Strengthening of 7175 Aluminum Alloy Through Multi-Step Aging Process

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Abstract

7175 is a heat-treatable aluminum alloy commonly used in aerospace forgings. This alloy is aged with a multi-step heat treatment. This treatment must balance strength with stress corrosion cracking resistance through a degree of overaging. The team was tasked by Weber Metals to increase the strength of this treatment without sacrificing stress corrosion cracking resistance. Both two-step and retrogression and reaging treatments were tested in experiments to find a heat treatment that could increase the yield and tensile strength by 1-2 ksi while maintaining a minimum electrochemical conductivity equivalence of 38% relative to copper. Two-step aging is the more conventional process for achieving this mixture of properties, while retrogression and reaging has seen promising results in the literature but is not widely used in industry. A two-step aging treatment that aged samples in a 117°C furnace for 6 hours followed by a 185°C step for 13 hours was identified as a suitable candidate. Twelve samples tested over three different runs showed this treatment to have an average yield and tensile strength 1.57 ksi and 1.18 ksi respectively higher than the control group. This was accompanied by an average conductivity of 38.6% relative to copper. None of the retrogression and reaging treaments had suitable properties.

Keywords

Acknowledgements

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Introduction

Company background

Weber Metals (Paramount, California) was originally a scrap metal business that turned into a forging business to help supply parts for the west coast aerospace industry during the early 1940s. After the death of the owner, Edmund Weber, his wife sold the company to OTTO FUCHS Metallwerke a Germany company in the 1980s, and during the next decade they increased the production capacity with larger closed die presses. These new presses are used in aluminum and titanium forgings for the aerospace industry. During the 1990s the company continued to grow and become a major supplier for the aerospace industry [1].

Forging Background

Weber Metals produces a variety of open and closed die forgings with both aluminum and titanium alloys. The main distinction between open and closed die forging, is that open die forging produces discontinuous material flow while closed die produces continuous flow[2]. 70% of closed die forgings in the world are less than a kilogram in mass [3]. Open die forgings are only limited in size by the size of the press used to manufacture them. Weber Metals has the capability to produce close die forgings up to 4,000lbs and open die forgings up to 11,000lbs. This project is focused on open die forgings made from 7000 series aluminum. Aluminum alloys are some of the most forgeable due to their high ductility, allowing for greater deformation and more complex geometries. Figure 1 shows an example of a part forged by Weber Metals from 7075 aluminum.

Figure 1. Landing gear shock strut produced by Weber Metals out of 7075 aluminum. The central column of the part is the thickest and poses the largest potential risk for not developing a homogenous microstructure during heat treatment. [1]

Problem Background

7175 Al is used extensively in helicopters and landing gear due to its high strength and excellent fatigue behavior. Unfortunately, in the peak aged (T6) condition this alloy shows susceptibility to stress corrosion cracking (SCC) that can occur in aircraft applications. This has led manufacturers towards different amounts of over-aging that reduces strength but

increases resistance to SCC. The most dramatic overaging is the temper T73 which provides a high degree of resistance to SCC, and results in around a 15% sacrifice in yield strength relative to T6 [4]. The other commonly used treatment is T76, which provides less resistance to SCC and results in only a 5 to 10% reduction in tensile yield strength relative to T6. While both of these heat treatments are relatively common, a number of other such tempers exist which are less commonly used and may even be proprietary. The tempers T74, T77, T78 and T79 are all used for treatments that lie somewhere between T76 and T73[5]. Weber Metals uses a type of T74 treatment but has been finding that it has not been meeting the strength requirements set by their customers.

Weber Metals is producing parts for ever larger vehicles that require increasingly large cross-sections. 7175 Al is a shallow hardening alloy which does not have uniform properties throughout thick cross-sections. This results in more parts missing their strength tolerances by only a few ksi. They wish to investigate how changing the heat treatment used for 7175 Al parts could marginally increase their strength and result in more parts meeting their clients' strength requirements. The strength of tensile samples heat treated in these different ways will be measured, and the conductivity will be measured to exceed 38% relative to copper at 100%. This conductivity measurement will act as a proxy for measuring the general corrosion properties of the microstructure developed by the heat treatment.

Alloy Information
7175 is an age-hardenable aluminum alloy with a maximum weight percent of 6.1% Zn, 2.9% Mg 2.0% Cu, 1.5% Si, 0.28% Cr, 0.20% Fe, 0.10% Mn, with the balance being aluminum [5]. 7000 series aluminum uses zinc as the supersaturating element. However, the binary Al-Zn system is not useful for determining the solutionizing temperature (Figure 2). For 7xxx series alloys a ternary phase diagram is required (Figure 3). ASM recommends that 7175 aluminum alloys are solutionized above 470°C.
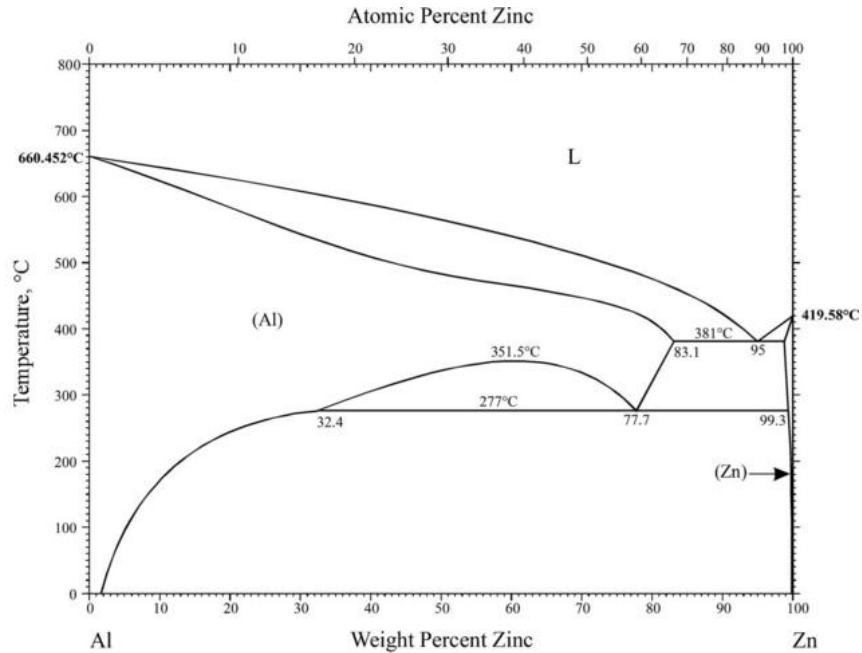
Figure 2. Binary phase diagram for Al-Zn system, useful for other alloys but not for 7xxx series aluminum[6].
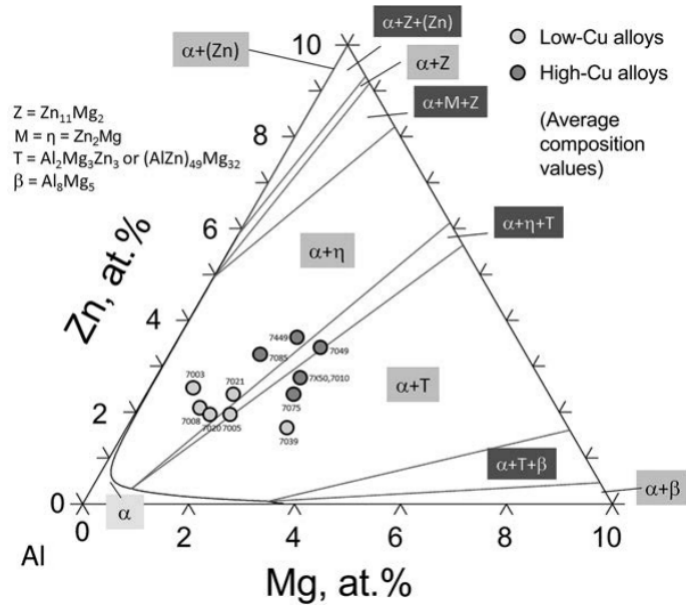
Figure 3. Isotherm of Al-Zn-Mg ternary phase diagram at 200°C. Calculated with Thermocalc and the COST507B database. The average composition of various industrial alloys is indicated by dots and solid lines indicate boundaries between phase fields. The high-Cu alloys are not exactly valid in this phase equilibria.[4]

Precipitation Behavior of the 7175 Aluminum Alloy

The 7xxx series aluminum produces a few precipitates, one of which transitions through two stages before reaching a bimetallic precipitate η that has the chemical structure of $MgZn_2$. The first precipitate that forms are coherent precipitates in a Guinier-Preston zone (GP zone). These GP zones contain 50% or more aluminum usually and have complex chemical formulas. As a GP zone continues to grow, it transitions into the intermediate

precipitate η′; this phase is a semicoherent phase that is thought to have a hexagonal structure [7]. Finally the incoherent η phase ($MgZn_2$) precipitates laths or plates at or from η′ [7]. These incoherent particle are not completely separate from the Al matrix, there are normally AlCuMg alloy at the boundary between the Al matrix and η precipitate [7] (Figure 4). Something to be mindful of is the depletion regions near precipitates that will be weaker than the supersaturated solid solution. The addition of magnesium allows the formation of $MgZn_2$ which allows for the aging response. In 7175 the precipitate of interest is the η phase $Mg(Zn, Cu, Al)_2$, or its precursor η′ for increasing stress corrosion cracking resistance. For strengthening purposed the coherent GP zones are the most beneficial.
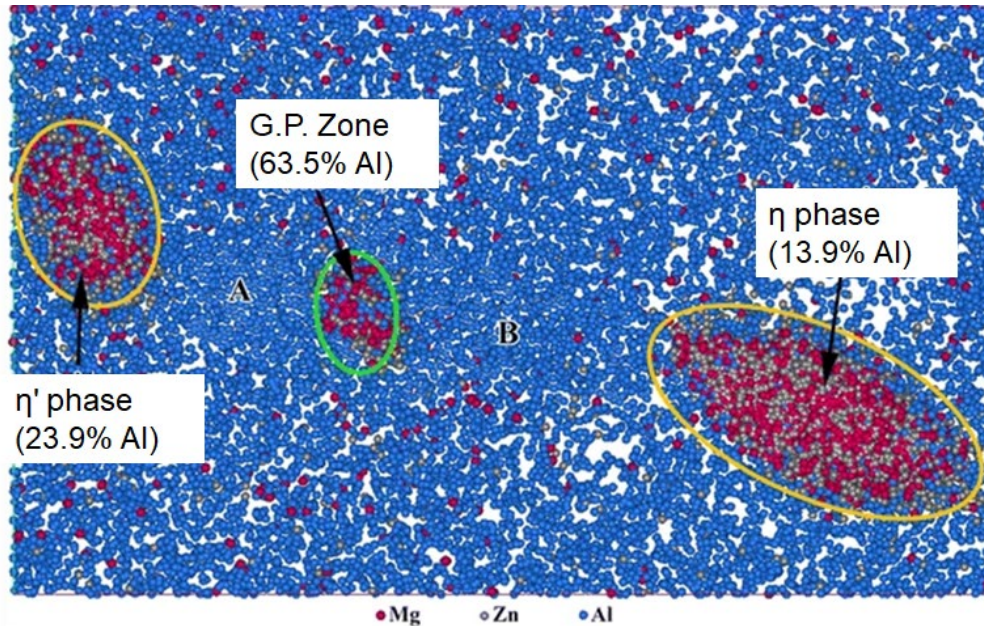
Figure 4. One nanometer thick atom map of the distribution of Mg, Zn, and Al atoms from an overaged 7175 sample, with A and B marking Mg and Zn depletion regions. [8]

Retrogression and Reaging (RRA)

Retrogression and reaging heat treatments were first investigated by Cina while working in the Israeli aircraft industry. [9]These heat treatments were used to solve a similar problem to that of Weber Metals. 7000 series aluminum was being overaged to reduce its susceptibility to stress corrosion cracking and exfoliation corrosion. A schematic of the standard retrogression and reaging treatment is presented in Figure 5. Parts are first solutionized, quenched and then aged at a similar temperature as other treatments. The unique portion is the retrogression step when the part is raised to a higher temperature between the two lower temperature aging steps. The retrogression step is responsible for dissolving Guinier-Preston (GP) zones. However, it does not dissolve the larger phases in the microstructure. This enriches the aluminum matrix and allows for new η and η′ phases to precipitate and for the existing precipitates to grow further. It is the growth of precipitates at the grain boundaries that is believed to be associated with the increase in resistance to SCC [10]. This is at least one of the prevailing models, as the process is not completely understood.
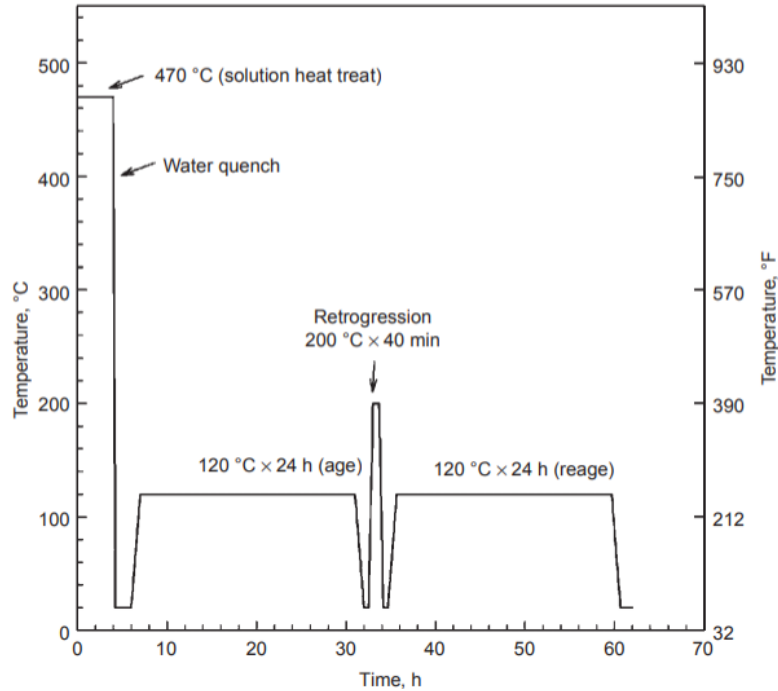
Figure 5. Retrogression and reaging general treatment. The exact temperature of retrogression is specific to part size and geometry. This treatment is most often performed in an oil bath.[10]

However, retrogression and reaging is a treatment that requires fine process control. The retrogression time and temperature are dependent on part size and geometry. The RRA process requires one to monitor the progression of the heat treatment and understand heat transfer into and out of parts. One of the most elegant ways to do this is to produce a real-time computer control system of the process. Despite these issues, the team still attempted RRA treatments as a potential solution to the problem.

Two Peak Aging

Two peak aging is an artificial aging method that employs two different aging steps after the producing a supersaturated solid solution (SSS). This method of aging is often used in industry to produce T7X heat treatments. Common heat treatments that follow this pattern for their heat treatment are T73, T74, T76. All of these heat treatments have a lower temperature for the first aging process that lasts 6-8 hours, and a second aging process at a higher temperature that lasts 10-12 hours (Figure 6) [5]. Any heat treatment with a TX51 or TXX51 has a straining process between the quenching of the sample to form the SSS and the first aging cycle [4]. In a lab setting, the components that are aging can be quenched between the first aging cycle and the second; however, the industry standard is to keep the components in the furnace while its changing temperature or simply swap furnaces[4].
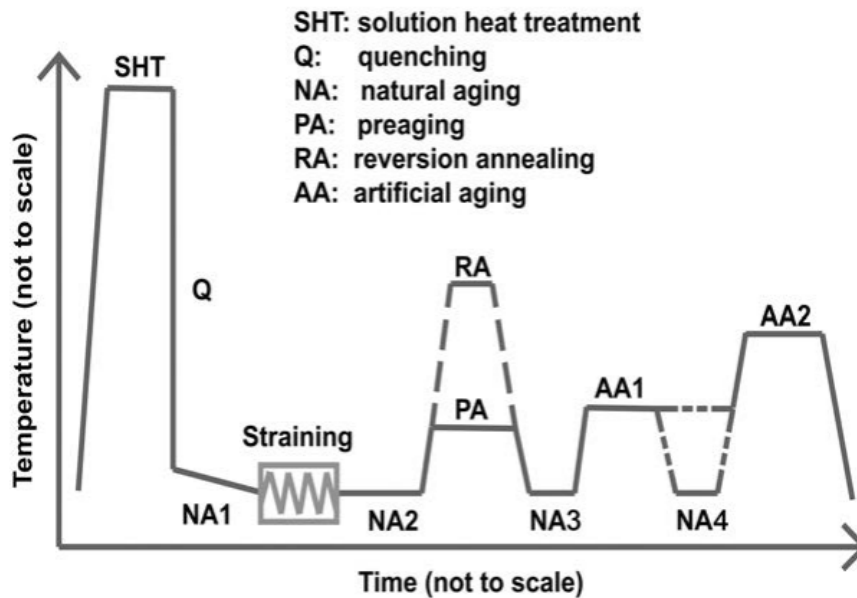
Figure 6. General form of two stage heat treatments, not all stages are used.

Experimental Procedure
Calibrating the Box Furnace

In order to accurately assess experimental heat treatments a high degree of precision was necessary. The Sentro Tech ST-1100C box furnace was used with a steel baffle inside of it that would prevent localized over heating of samples through radiation from heating elements. The result of this is that any samples placed below the baffle would experience a lower temperature than the atmosphere above the baffle where the thermocouple of the box furnace measures. Thus, the team designed an experiment to measure the temperature reached in the interior of the samples when the furnace was programmed at different temperatures (Figure 7).

The team found a scrap piece of aluminum to drill a hole into so that a thermocouple could be placed within it to monitor its internal temperature. This sample analogue was exposed to a treatment where eleven different 6.5hr isothermal holds were programmed from 100°C to 200°C with 10°C increments (Figure 8).The difference between the programmed temperature and sample analogue equilibrium temperature grew as the temperature increased, ultimately ranging from 9-19°C (Table I).
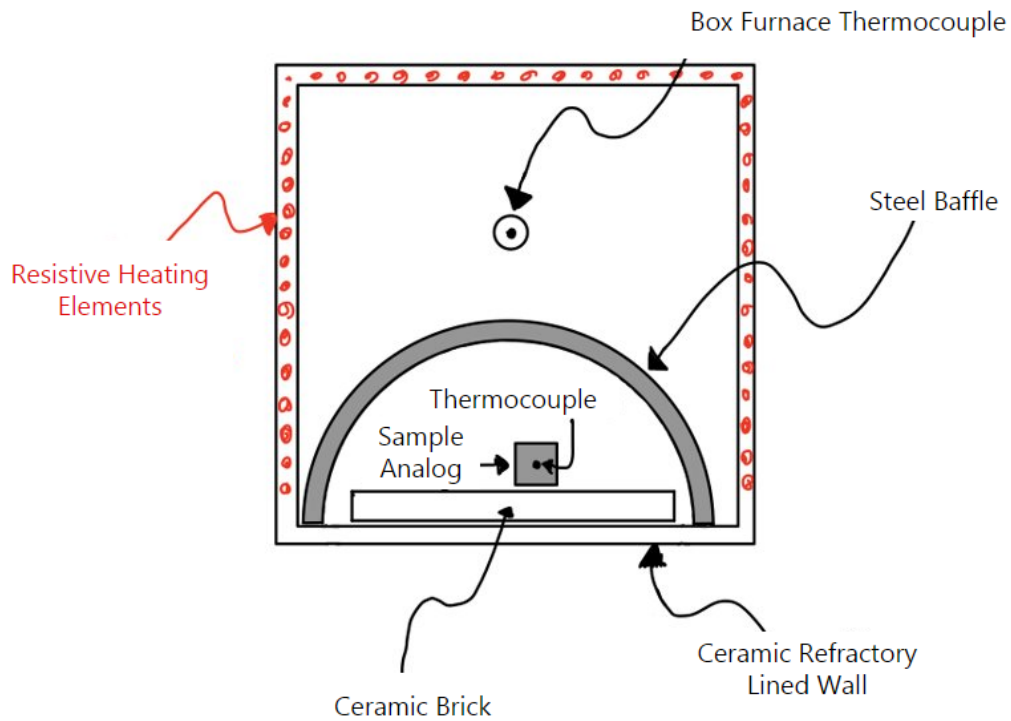
Figure 7. Furnace schematic showing the testing conditions used to find the temperature within a sample analogue at different furnace set temperatures.
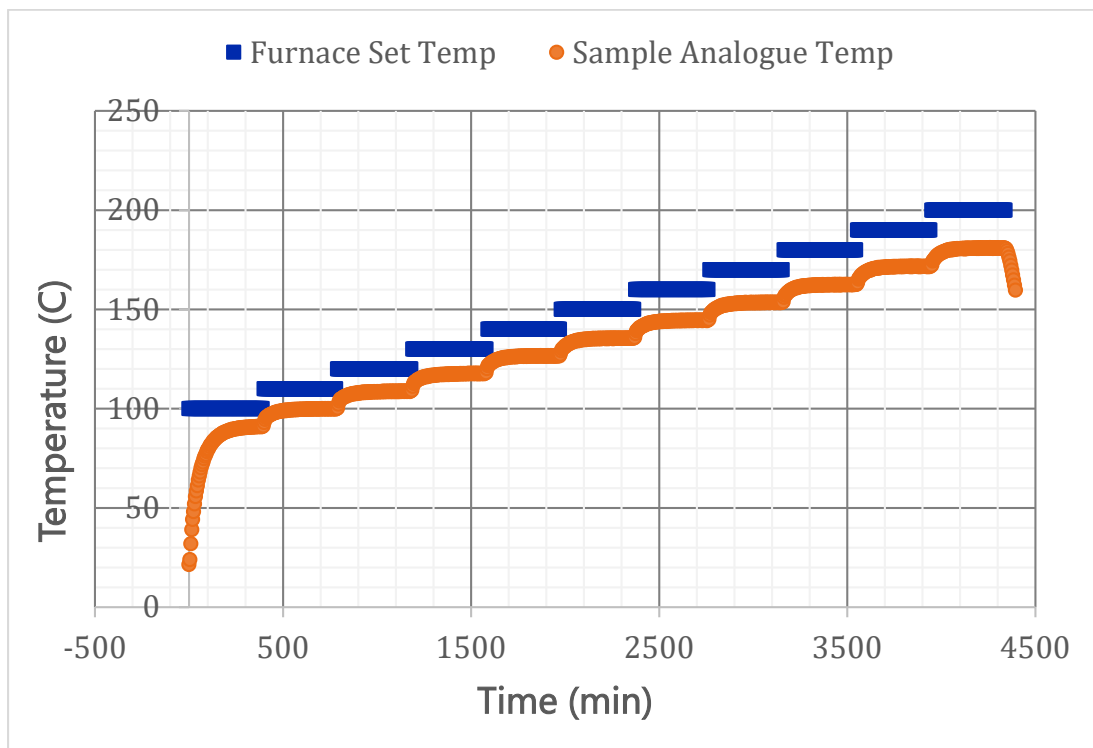
Figure 8. Progression of sample analogue temperature with the furnace set temperature plotted on the same axis. Note how the difference increases with increasing furnace set temperature.

Table I. Results of Test Comparing Furnace Set Temperature and Sample Analogue Internal Temperature

Step Number	Furnace Set Temperature (°C)	Sample Analogue Equilibrium Temp. (°C)	Temperature Difference (°C)
1	100	91	9
2	110	100	10
3	120	109	11
4	130	118	12
5	140	127	13
6	150	135	15
7	160	144	16
8	170	153	17
9	180	162	18
10	190	172	18
11	200	181	19

Tensile Testing

Tensile testing was performed on an Instron 5584 following ASTM E8. Samples were threaded into a flat to round adapter as is specified in ASTM E8. A crosshead displacement rate of 3 mm/min was used for the first 1.5% strain of the sample while an extensometer was used to measure strain, and then at 8 mm/min for the remainder of the test [11]. Tensile testing was successfully performed on all but two of the 48 samples.

Testing Plan

The team received 48 tensile samples of 7175 aluminum from Weber Metals that were machined using CNC to be 3 inches long. The average gauge length was 1.5 inches and the average diameter of that length was 0.25 inches (Figure 9). These tensile samples were sent to the team by Weber Metals already having been solutionized to achieve a supersaturated solid solution ready for aging. Additionally, the team received 12 2 inches by 0.75 inches rectangular blocks of the same material that Weber Metals could use to perform electrical conductivity (EC) tests for each of the treatments. The team sent multiple batches of these EC blocks to Weber Metals during the course of heat treating and testing.
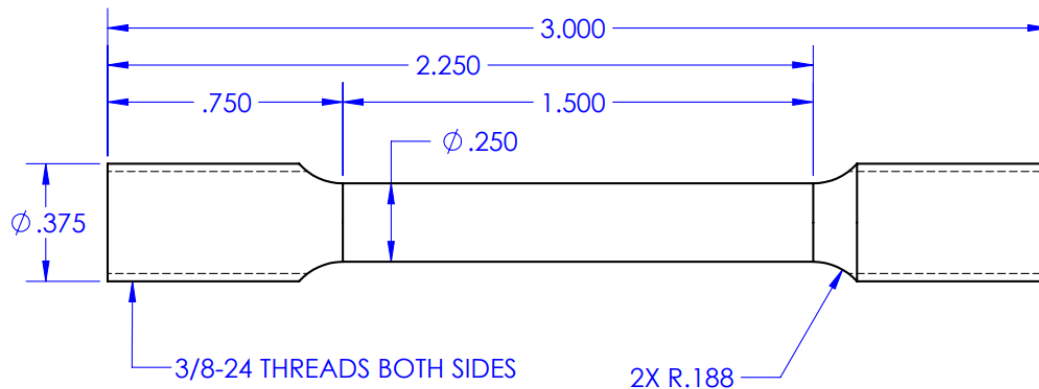
Figure 9. Tensile testing sample schematic. All units reported are in US customary inches.

These samples were separated into twelve groups of four tensile samples that were treated at the same time. Six of these twelve groups were treated using two-step aging treatments, five were treated using retrogression and reaging treatments, and one group was improperly treated due to an error operating the furnace and will not be considered in this report.

Instead of a rigid treatment plan, the team continued to plan and change the experimental heat treatments in response to incoming results. Tensile testing was performed immediately following each treatment while EC blocks were sent to Weber Metals after every two or three group treatments. The goal of this process was to identify a treatment that appeared to meet the project's goal of a 1-2 ksi increase in tensile and yield strengths while maintaining 38% conductivity relative to copper during one of the four sample group tests, so that this treatment could be repeated to increase the statistical significance of this difference and to confirm that the treatment was repeatable. A potential solution was identified in the two-step treatment used in Group 4 which led to this treatment being repeated for Groups 8 and 9. This means that out of the six groups dedicated to two-step aging treatments only four unique treatments were performed, detailed in Table II. No such treatment was identified for retrogression and reaging, and thus all five RRA treatments were unique, detailed in Table III.

Table II. Two-Step Aging Heat Treatments

Group Number	Step 1 Time (min.)	Step 1 Temperature (°C)	Step 2 Time (min.)	Step 2 Temperature (°C)
2	360	107	720	169
3	360	112	720	175
4 (8,9)	360	107	780	169
6	360	107	750	169

Table III. Retrogression and Reaging Heat Treatments

Group Number	Step 1 Time (min.)	Step 1 Temperature (°C)	Step 2 Time (min.)	Step 2 Temperature (°C)	Step 3 Time (min.)	Step 3 Temperature (°C)
5	600	119	120	181	600	119
7	600	119	120	181	600	169
10	600	119	120	264	600	119
11	600	169	120	264	600	119
12	600	169	60	264	600	119

Safety

Proper safety procedures were followed during testing. Long pants and safety glasses were always worn while in the lab. Although the temperatures used in operating the furnace are relatively low, moving samples in and out of the furnace still presents a risk for burns. The team always used a two-person system when operating the furnace where one person controls the door and the other uses tongs with thermal gloves to manipulate samples. Covid safety protocol was also maintained by always wearing face coverings and not operating above the number of people allowed in lab by the university.

Results

Tensile Results

The tensile testing of all the samples were done using the same parameters. Starting with the two-step aged samples (G2,G3, G4, G6, G8, G9), when looking at the yield strength, all samples except the G3 heat treatment are above the dotted red line that is 1 ksi above the control samples (Figure 10). This is a good start for prospective heat treatments.
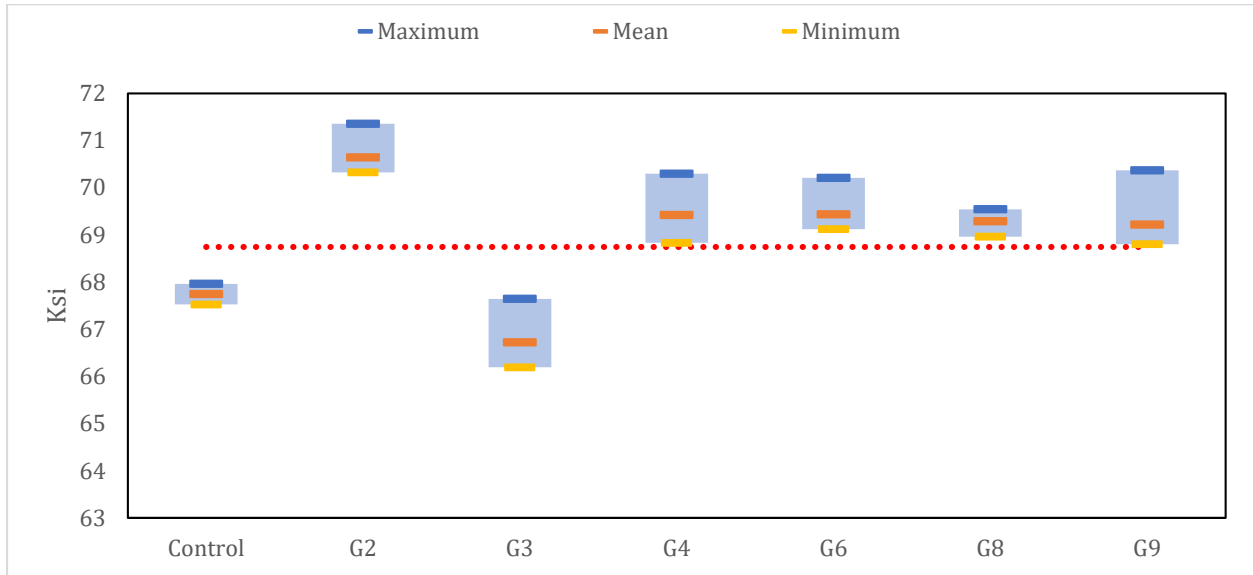
Figure 10. Yield strength range of each group with the mean marked by the orange line in the blue box

Next looking at the tensile strength for these same samples, there are more batches that are centered around that dotted red line that is 1 ksi above the control samples (Figure 11).
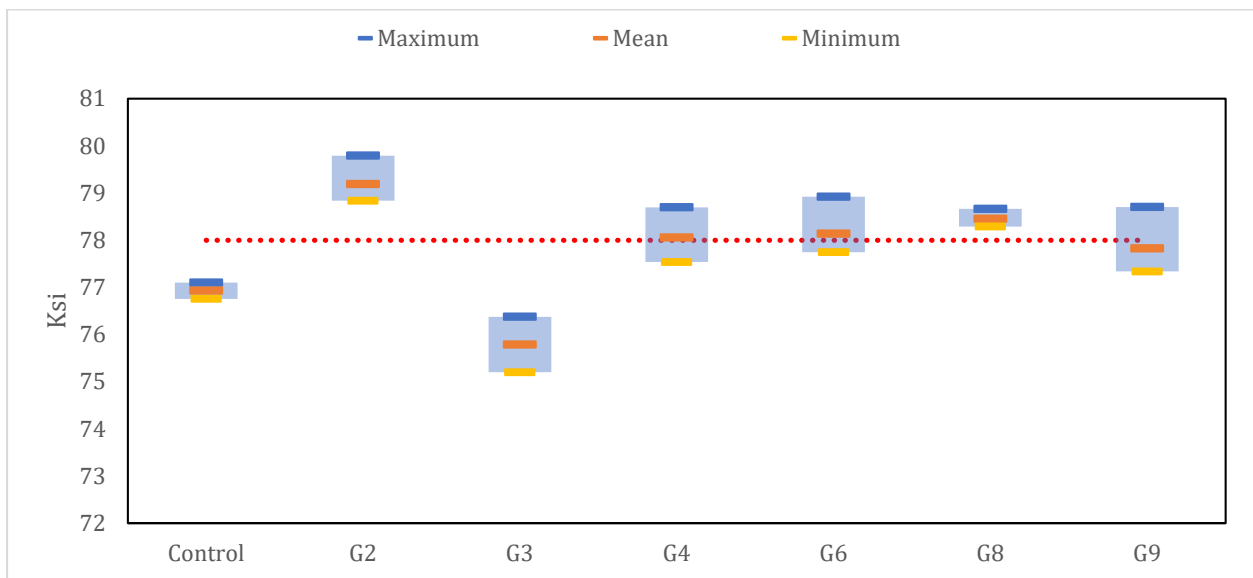
Figure 11. Tensile Strength of two-step aging tensile bars separated by batch.

The G6 heat treatment has a tighter spread of tensile strengths, and all samples were above the 1 ksi line on the graph. Looking at the percent elongation, the two-step aging samples have similar elongation to the control samples and above 9% elongation (Figure 12).
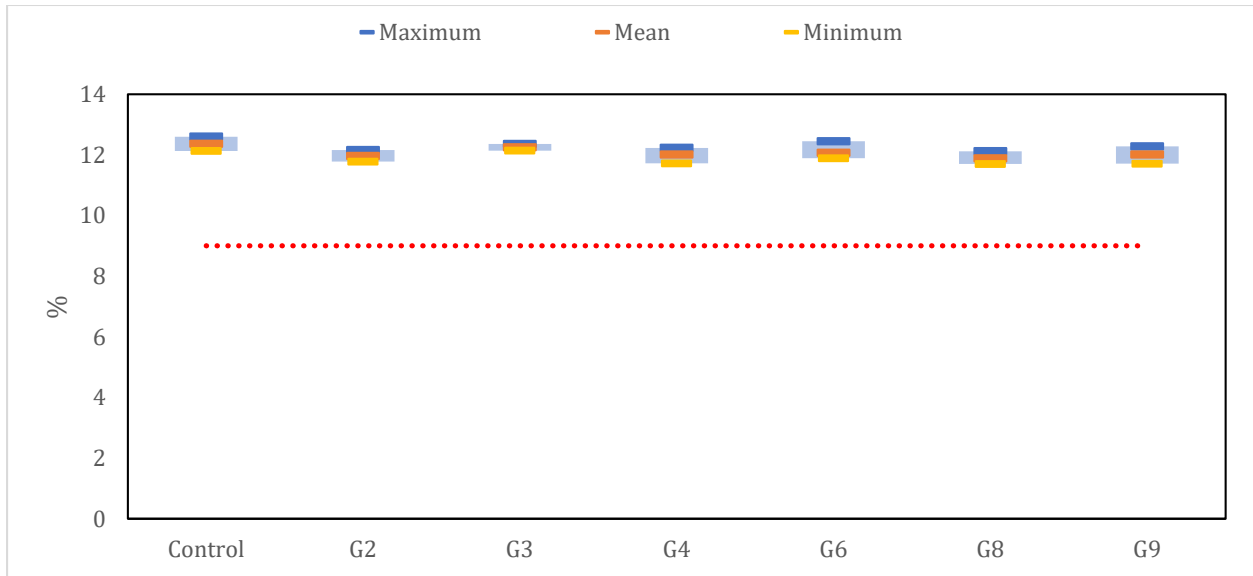
Figure 12. Percent elongation of two-step aging samples separated by group.

Moving on to the Retrogression and Reaging batches (G5, G7, G10, G11, G12) there was a larger spread in the data. The G5 heat treatment had the highest yield strength out of both heat treatment types (Figure 13).
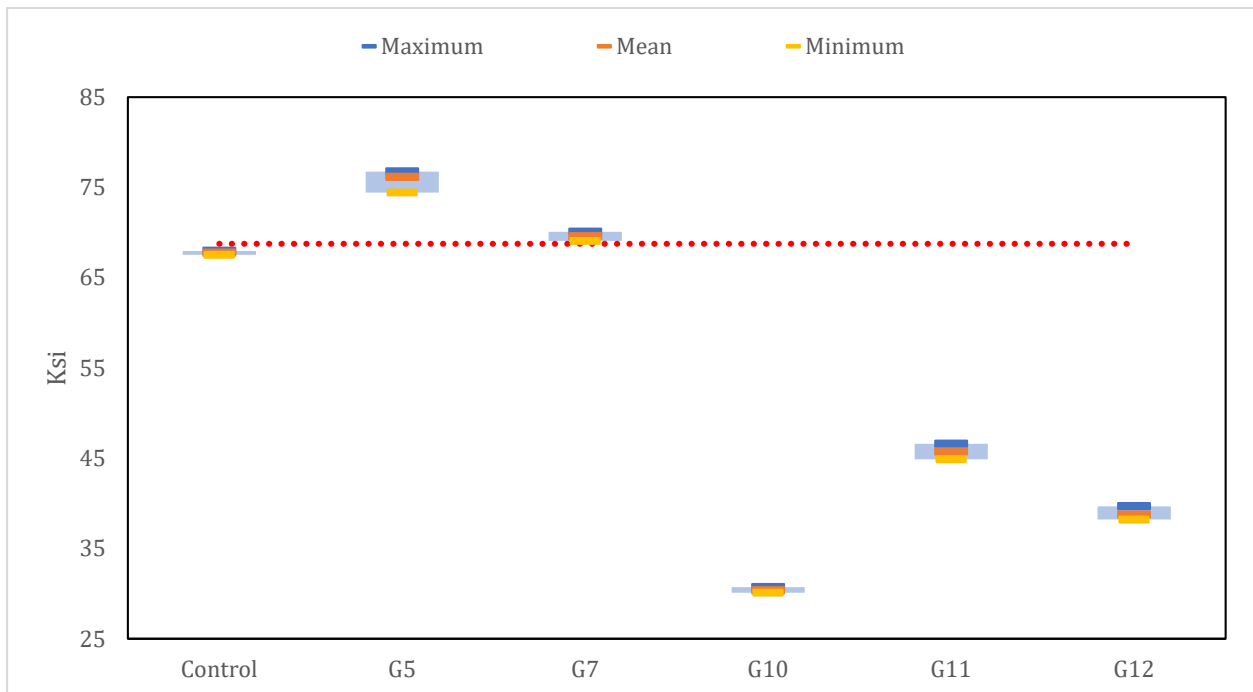
Figure 13. Yield Strength of Retrogression and Reaging samples separated by batches.

Looking at the tensile strength data from the RRA samples, a similar trend of which heat treatments are above and below the 1 ksi line (Figure 14) with all heat treatments shifted approximately 0.5 ksi lower relative to the tensile strength 1 ksi reference line. This pattern is also visible in the two-step aged samples.
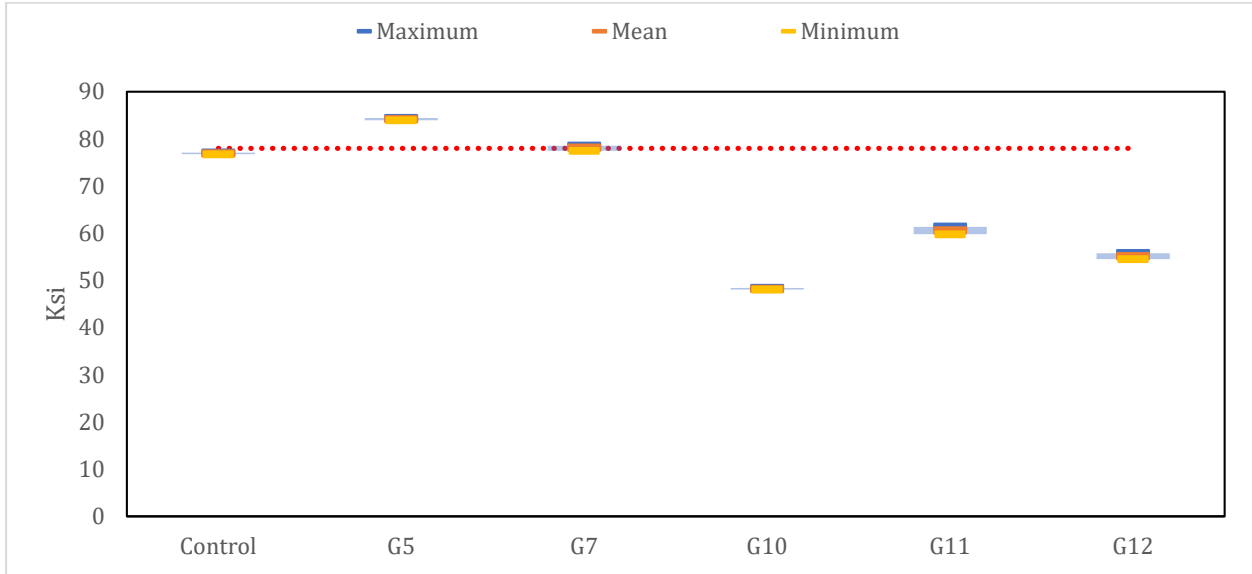
Figure 14. Tensile Strength of Retrogression and Reaging sample, separated by batch

Looking at the elongation of the RRA samples, the low strength samples have the highest elongation of all the heat treatments topping out at 15% with G10 (Figure 15), but all samples have a high elongation similar to the reference samples from Weber Metals.
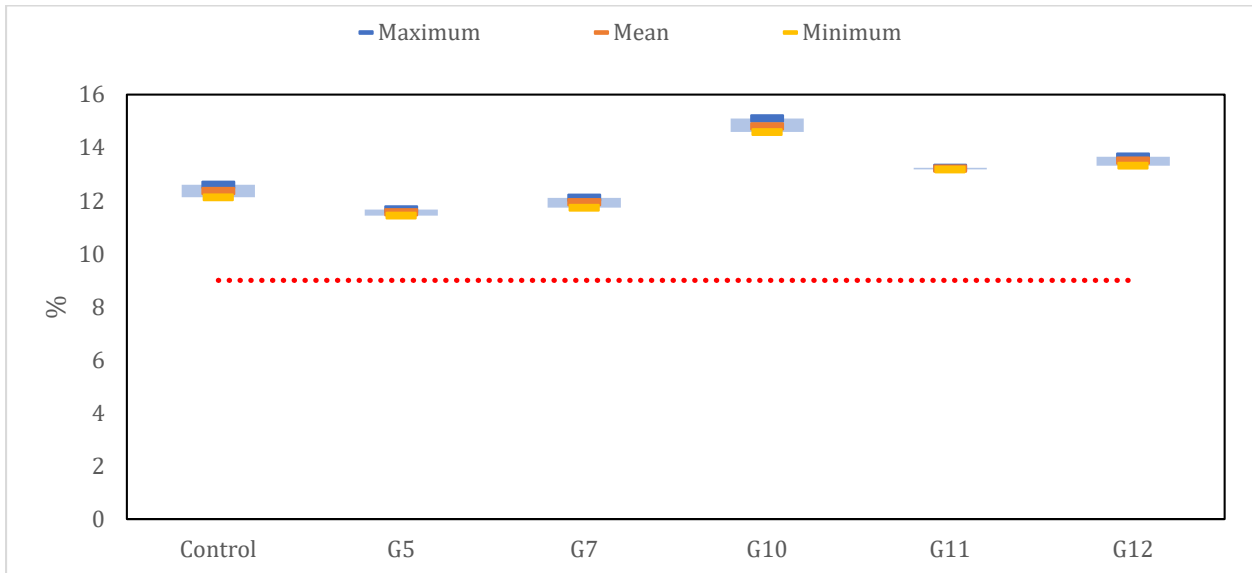
Figure 15. Percent elongation for Retrogression and reaging samples separated by batch.

For comparisons and convenience Table IV is a summarized listing of the mechanical properties for all heat treatments and the controls.

Table IV. Average Values for all Mechanical Properties

		Yield Strength	Tensile Strength	% Elongation
	Control	67.74	76.92	12.36
Two-Step Aging	G2	70.64	79.18	11.96
	G3	66.72	75.78	12.24
	G4	69.42	78.05	12.01
	G6	69.43	78.13	12.06
	G8	69.281	78.45	11.88
	G9	69.21	77.82	12.01
Retrogression and Reaging	G5	76.15	84.17	11.56
	G7	69.56	78.15	11.94
	G10	30.35	48.20	14.79
	G11	45.74	60.58	13.21
	G12	38.741	55.12	13.51

Conductivity Results

The conductivity of each heat treatment was tested using 2-inch by 0.75-inch block that were machined down to produce a flat surface and conductivity is measure across the surface using a special probe that compares it to the conductivity of copper. The two-step aging samples all passed the minimum conductivity apart from the G2 heat treatment (Figure 16). There is a tight spread of 1.9% which is expected since the heat treatments are similar.
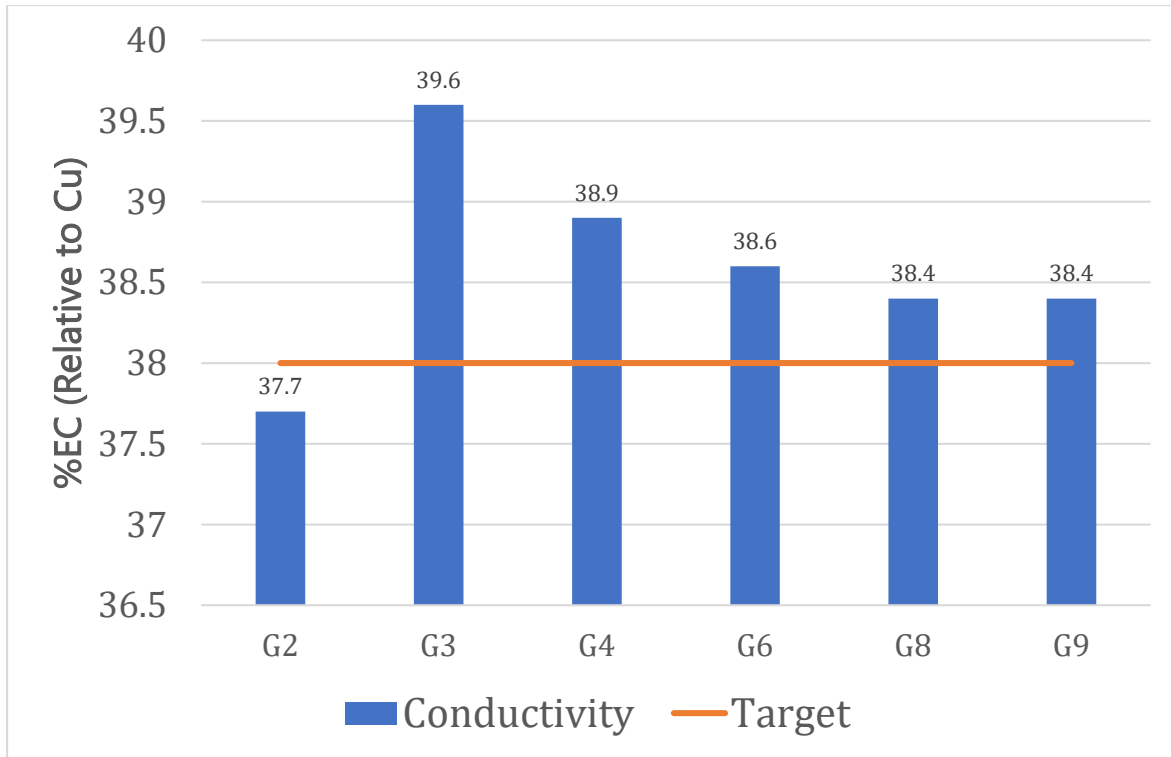
Figure 16. Conductivity results for the EC block tested from each of the six two-step aging treatments. Note that Groups 4, 8, and 9 all have the same treatment.

Next, with the retrogression and reaging EC blocks, the spread of relative conductivity is larger than the two-step aging at 7.6% range (Figure 17). There was one heat treatment (G7) that just met the conductivity minimum and strength minimum but there was no room for error, so it is unlikely to hold up in an industrial process.
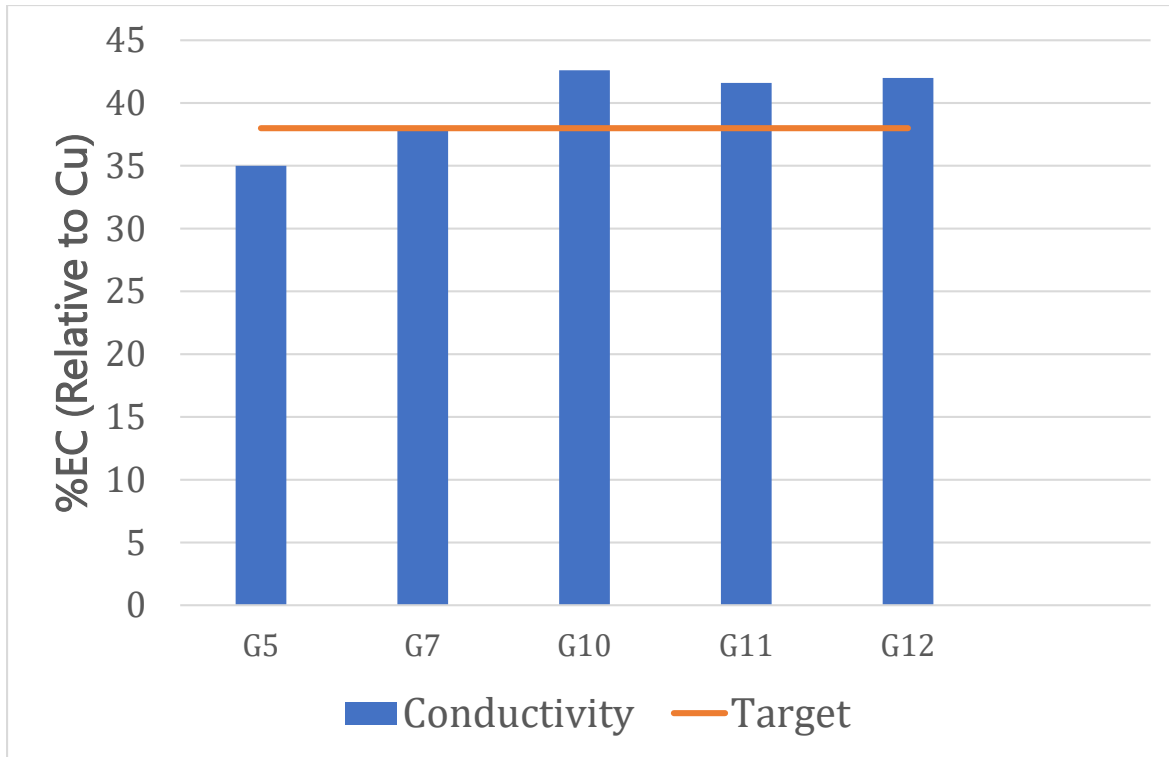
Figure 17. Conductivity block results from each of the five retrogression and reaging treatments.

Statistical Tests

The replicated samples using the G4 heat treatment. The first step for statistical analysis is to determine which tests are most appropriate. When looking at the data set the 12 data points leans towards a t-test, because of the small sample size. From that there are two options: a one-sample t-test, or a two-sample t-test. The one sample t-test might be more appropriate under the assumption that the sample mean produced by the two control samples from Weber Metals is representative of the population mean of parts produced by the manufacturing process and the sample mean is the same as the population mean, so that is used when comparing the G4 heat treatment samples against a population mean. Conversely, the two-sample t-test would be more appropriate under the assumption that the control samples are from a normally distributed population, so the difference between the control sample mean and the G4 heat treatment sample mean can be used when testing for a significant difference. To make less assumptions the two-sample t-test was chosen to test the significance of the heat treatment.

Minitab 19 Software was used for statistical analysis of the 12-sample data pool. When conducting the two-sample t-test there are a few conditions that must be met. One, the sample size must be large enough to be normally distributed; Two, the sample is a random sample from the population. [12]. When checking for normality in a sample, a visual inspection of a box-and-whisker plot (Figure 18) to see if there are any major skews then conducting the Anderson-Darling Test (Figure 19) is most appropriate since it has no assumptions to make or condition to meet. All the experimental samples are tested there is no need for the samples to be random since the entire population is being tested.

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(a)   (b)   (c)

Figure 18. Box plots of the mechanical properties of the G4 heat treatment. a) is the yield strength and looks skewed, b) is the tensile strength and is fairly normally distributed c) is the percent elongation and looks normally distributed

Visual inspection of the box-and-whisker plot concludes that the normality of the yield strength data is in question; the tensile strength data is reasonably symmetric with a slight skew but a test of normality would be beneficial; the percent elongation plot is nearly symmetric but the small sample size warrants a normality test.

(a)   (b)   (c)
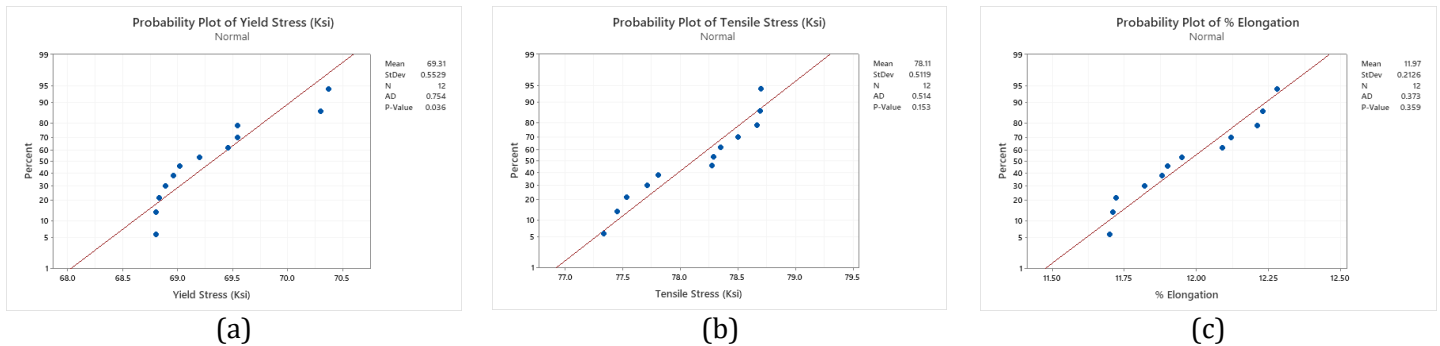
Figure 19. Anderson-Darling normality plots of mechanical data. a) is the yield strength and it failed the normality test, b) is the tensile strength and passed the normality test, c) is the percent elongation and it passed the normality test.

Minitab was used to conduct the Anderson-Darling test and produce the normality plots. The yield strength samples did not pass the test of normality (Table V). The Tensile strength and % elongation failed to reject (FTR) the null hypothesis (H_0) that the sample is from an approximately normally distributed population. Since the yield strength rejected the null hypothesis, it does not meet the first condition of the two-sample t-test so no statistical analysis can be conducted on this set of data.

Table V. Test Statistics of Anderson Darling Tests

Mechanical Property	Test Statistic	P-Value	FTR or Reject H_0
Yield Strength	0.754	0.036	Reject H_0
Tensile Strength	0.514	0.153	FTR H_0
% Elongation	0.373	0.359	FTR H_0

From here, the only data sets that can be analyzed with statistics are the tensile strength and percent elongation data. Starting with the tensile strength, the hypothesis test, given by Equation 1, will be testing if the mean of the G4 heat treatment (G4HT) is the same as the control sample mean. Where μ_{TS} is the sample mean of G4HT and μ_C is the sample mean of the control group for tensile strength. The test will be run with an $\alpha = 0.05$.

$$H_0 = \mu_{TS} - \mu_C = 0 \text{ ksi}$$
$$H_a = \mu_{TS} - \mu_C > 0 \text{ ksi} \tag{1}$$

The T-value of this test is 5.22 and the p-value is 0.017, therefore the null hypothesis is rejected and accept the alternative hypothesis that the G4HT population mean is greater than the control group. Now it is confirmed that the G4HT mean is greater than the control mean with 95% confidence; it is pertinent to check if the difference between the samples is 1 ksi (Equation 2). The test will be run with an $\alpha = 0.05$.

$$H_0 = \mu_{TS} - \mu_C = 1 \text{ ksi}$$
$$H_a = \mu_{TS} - \mu_C \neq 1 \text{ ksi} \tag{2}$$

The T-value from this test is 2.09 and the p-value is 0.171, therefore failing to reject the null hypothesis and leading to the conclusion that there is no reason to suspect the difference between the G4HT mean and the control mean is not 1 ksi. For the percent elongation data sets, a two sample t test with the following hypothesis was test was done (Equation 3), using an $\alpha = 0.05$, and $\mu_{\%E}$ is for G4HT percent elongation mean.

$$H_0 = \mu_{\%E} - \mu_C = 0 \text{ \%}$$
$$H_a = \mu_{\%E} - \mu_C \neq 0 \text{ \%} \tag{3}$$

The T-value is -1.64 and the p-value is 0.349, so there is no reason to suspect that the population means for percent elongation are different between the two samples.

Discussion
Two-Step Treatments Tested
The first two-step treatment the team tested, Group 2, was remarkably close to a mixture of properties that would meet the project goals. The average yield strength of the group was found to be 2.9 ksi above the control group averages, while the average tensile strength was found to be 2.3 ksi above the control group averages. However, the conductivity test fell just 0.3% below the minimum 38% conductivity relative to copper that was necessary to have acceptable stress corrosion cracking resistance properties. Groups 3, 4, and 6 all made alterations to this initial treatment to produce a slightly higher degree of overaging.

Group 3 raised the temperature of both aging steps by 5°C. This change dramatically altered the mechanical properties developed, producing an average yield strength 1.0 ksi below the control group average and an average tensile strength 1.2 ksi below the control group average. This was also associated with a higher conductivity score of 39.6%. This change showed the fine sensitivity of the aluminum samples to changes in temperature. It

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was for this reason that Groups 4 and 6 kept the same temperature steps as the Group 2 treatment and only altered the time allowed for the second step.

Group 4 added an hour to the second 169°C step, while Group 6 added only half of an hour. Both of these treatments successfully increased the degree of overaging so that their conductivities (38.9% and 38.6% for Group 4 and 6 respectively) surpassed the minimum required. Both of their mechanical properties also maintained the project goal of a minimum 1 ksi strength increase with Group 4 achieving a 1.7 ksi increase in average yield strength over the control group, and a 1.1 ksi increase in average tensile strength. Group 6 achieved a slightly higher increase of 1.7 ksi to average yield strength over the control group and a 1.2 ksi increase over average tensile strength when compared to the control group. However, Weber Metals informed the team that the Group 6 EC block fell below requirements on the edges of the block. This meant that this block passed by an extremely narrow margin and the treatment was unlikely to meet stress corrosion cracking resistance requirements. For this reason, the team decided that the Group 4 treatment with a slightly higher degree of overaging was the best candidate for meeting the project goals. This treatment was then replicated in Groups 8 and 9 to build a stronger statistical basis for this observed difference.

Retrogression and Reaging Treatments

The team tried a variety of different retrogression and reaging treatments but did not find one with a good mix of properties that warranted replications. The first treatment the team tried Group 5 with two 119°C low temperatures punctuated by a 181°C retrogression temperature for two hours, had high strengths but fell three points below the conductivity minimum. This meant that the samples needed to be significantly more overaged. The second RRA treatment Group 7 increased the final temperature to 169°C, the same as the two-step aging treatments. This was done so that a comparison could be made to the two-step aging treatment. Group 7 met mechanical properties but was another that technically passed conductivity testing with a 38.1% but failed the test on the edges of the block. Group 7 had an average yield strength increase over the control group of 1.8 ksi and an average tensile strength increase of 1.2 ksi. These properties were remarkably similar to the Group 4 strengths, suggesting that this treatment was operating more as a two-step aging treatment. To try and remedy this the team increased the retrogression temperature to 264°C for Groups 10, 11, and 12.

Groups 10, 11, and 12 all fell tens of ksi below the necessary yield and tensile strengths. In Group 10 the team attempted the same treatment as Group 7 with this increased retrogression temperature. This increased temperature did succeed at increasing the degree of overaging. However, this treatment greatly overshot the mark with a %EC of 42.6%. In Group 11 a higher first step of 169°C was used to increase the degree of overaging before retrogression. This slightly increased the strengths of the samples, but not by a significant amount. Finally, in Group 12 the retrogression time was reduced to one hour with the same 169°C first step. Halving the retrogression time had a surprisingly small impact on the overall properties, resulting in similar strengths to Group 10 and a %EC of 42.0%.

The Strength Conductivity Trade-off

Summing up all the results in one graph, this comparison chart (Figure 20) has the percent conductivity and average tensile strength of each heat treatment plotted against each other. The data points above and to the right of the dotted line meet both minimum criteria for the project. There are two trends, one that related the two-step aging heat treatments and one that follows the RRA heat treatments. The two-step trend based on visual inspection is roughly linear and the RRA heat treatment looks roughly parabolic or a combination of two linear regions based on the retrogression temperature. This is a component that will require further investigation to determine if there is a relationship between the slope of the trade-off curve and the retrogression temperature.
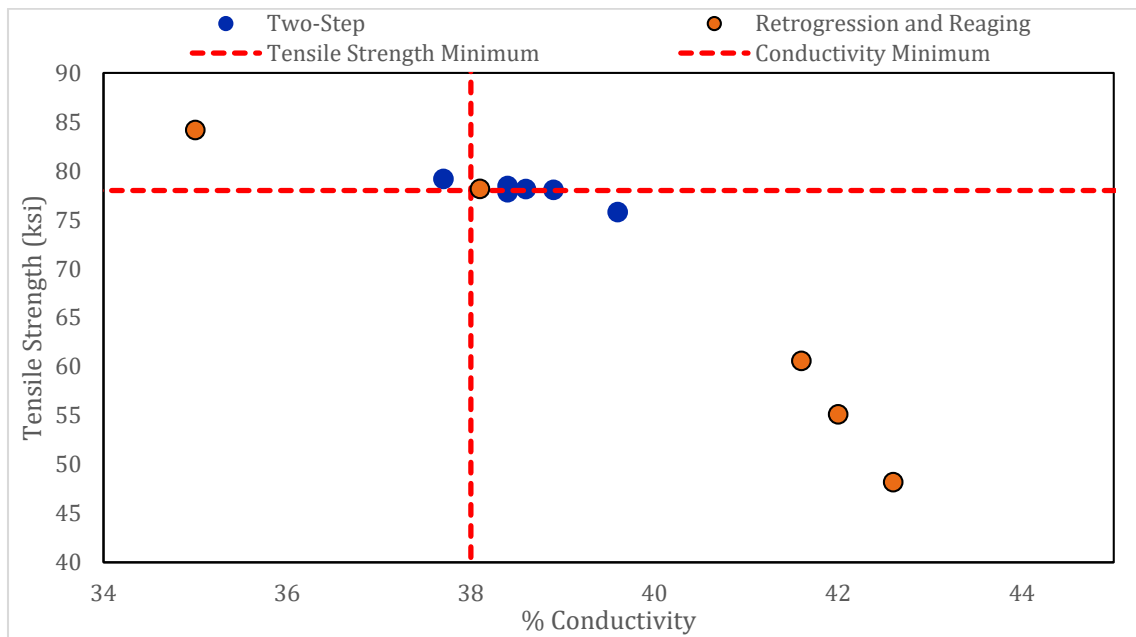

Figure 20. Tensile strength versus percent conductivity showing the average properties of all groups heat treated and tensile tested.

Conclusions

1. A two-step aging treatment that achieves an internal sample temperature of 107°C for 6 hours and 169°C for 13 hours was found to have an average tensile strength of 78.11 ksi, yield strength of 69.31 ksi, elongation of 11.97%, and conductivity of 38.57% relative to copper.

2. No retrogression and reaging treatments met the mix of strength and stress corrosion cracking properties required by the project.

Recommendation

The team recommends that Weber Metals test the validity of the Group 4 treatment for achieving this strength increase using actual industrial conditions.

References

[1]   "HISTORY," *Weber Metals*. 2020, [Online]. Available:
        https://webermetals.com/history/.

[2]   S. L. Semiatin and O. Forging, "Open-Die Forging," vol. 14, pp. 99–110, 2005, doi:
        10.31399/asm.hb.v14a.a0003978.

[3]   C. Forging, "Closed-Die Forging in Hammers and Presses," vol. 14, pp. 111–118, 2005,
        doi: 10.31399/asm.hb.v14a.a0003979.

[4]   J. Banhart, "Age Hardening of Aluminum Alloys," *Heat Treat. Nonferrous Alloy.*, vol.
        4E, pp. 214–239, 2016, doi: 10.31399/asm.hb.v04e.a0006268.

[5]   G. E. Totten, Ed., "Aluminum Alloy Nomenclature and Temper Designations[1]," *Heat
        Treat. Nonferrous Alloy.*, vol. 4E, pp. 114–136, 2018, doi:
        10.31399/asm.hb.v04e.a0006251.

[6]   A. J. Mcalister, "Al (Aluminum) Binary Alloy Phase Diagrams," *Alloy Phase Diagrams*,
        vol. 5, no. 6, pp. 113–139, 2018, doi: 10.31399/asm.hb.v03.a0006144.

[7]   M. J. Starink and X. M. Li, "A model for the electrical conductivity of peak-aged and
        overaged Al-Zn-Mg-Cu alloys," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 34
        A, no. 4, pp. 899–911, 2003, doi: 10.1007/s11661-003-0221-y.

[8]   Y. L. Wang, Y. Y. Song, H. C. Jiang, Z. M. Li, D. Zhang, and L. J. Rong, "Variation of
        nanoparticle fraction and compositions in two-stage double peaks aging
        precipitation of Al–Zn–Mg alloy," *Nanoscale Res. Lett.*, vol. 13, 2018, doi:
        10.1186/s11671-018-2542-1.

[9]   B. Cina, "Reducing the Susceptibility of alloys, Particularly Aluminium alloys, to
        Stress Corrosion Cracking - Google Patents." 1973, [Online]. Available:
        https://patents.google.com/patent/US3856584A/en.

[10]   J. S. Robinson, "Retrogression and Reaging," *Heat Treat. Nonferrous Alloy.*, vol. 4E, pp.
        240–244, 2016, doi: 10.31399/asm.hb.v04e.a0006262.

[11]   ASTM E8, "ASTM E8/E8M-21 Standard Test Methods for Tension Testing of Metallic
        Materials," *Annu. B. ASTM Stand. 4*, no. C, p. 1/27, 2010, [Online]. Available:
        www.astm.org.

[12]   D. M. Levine, P. P. Ramsey, and R. K. Smidt, *Applied Statistics for Engineers and
        Scientists: using Microsoft Excel and MINITAB*. Upper Saddle River: Prentice Hall Inc.,
        2001.