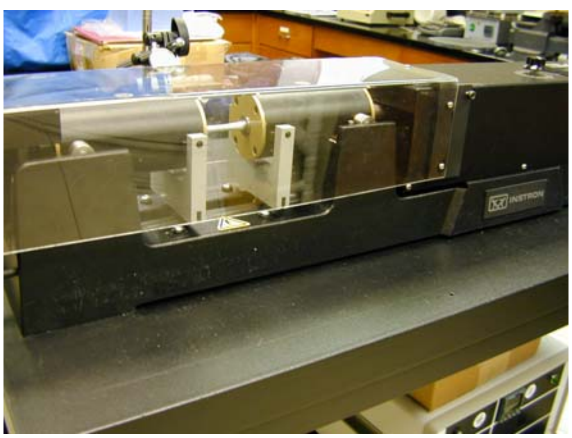


Figure 12: Photograph of Instron, R.R. Moore fatigue testing machine.

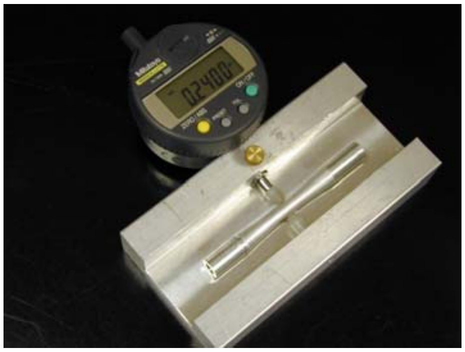


Figure 13: Special gauge made to measure the diameter of fatigue specimens. The anvils are made of nylon so as not to damage the polished surface of the specimen.

The sample blanks such as shown in Figure 10 were machined on a CNC lathe to the geometry shown in Figure 14, according to the guidelines set forth in the ISO 1143 standard and the Instron user manual.[15] ISO 1143-1975 sets forth specific machining requirements, such as depths of cut and feed rates. Final polishing with successively finer grades of abrasive papers (400 and 600 grit SiC paper) were used for the final surface preparation. A small laboratory lathe was used for the final polishing operation. The surface of such a sample (that had undergone testing) is shown in Figure 15.

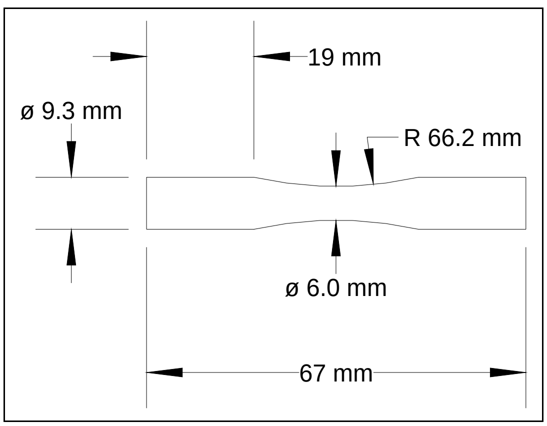


Figure 14: Sketch of HCF R.R. Moore fatigue specimens used for this study.

Figure 15: Photo of the polished surface of a fatigue specimen (in the neck region). This sample had been tested and the fracture is on the left side of the photo.

Fatigue test stress levels were chosen at approximately 90%, 80%, 70% and 60% of the average yield stress. For a desired stress level, the applied load is given by Equation 1.[16]

$$W = \frac{\pi d^3 \sigma}{16l} \tag{1}$$

W = Total load on specimen (lbs)
d = Minimum diameter in the neck region (in.)
σ = Extreme fiber stress (psi)
l = moment arm (4 inches for this machine)

Three samples were tested at each stress level, with each specimen being taken from a different forging upset in the group. Note that three upset forgings for each of the three conditions were produced. The test sequence was randomized prior to testing to prevent any possible bias.

2.3.4 Low Cycle Fatigue Testing

Low cycle fatigue (LCF) tests were performed largely in accordance with ASTM Standard E606-04e1, *Standard Practice for Strain-Controlled Fatigue Testing*. A servo-hydraulic MTS machine with a TestStar IIs controller and Multipurpose Testware software was used for the testing and data collection. Alignment of the ram and crosshead of the MTS machine was verified according to ASTM Standard E1012. An ENCO CNC lathe was used to manufacture the specimens per ASTM E606-04e1, similar to tensile test specimens. After machining, the specimens were polished on a mini-lathe with 600 grit SiC paper to achieve a fine and consistent finish.

The array of tests performed ranged from 0.2% to 1.0% strain. From the IR heat-treated upsets (20 min @ 539 C and 40 min @ 530 C) twelve specimens were tested, and eleven specimens were tested from the conventionally heat-treated upsets (8 hrs @ 530 C). In accordance with ASTM E606-04e1, the specimens were of uniform cross-section in the gauge length. The specimens were machined with a gauge section length of 1.25 inches (31.75 mm) and a diameter or 0.25 inch (6.35 mm). The conventionally heat-treated specimens had a slightly smaller gauge section diameter of 0.22 inch (5.59 mm). A 1-inch (25.4 mm) extensometer was used to provide the strain-controlled feedback. A photo of a specimen and test configuration is shown in Figure 16. Specimens were tested in a randomized order with respect to strain level to avoid any potential bias in the data. Axial test loading was completely reversed for a stress ratio, $R = -1$. The test frequency in strain control was 1 Hz. Figure 17 shows hysteresis data for an IR solutionized sample (20 min @ 539 C). These data are sufficiently consistent; a slight shift in the data is evident in the first cycle, however this offset disappears after approximately the 10th cycle. Figure 18 shows LCF samples before and after testing.

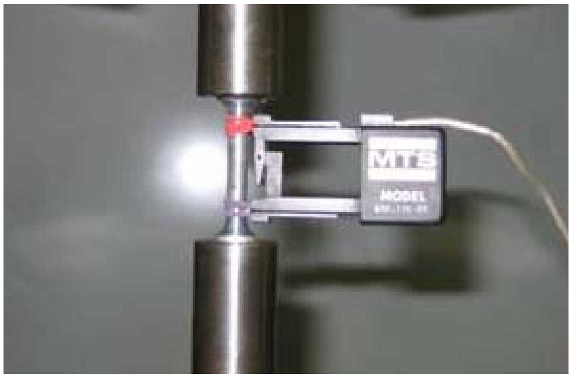


Figure 16: LCF test configuration.

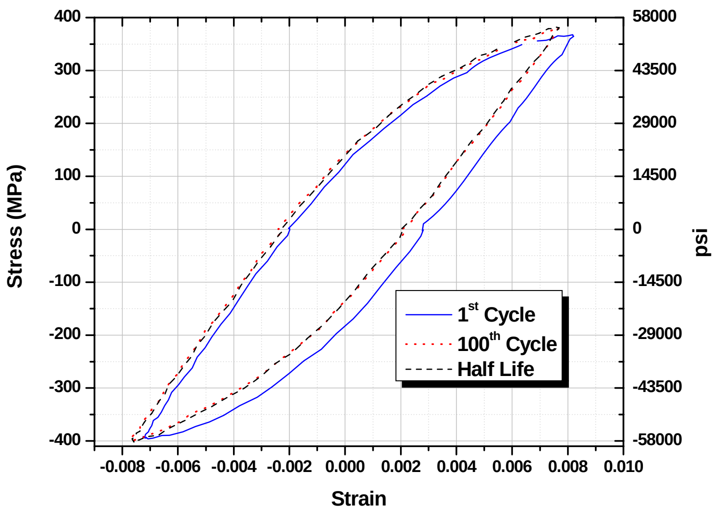


Figure 17: Hysteresis of strain controlled, low cycle fatigue testing. Data were for an IR solutionized sample (20 min @ 539 C).

Figure 18: AA2618 LCF samples before and after testing.

3.0 Results

This section presents the results of mechanical testing (tensile, hardness, HCF and LCF testing), and grain size measurements. In addition, prototype production data from an actual part was supplied by Queen City Forging Company. These data were evaluated and compared with the data from the forging upsets.

3.1 Mechanical Properties

The results of the tensile and hardness tests are presented in Table 2. The last entry in the table shows the minimum specified values for the T61 temper. For all the conditions and samples tested, the T61 properties are exceeded. Yield and tensile stress are very similar for all three conditions and no difference was statistically resolved. Elongation values for the conventionally heat-treated samples were slightly larger than IR treated samples in all but one case. This may be attributed to a small amount of micro-porosity that can develop in this alloy due to eutectic melting during rapid solution treatment[17]; however this was not verified in these samples.

Table 2: Tensile and hardness test values for IR solution treated samples and conventionally solution treated samples. All samples underwent a standard aging cycle. Each sample was taken from a different forging upset of that lot. The bottom entries in the table are handbook specifications for comparison.

Condition	Sample	0.2% yield stress ksi (MPa)	Tensile stress ksi (MPa)	Elongation (%)	Hardness* (HRB)
IR solution-treated 20 min @ 539 C	1	51.5 (355)	62.9 (434)	12.0	75.8
	2	49 (338)	64.4 (444)	9.9	75.6
	3	49 (338)	61.7 (425)	10.0	75.5
IR solution-treated 40 min @ 530 C	1	50 (354)	62.4 (430)	10.1	75.5
	2	50 (345)	62.3 (430)	10.0	76.0
	3	49.5 (341)	61.7 (425)	10.1	75.8
Conventionally solution-treated 8 hrs @ 530 C	1	49.0 (338)	60.4 (416)	11.1	74.0
	2	51.2 (353)	62.6 (432)	11.4	75.6
	3	50.2 (344)	62.7 (432)	12.3	74.2
Minimum Specification[18]	N/A	48 (331)	58 (400)	6	72

* Hardness data were obtained using 100kg load and 1/16 inch ball. Data are an average of 5 measurements.

The results of the high cycle fatigue (HCF) tests are shown in Figure 19. Data are plotted for each condition with published data from the Aerospace Structural Metals Handbook.[19] From the data, it is seen that the fatigue life of the IR heat-treated specimens is generally greater than that for the conventional heat-treatment. This appears to be consistent with other work that has recently been published.[20] It was hypothesized that this effect was possibly due to larger grain size and a decrease in age hardening behavior from the formation of stable copper compounds during the longer solution times of the conventional heat treatment.[21] However, in the samples tested for this report, no significant difference in grain size was observed, as presented in Section 3.2.

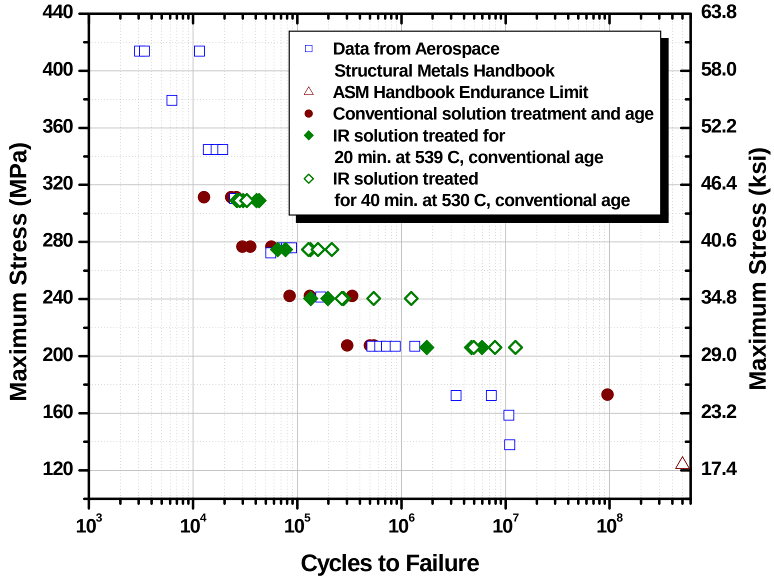


Figure 19: High cycle fatigue data. Graph shows a comparison of high-cycle fatigue data for T61 treated specimens that were conventionally solution treated, IR solution treated and data from the Aerospace Structural Metals Handbook.[22]

The results of the low cycle fatigue (LCF) tests are shown in Figure 20. No discernable difference between conventionally heat-treated and rapid IR treated samples could be resolved.

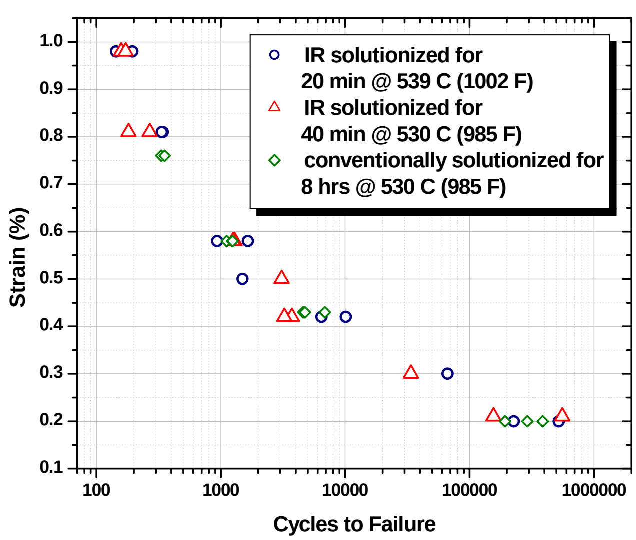


Figure 20: Low cycle fatigue data for conventionally heat-treated and rapid IR treated samples.

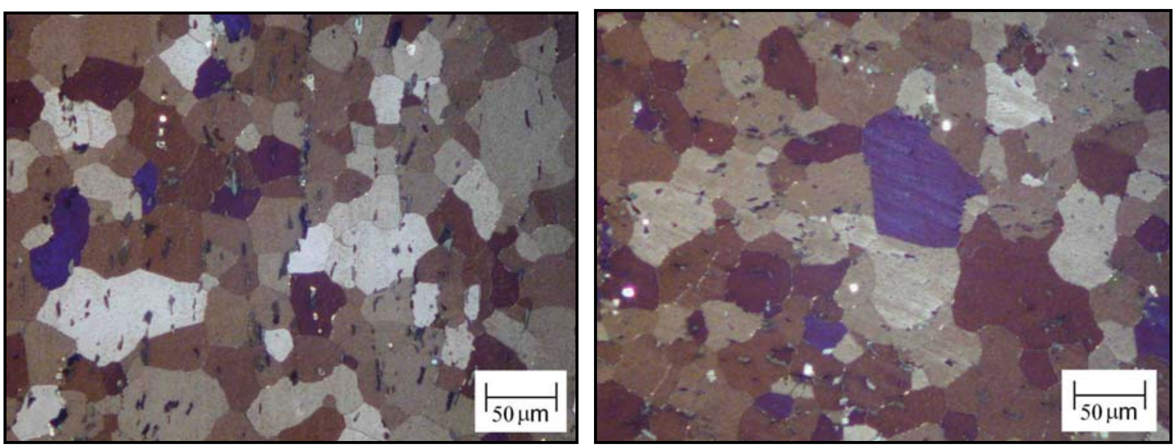
3.2 Grain Size

Grain size measurements were made by the ASTM line intercept method.[23] The specification defines one intersect as a segment of line that overlays one grain. The results from grain size measurements are shown in Table 3. These measurements were taken from sections of the specimens that were tensile tested, but that were outside the areas of deformation. In this region of the upset billet (along the mid-radius), no significant difference in grain size was observed. Although it has been reported that rapid IR processing can produce a smaller grain size,[24] this was not observed in these specimens for a 50% forging reduction. Thus, improvements in HCF behavior in these specimens can not be attributed to a smaller grain size.

Table 3: Average grain sizes of AA 2618 specimens for the different solution treatment conditions.

Condition	Grain size (μm)
IR solution-treated 20 min @ 539 C	34
IR solution-treated 40 min @ 530 C	34
Conventionally solution-treated 8 hrs @ 530 C	30

Figure 21 shows photomicrographs of aged specimens that were IR solution treated and conventionally solution treated.



(a) (b)

Figure 21: Micro-graphs showing the grain size in (a) an IR solution treated sample (530 C for 40 min) after ageing, and (b) a sample that was conventionally solution treated and aged. The section shown in (a) is parallel to the forging direction and the section in (b) is transverse to the forging and extrusion directions.

3.3 Prototype Part Production Results

Data from a complex forging were provided by QFC for further analysis with regard to this effort. These parts were IR solution treated at 530 C from 10 minutes (soak time) to 2 hours. Hardness test results using the Rockwell B scale are shown in Figure 22. The data indicate that a solution soak time of about 40 minutes at 530 C is required to minimize variability and ensure a "complete" solution treatment. This is consistent with the experimental data presented above.

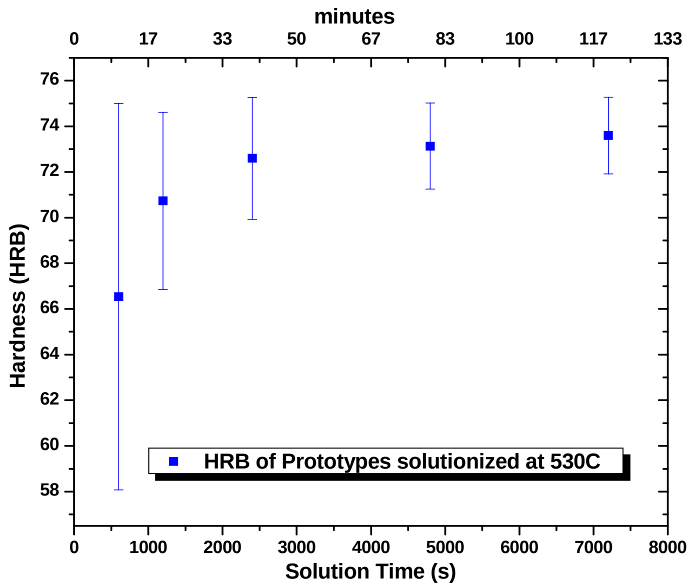


Figure 22: Hardness in forged and IR solution treated prototype parts as a function of time at temperature. Parts were given a conventional artificial ageing cycle. Error bars represent ±1 standard deviation.[25]

Figure 23 shows an array of grain size measurements made in high and low deformation regions of these forged parts for solution treatments for up to 2 hours soak time. The data show that at a high deformation region, the grain size has low variability and essentially remains the same for all of the soak times. At a low deformation region however, the grain size and variability increase after a 40 minute soak time. From the data presented in this section, it can be concluded that the optimum solution soak time is about 40 minutes for AA 2618 and the processing conditions presented herein.

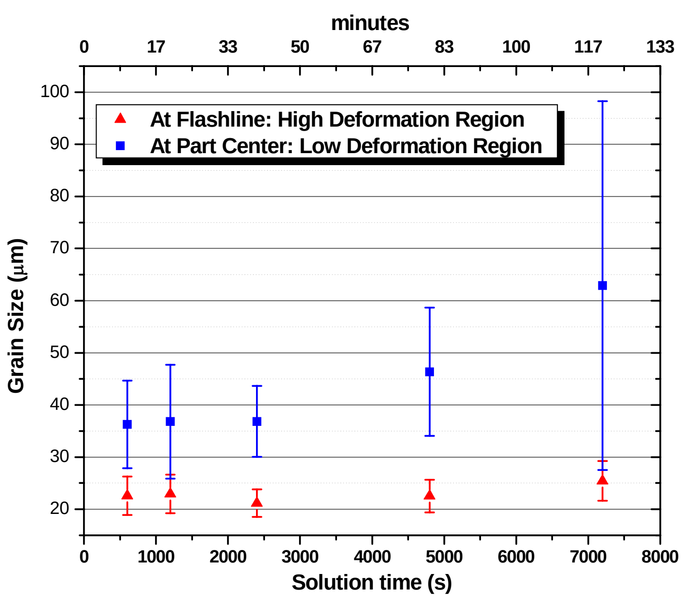


Figure 23: Variation of grain size in forged and IR solution treated prototype parts. Error bars represent ±1 standard deviation.[26]

4.0 Conclusions

- The solution heat-treatment cycle can be shortened by over 80% using rapid IR heating, compared to the published standard, which implies a conventional gas-fired heat treating operation.
- Rapid IR solution treated parts exceeded specified mechanical properties; tensile and yield stress, elongation and hardness. These mechanical properties were essentially the same as parts that were given a conventional solution treatment.
- Rapid IR solution treated parts exceeded HCF performance of conventionally solution-treated parts and of data obtained from the literature.
- LCF performance of rapid IR treated specimens were essentially the same as that for specimens that were from conventionally solution treated upsets.
- Grain size can be held at a minimum, especially at low deformation regions, using rapid IR solution heat treating.

Citations:

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