Elevated Temperature Effects on the Mechanical Properties of Age Hardened 6xxx Series Aluminum Alloy Extrusions

A Senior Project Presented to
The Faculty of the Materials Engineering Department
California State University, San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree:
Bachelors of Science in Materials Engineering

by
Rachael Donovan
Rose Fortune
Robert Trout

June 2015

Abstract

The purpose of this project is to determine if over-aging of aluminum causes the yield or tensile strength to fall below the minimum strength values set by the aluminum industry. Extruded aluminum alloys, 6061-T6, 6063-T6, and two proprietary alloys, HS6X-T6 and RX82-T6, were exposed to reheating treatments at extended times and temperatures. The three temperatures were 350°F, 390°F, and 425°F. The times of reheat increased logarithmically from 30 minutes to 64 hours. The samples were tensile tested to determine the tensile strength and yield strength. Statistical methods helped model the behavior of yield and tensile strength as a function of alloy, time, and interaction of alloy and time for each temperature. This showed which alloy experienced a change in strength and at what time and temperature the strength fell below minimum acceptable values. The strongest to weakest untreated alloys respectively were HS6X, RX82, 6061, and 6063. As time progressed at each temperature, the strongest to weakest alloys changed to HS6X, 6061, RX82, and 6063 respectively. For the 6061 and 6063 alloys, the yield strength did not go below the lower bound value at 350°F, at 390°F it took 16 hours, and for 425°F it took 4 hours. For the HS6X alloy, the yield strength fell below the lower bound after 8 hours at 350°F, at 390°F it took 2 hours, and at 425°F it took 30 minutes. For the RX82 alloy, at 350°F, it took 32 hours for the yield strength to fall below the lower bound, at 390°F it took 8 hours, and at 425°F it took 30 minutes.

Keywords: Aluminum, Aluminum Alloys, 6xxx Series, Precipitation Hardening, Extrusions, Yield Strength, Tensile Strength, Tensile Test, Automotive Industry, Materials Engineering

Acknowledgements

We would like to thank Sapa Extrusions for sponsoring this project. Our contacts from Sapa Extrusions were Ken Fischer, Dave Lukasak, and Matthias Kapp. We would like to thank them for their help throughout our project. We would also like to thank Professor Steven Rein from the statistics department at Cal Poly for assisting us in completing our statistical analysis. Finally, we would like to thank Professor Blair London, our senior project advisor, for his advice and support in completing our project.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Problem Statement and Project Goals

Sapa Extrusions supplies aluminum-extruded pieces for use in vehicle frames, such as the Ford F150 and the Jaguar XJ. The extruded parts are typically 6xxx series aluminum and will undergo a paint heat treatment by automotive companies before being installed. During manufacturing of the vehicles, there is a possibility for line stoppages in the paint oven cycle, which increases the likelihood of over-aging the aluminum.

The purpose of this project is to determine if over-aging aluminum causes the yield or tensile strength to fall below the minimum strength values set by the aluminum industry. The results of this experiment show that a relationship exists between over-aging of 6xxx series aluminum alloys and a loss in tensile and yield strength.

It is predicted that in the next 10 years the amount of aluminum currently in circulation will no longer be enough to meet the demands of the automotive industry. The transition from steel to aluminum can be attributed to a few factors including better strength-to-weight ratio, more recyclability, lower carbon emissions, and corrosion resistance. There are, however, challenges that must be faced when making a new material selection. Auto bodies go through a paint cure cycle during the manufacturing process which exposes them to elevated temperatures for a short period of time. This is not an issue with steel, but for 6xxx series aluminum, which gets its strength through relatively low temperature heat treatments, there may be a loss in material properties. In this project, four 6xxx series age hardened extruded aluminum alloys were exposed to reheating treatments at extended times and temperatures in order to replicate these paint oven cycles. The chosen temperatures were 350°F, 390°F, and 425°F. The times of reheat increased logarithmically from 30 minutes to 64 hours. The samples were tensile tested to determine the tensile strength and yield strength.

1.2 Background

1.2.1 Company Background

Sapa Extrusions is a recent merger of two aluminum companies, Orkla ASA and Hydro ASA. Sapa's company goal is to shape a sustainable future through innovative aluminum solutions.[1] If there exists a heavy steel part, it is likely that Sapa can replace that part with an aluminum extrusion, resulting in weight savings while maintaining strength and quality. As the automotive industry looks for ways to reduce their overall greenhouse gas footprint, Sapa offers a solution to building light-weight vehicle frames. The demand for all aluminum car frames is so high that Sapa has dedicated one of their extrusion plants solely to the automotive industry.[1]

1.2.2 6xxx Series Aluminum Alloys in the Automotive Industry

Aluminum is the most abundant metallic element in the earth's crust, of which it forms nearly 8%. It always occurs as a compound, such as bauxite, which is the basic raw material from which the metal aluminum is produced. Impurities are removed from the bauxite by chemical processing to make alumina (aluminum oxide). Four pounds of bauxite produces approximately two pounds of alumina. The alumina is smelted by electrolyzing a solution of alumina in molten fluorides to make aluminum. The reduction process removes the oxygen from alumina, which consists of almost equal parts oxygen and aluminum, and leaves pure aluminum. Two pounds of alumina produces approximately one pound of aluminum.[1]

Aluminum alloys are desirable materials to use in structural applications because of their high strength-to-weight ratio. They are also easily machined and extruded, have good corrosion resistance, good thermal and electrical conductivity, and are heavily recycled. It is estimated that 78% of the aluminum that has ever been extracted is still in use today. It only takes 5% of the original amount of energy it took for extraction to recycle and reclaim the aluminum.[1] These desirable properties are the reason aluminum's use has recently increased in the automotive industry. The newest models of the Tesla, the Ford F150, and the 2010 model of the Jaguar XJ all have a large percent of their body and frame made of extruded aluminum. In the Jaguar XJ, the cantrail is made from a combination of hydroformed and extruded parts that are assembled together. The change from steel to aluminum parts saves 7.4 lbs of weight from the cantrail. Jaguar reports in their life cycle analysis of the cantrails a CO_2 reduction of 3,452 tons over the car's lifetime.[1] The 2015 Ford F150's aluminum body reduces the total vehicle weight by up to 700 lbs (**Figure 1**).

Figure 1 - The new 2015 Ford F-150 body is made entirely of extruded aluminum. The benefits in transitioning from steel include better corrosion resistance, a better strength-to-weight ratio, and a 700 pound reduction in vehicle weight.[1]

The two most commonly used aluminum alloys are 6061 and 6063, which are alloyed with magnesium and silicon. They are hardenable alloys, meaning they can undergo further heat treatments once extruded to produce a stronger material by precipitation hardening. 6061 is used as a benchmark for structural alloys due to its high strength and toughness, as well as its ease of anodization and machining. 6063 is not as tough or strong as 6061, but it has a better surface appearance and good formability.[2] 7xxx series is another option for a structural aluminum alloys, however it is not easily extruded, making the cost too high for most applications.[1]

1.2.3 Aluminum Extrusion

The first step in aluminum extrusion is the preparation of the aluminum alloy. The aluminum begins as cast logs or billets. The aluminum is melted in a furnace then transferred to a gravity fed casting system. As the liquid aluminum cools, crystals begin to nucleate via heterogeneous nucleation. As the temperature is lowered, the crystals begin to grow and impinge on each other to form grains. The alloying elements are forced along the grain boundaries. From there, the aluminum gets solution heat treated to homogenize the billet (**Figure 2**). This is done to diffuse the alloying elements out of the grain boundaries, which improves extrudability, and gives a better surface finish and mechanical properties.[2,3]

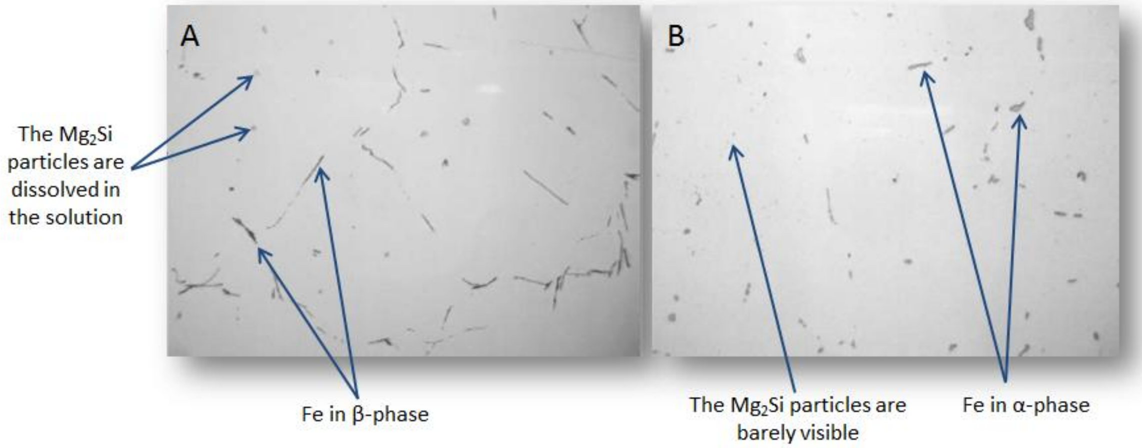


Figure 2 - **(A)** shows an aluminum microstructure (500x magnification) of a 6063 aluminum alloy before homogenization. The Mg_2Si precipitates are dissolved in the solution and the Fe precipitates surround the grain boundaries. **(B)** shows the alloy after homogenization (at 500x magnification), where the Fe precipitates have broken up and become more rounded and the Mg_2Si precipitates are barely visible.[2]

The billets may not be extruded right away. Natural age hardening can occur in the interim between casting and extruding. Because of this, the billets need to be homogenized by heating them up to just below the solvus line (about 932°F). When the aluminum gets pushed through the extrusion die, the friction causes a slight increase in temperature to just above the solvus line. At this point, the Mg_2Si particles dissolve and the iron particles change from the β-phase to the α-phase, becoming more rounded and thus more ductile. After extrusion, the aluminum is quenched to keep the material in a supersaturated solid solution state. If there are large Mg_2Si particles present in the billet before extrusion, it is possible that they will not fully solutionize during extrusion. These non-homogenized particles will leave streaks in the extruded aluminum.[3] The size of the precipitates in the aluminum billet prior to extrusion also plays a role in the surface finish of the extruded pieces and the speed at which extrusion can occur. When Mg_2Si particles are large in 6xxx series aluminum, tearing of the surface can occur during extrusion. The tearing is caused by incipient melting, a variation in local chemistry leading to an area of lowered T_m caused by the heat of the die and the friction from extrusion.[3]

There are two types of extrusion, direct and indirect. In direct extrusion, the most common type of extrusion, the die remains stationary and the aluminum billet is pushed through the container with a ram (**Figure 3**). There is a build-up of compressive stress as the aluminum is pushed through the smaller cross section of the die. These high compressive stresses help reduce cracking of the billet. Indirect extrusion occurs when there is no displacement of the billet and the container, while the die is attached to a hollow stem, which moves relative to the container (**Figure 3**). Because this causes a decline in the total load pressure, the container does not have the same compressive forces as compared to direct extrusion.[4]

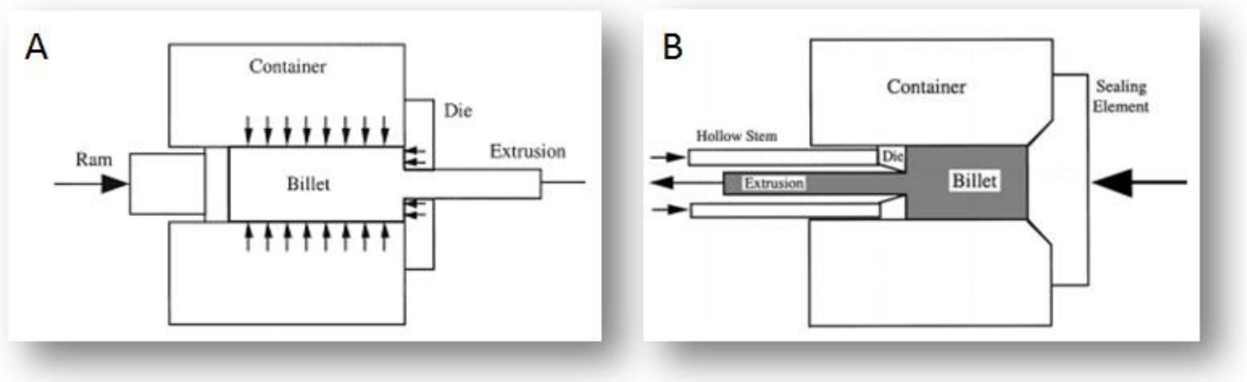


Figure 3 – Schematic showing **(A)** direct extrusion and **(B)** indirect extrusion. The compressive forces on the billet are shown in the direct extrusion schematic. The stem being pushed into the container as the extrusion gets pushed out the opposite side is shown on the indirect extrusion schematic.[4]

Sapa quenches the extruded material as it comes out of the die, retaining the supersaturated solid solution state. Water or air quenches can be performed with the assistance of water jets or fans. Typically, 6061 aluminum is treated with a water quench, and 6063 aluminum is air quenched. As the aluminum profiles (**Figure 4)** are quenched, they are pulled by an extrusion puller. This improves the straightness and twist in the aluminum and helps to maintain the tension on the profile. The extruded aluminum profiles are cut to length and moved to a secondary stretching process. The stretching relieves stresses in the material and gives the profiles their desired straightness.[5]

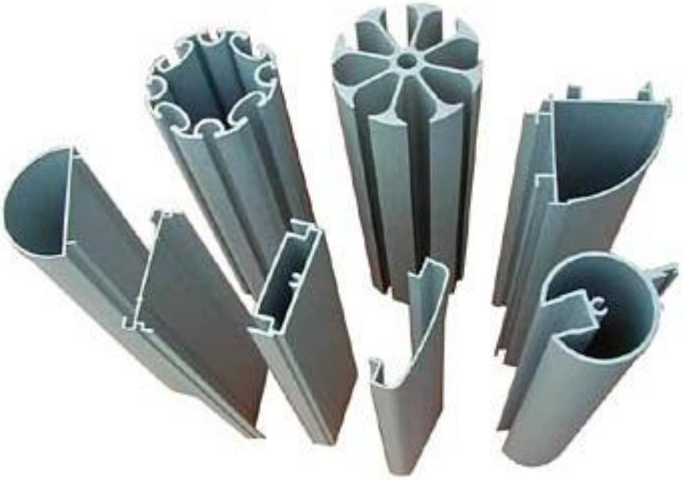


Figure 4 - An aluminum profile is the specific shape of the extruded metal after it is pushed through the die. Companies such as Sapa have thousands of different dies for profiles that may be used in many applications. Most dies are custom made for a specific profile and a specific application.[1]

1.2.4 Precipitation Hardening (Age Hardening)

The final strength of the aluminum alloy is controlled by the aging process.[1] Precipitation hardening is when precipitates in the alloy impede the movement of dislocations within the crystal lattice. Precipitates grow in size resulting in a stronger material. This growth can occur at room temperature, but may require long periods of time to achieve the desired precipitation size. Artificial aging is a process where an extruded profile is placed in an oven around 350°F, expediting the growth of precipitates and producing a measurable increase in strength.[5] The phase diagram shown in **Figure 5** outlines the effect of the weight percent of Mg_2Si as well as the phase transition temperatures. The aluminum association designates each type of aging with a certain nomenclature (**Appendix A**).[6] 6xxx series alloys are solution heat treated and artificially age hardened, giving them a temper designation of T6. For 6061 alloys, the alloy is peak aged, which is the maximum possible strength achieved by aging.

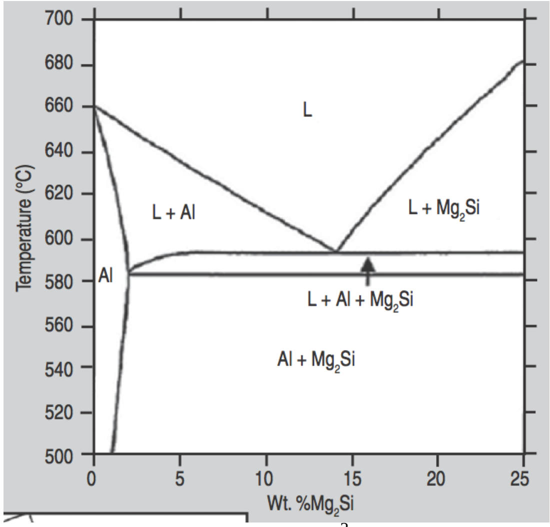


Figure 5 - Phase diagram of wt%Mg_2Si and aluminum.[3] The amount of Mg_2Si changes the T_m that an alloy will experience. 6xxx series alloys can have varying amounts of alloying elements present. For example, 6061 typically has higher amounts of alloying elements with 0.40 – 0.8 wt%Si and 0.80 – 1.2 wt%Mg. 6063 has 0.20 – 0.60 wt%Si and 0.45 – 0.90 wt%Mg.[2]

The formation of precipitates as the material is cooled from a supersaturated solid and then aged is reported as:

- Clusters of Si atoms and clusters of Mg atoms
- Guinier-Preston (GP) zones
- Intermediate precipitate ß″
- Intermediate precipitate ß′
- Equilibrium phase ß-Mg_2Si

The ß″ precipitates are coherent with the aluminum matrix, the ß′ precipitates are semi-coherent, and the ß-Mg_2Si are incoherent. The strengthening mechanism is based on how easily a dislocation can move through the material. Any precipitate that impedes a dislocation from moving through the aluminum matrix will add strength to the alloy. When the precipitates are small and coherent with the aluminum matrix, dislocations shear through the precipitate. Although this adds a measure of strength, the greatest amount of strength can be achieved by continued aging. As the incoherency of the precipitates increases due to elevated temperature and time, the dislocations have to bow around the precipitate. The top of the peak shown in **Figure 6** is referred to as the peak age condition, and is where the maximum strength of the material is found. Past this point where the equilibrium phase is reached is known as over-aging. Before the peak where the ß″ phase is present is known as under-aging. Over-aging results in a loss of strength because as the precipitates grow larger, the overall amount of precipitates in the system lowers. The particles are too large to be sheared, so they are bypassed by dislocations moving through the material.[3]

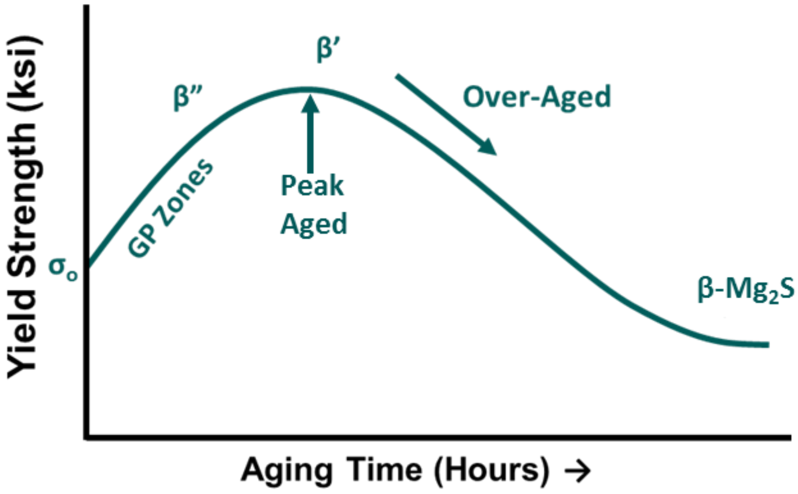


Figure 6 - A diagram of the precipitate phases that form during precipitation hardening. The top of the curve represents the peak age, where the alloy is the strongest. After added time and temperature, the alloy then begins to over-age.

1.2.5 Aluminum Surface Treatments

There are many different surface treatments used on aluminum to improve properties such as wear resistance, corrosion resistance, hardness, and electrical insulation. Surface treatments are also used to improve aesthetics by changing the color, reflectivity, and overall finish. These treatments can be divided into a few groups, such as electrochemical treatments, chemical treatments, mechanical treatments, and coatings.[8]

Coatings usually involve chemical treatments and a pre-cleaning as well as a post coating oven cycle. The two main types of aluminum coatings are powder and wet. These finishing methods differ in several ways, most notably in the application and cure of their films. Powder coatings are said to be one of the lowest cost finishing methods used today. While the material and equipment costs are similar to those used in liquid, the savings in energy, labor, and waste disposal, make powder coating a much more attractive method.[9]

Powder coatings are applied electrostatically, usually from an air fluidized hopper. Primary powder ingredients consist of a binder, prime color pigments, and additives. The binder consists of a resin, polymer, and cross-linker and provides the coating with its fundamental film properties. The pigments can be either organic or inorganic and provide the paint with its color. The additives serve numerous functions but usually affect fluidity and application properties. After the proper amount of powder is applied the part is then baked, allowing the particles to melt and fuse together into a homogeneous film. The film has final physical properties that meet many stringent performance criteria while also meeting environmental regulations limiting the use of volatile organic compounds (VOCs) inherent in many solvent-based liquid coatings.

Liquid coatings are composed of a binder, pigments, solvents, and additives. The binder, pigments, and additives are similar to those used with powder coatings in composition and functionality. The solvent acts to control application characteristics and usually consist of VOCs. After the part is cleaned the liquid paint is applied and then the part is cured in an oven. During the curing cycle the VOCs evaporate leaving behind the solid portion of the coating.

When General Motors (GM) paints their car frames, the entire auto body is sent through a paint oven cycle. During the cycle the frames experience a temperature profile, which includes slow heating, a short isothermal hold, and an air cool. When the manufacturing line is running at full efficiency, each car body will spend between 15 to 45 minutes in the oven. The disparity in times comes from differences in ovens. If the oven is set at a higher temperature, then the car body will spend less time in the oven.

1.3 Previous Work on Similar Projects

1.3.1 Determining the Effect of Precipitation on Mechanical Properties of 6063 Aluminum Alloy at Under-, Over-, and Peak-Aged Temperatures

A study testing the mechanical properties at different aging temperatures and various times of 6063 aluminum alloys shows how time and temperature cause the strength of the alloy to change. This study was done by heating the aluminum samples to 967°F and quenching with cold air to form a supersaturated solid solution. In this experiment, the solution heat treated samples were age hardened at various temperatures between 212°F and 437°F, for times ranging from 2 to 14 hours and tested for the tensile strength, hardness, and ductility.

The tensile and yield stresses, hardness and fatigue initially increase as the temperature increases because of the presence of GP zones, which cause irregularities in the crystal lattice, obstructing the movement of dislocations. As the temperature increases, the size of the precipitates increases, decreasing the number of total precipitates. This causes fewer obstructions and decreases the mechanical properties of the aluminum. It was experimentally determined that heat treatments between 8 and 10 hours at 347°F resulted in peak age strength.[10]

Figure 7 shows the tensile and yield strengths in relation to the aging temperatures and the length of time the alloy had been held at each temperature during this study. Typical aging curves are only two-dimensions and do not show how the time of heating can affect the strength of the material. Both time and temperature influence the growth of precipitates. An increase in temperature can have a more drastic effect on the strength. As the temperature increases from 380K to 480K, the strength increases and then decreases rapidly (**Figure 7**). The z-axis of the graph, where time is displayed, shows that past two hours the strength increases, but eventually levels out at excess of 10 hours.[10]

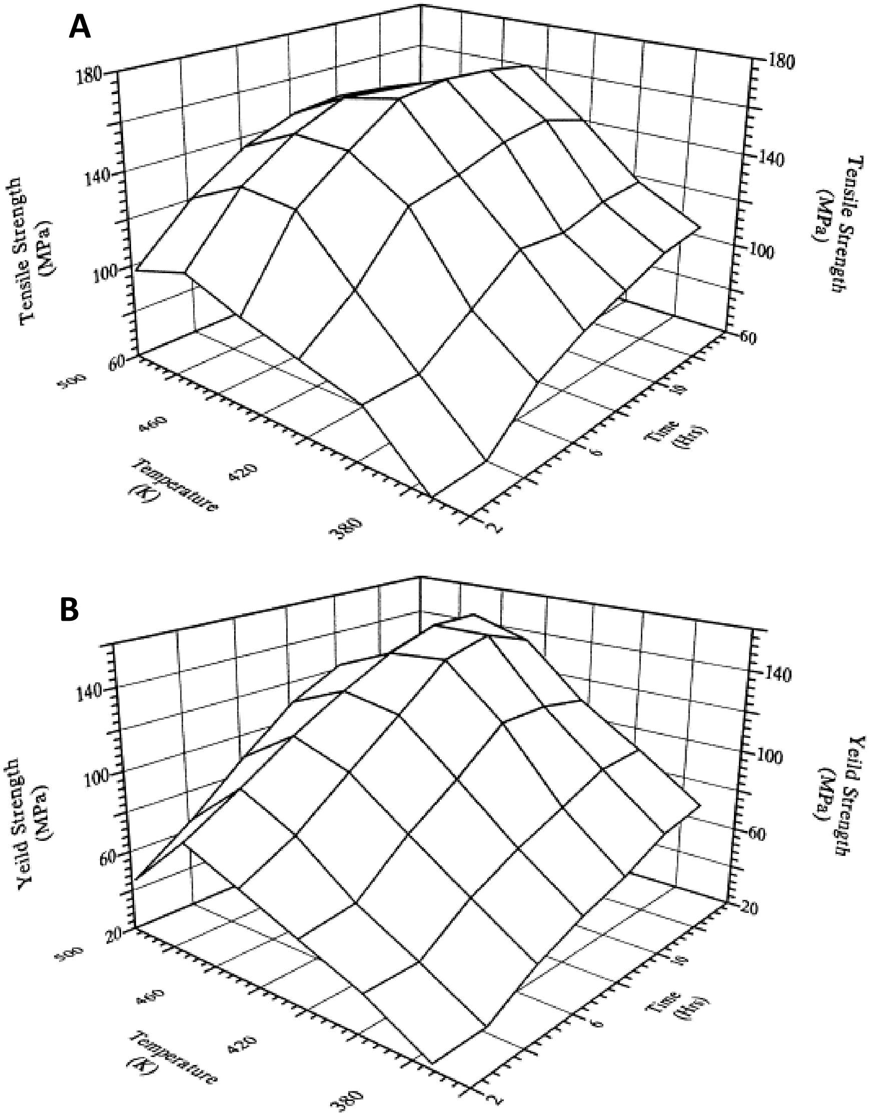


Figure 7 – The effect of both time and temperature on the **(A)** tensile strength and the **(B)** yield strength of the 6063 alloy. These figures show temperature on the x-axis, strength on the y-axis, and time on the z-axis. The typical aging curve only shows strength and temperature, but because time and temperature both affect the strength of the material, these figures are a unique way to visualize the response.

2. Experimental Procedure

2.1 Safety

Safety precautions were taken during the entirety of this project. During the heat treatments, gloves, a face shield, long pants, closed toed shoes, and safety glasses were worn when working with the oven. During tensile testing, long pants, closed toed shoes, and safety glasses were worn. When removing a broken aluminum sample from the tensile tester, caution was taken to avoid any scratches or cuts.

2.2 Heat Treatments

Sapa Extrusions provided 400 tensile samples of 6xxx series alloys, 100 of each alloy. The alloys were 6061, 6063, RX82, and HS6X, the last two of which are proprietary alloys produced by Sapa. Three temperatures were chosen that would simulate the reheating that an aluminum car frame could experience during a paint cure cycle. **Table I** includes data provided by General Motors for three of their paint cure cycles. The minimum, average, and maximum temperatures and times were calculated. The temperature is recorded by thermocouples attached to the car frame. The temperature in the oven is set higher than what the frame actually experiences because the cars go through a conveyer system, and only spend a short amount of time in the oven. For this reason, 350°F and 390°F were chosen to simulate the temperatures that the car frames experience on a normal run. If there is any stoppage in the paint cycle the temperature that the aluminum frame experiences can rise. For this reason a higher temperature of 425°F was chosen to replicate the environment that a car frame could experience while stopped in a paint oven. Each sample was air cooled after removal from the oven. **Table II** shows the final times and temperatures chosen for this project.

Table I – Maximum, Minimum, and Average Heat Treatment Values of the Three GM Paint Ovens

	Temp (°F)	Time
Maximum	380	45 min
Average	291	30 min
Minimum	268	15 min

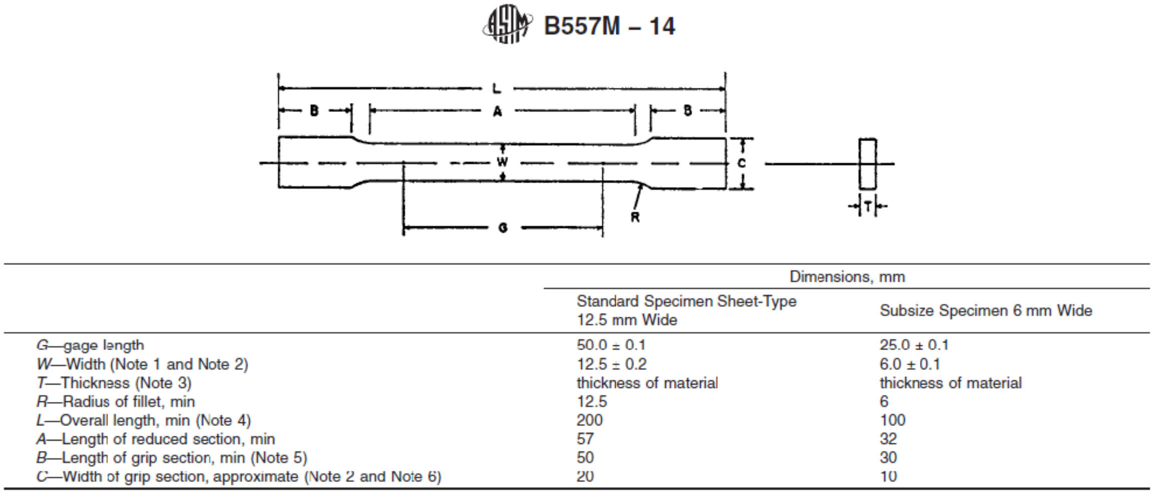
Table II – The Times and Temperatures Used for all Reheating Treatments

Temperature	Time						
350°F	2 hr	4 hr	8 hr	16 hr	32 hr	64 hr	
390°F	2 hr	4 hr	8 hr	16 hr	32 hr	64 hr	
425°F	0.5 hr	1 hr	2 hr	4 hr	8 hr	16 hr	32 hr

Five samples of each alloy were used in each of the heat treatments in order to gather enough data for statistical analysis. An additional five samples of each alloy were tensile tested in the untreated state to act as the control. In total, 400 samples were tensile tested.

2.3 Tensile Testing

Testing was done on an Instron Tensile Tester with a 150 kN load cell. ASTM B 557 *Standard Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products* was used as the testing method to tensile test the aluminum alloys.[11] The standard dimensions for the tensile specimen are shown in **Figure 8.** An Epsilon extensometer was used to measure the strain to get an accurate reading of the elastic modulus. The cross head speed was set to 0.10 in/min. Once the samples reached a 1.5% strain, the cross head speed increased to 0.25 in/min and the extensometer was removed. From the tensile tests, the 0.2% offset yield strength, tensile strength, and percent elongation were determined. For the purposes of this project, yield strength is the most important material property. In any material, yielding is the point where elastic deformation changes to plastic deformation. With the application of an aluminum car frame, any plastic or permanent deformation would cause the car frame to be unusable. **Figures 9** and **10** show the equipment used in the experiment.



	Dimensions, mm	
	Standard Specimen Sheet-Type 12.5 mm Wide	Subsize Specimen 6 mm Wide
G—gage length	50.0 ± 0.1	25.0 ± 0.1
W—Width (Note 1 and Note 2)	12.5 ± 0.2	6.0 ± 0.1
T—Thickness (Note 3)	thickness of material	thickness of material
R—Radius of fillet, min	12.5	6
L—Overall length, min (Note 4)	200	100
A—Length of reduced section, min	57	32
B—Length of grip section, min (Note 5)	50	30
C—Width of grip section, approximate (Note 2 and Note 6)	20	10

Figure 8 - ASTM standard dimensions for wrought aluminum tensile specimens.[11] The dimensions of the samples used in this experiments had a 2.5 inch gauge length, a 0.50 inch width, and a 0.10 inch thickness.

Figure 9 – The low temperature oven's internal thermometer varies by a considerable amount. A more accurate thermocouple is used to measure temperature during heat treatments.

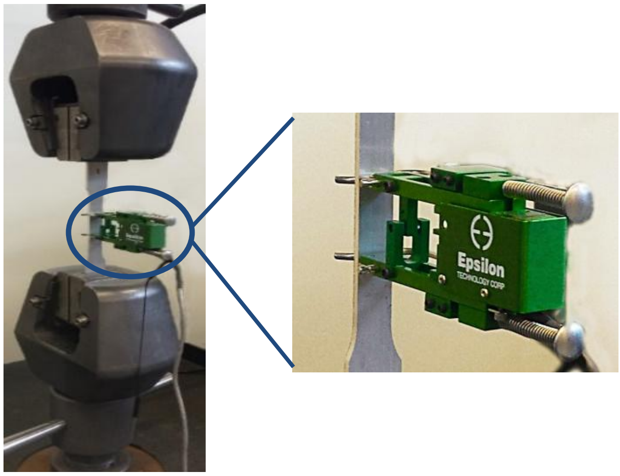


Figure 10 – An aluminum tensile bar during mechanical testing. The extensometer (green) is attached at the start of the test to measure the strain. Once the sample reaches 1.5% strain the extensometer is removed.

3. Results

3.1 Stress-Strain Curves

A tensile test generates a stress-strain curve which gives valuable information about a material. **Figure 11** is a stress-strain curve of the untreated samples. Each colored line represents one of the four alloys in its untreated state. Each line has three markers; from left to right, the first is the 0.2% offset yield strength, the second is ultimate tensile strength, and the third is failure. In the untreated condition, the four alloys exhibit a clear difference in yield strength with the strongest being HS6X followed by RX82, 6061, and 6063 in descending order of yield strength. A decrease in strength generally resulted in an increase in percent elongation, except for the RX82, which exhibits the least amount of percent elongation in the as-received form.

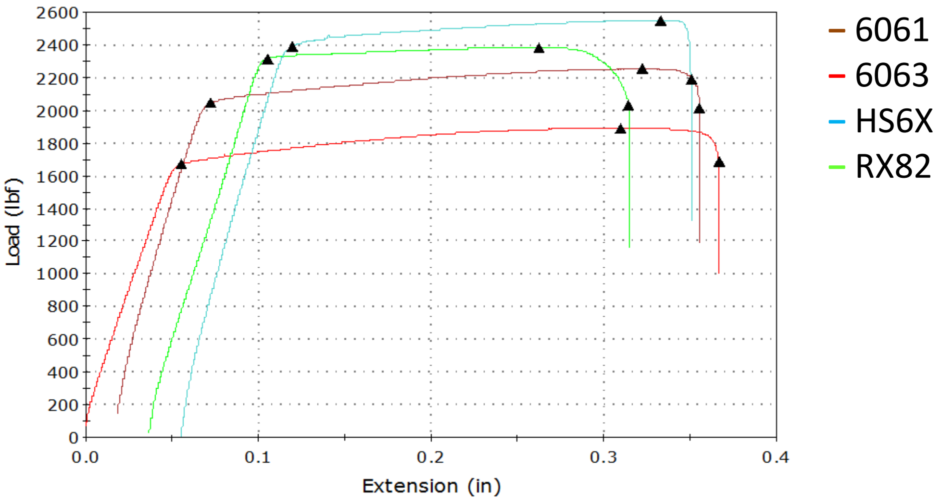


Figure 11 – A stress strain curve of the as-received 6xxx series alloys. This graph shows yield strength, ultimate tensile strength, and percent elongation.

3.2 Statistical Analysis

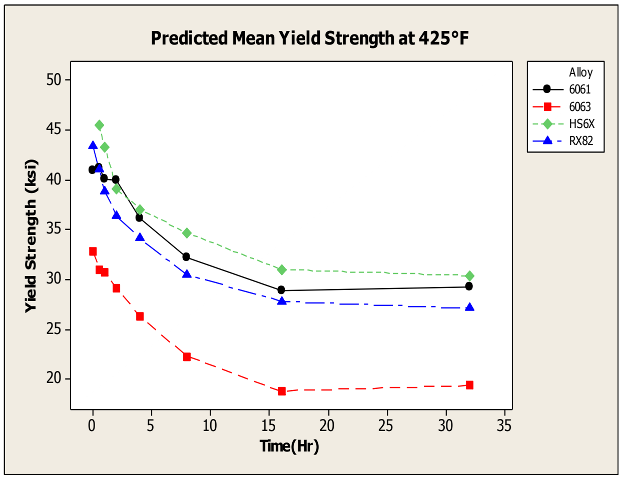
The results of the tensile tests were entered into Minitab in order to conduct statistical analysis and to better compare yield strength values. The first set of graphs shown in **Figure 12** plots the yield strength of all four alloys at each individual temperature. Two graphs were generated for each temperature. The first gives the predicted mean yield strength values of each alloy at the different reheat times. These values model yield strength as a function of alloy, time, and the interaction of alloy and time. The second graph for each temperature gives lower bound yield strength values generated with **Equation 1**.[12]

$$Lower\ Bound = \ Fits - \ 3.174\sqrt{S.D.^2 + S.E.^2} \qquad \text{(Eq. 1)}$$

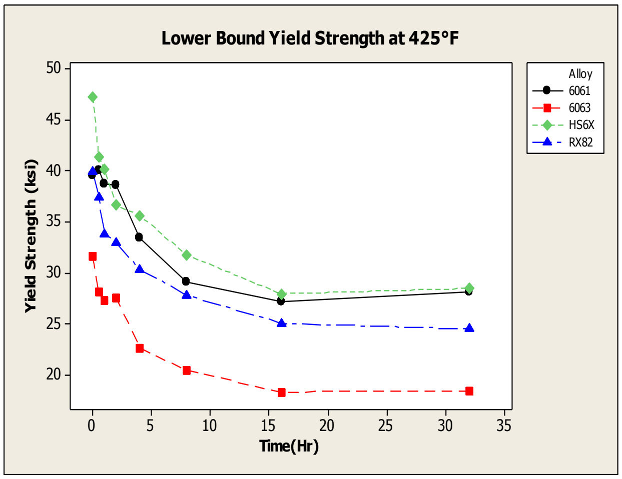
where S.E. is the standard error, S.D. is the standard deviation, and 3.174 is a t-value which gives 99.9% confidence. The purpose of a t-test is to determine if there is a significant difference between sample means. In other words, it measures the size of the difference in variation in relation to the size of a sample. Different t-values give different confidence levels and for the purpose of this project a 99.9% confidence level was desired. The lower bound values give a high confidence level that the yield strength will not fall below the minimum acceptable yield strength unique to each alloy.

3.3 Varying Temperature

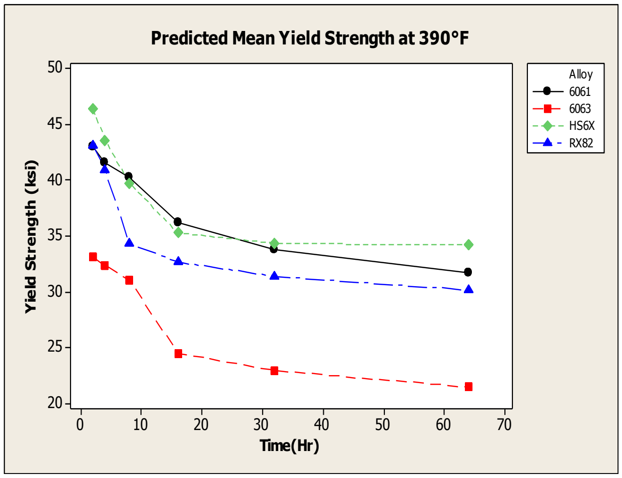
Although each alloy has a different response to each heat treatment, some general trends can be observed for each temperature (**Figure 12**). The 425°F heat treatment had the greatest effect on the yield strength of each alloy. For this temperature, even at low times, a rapid decrease in strength occurs. Eventually, at around 16 hours, the yield strength begins to level off and no further decrease is observed. At 390°F the decrease in yield strength is more gradual over time. A similar trend occurs where strength levels off, however the minimum values observed in the 425°F treatment are lower than those seen in the 390°F treatment. The 350°F heat treatment begins with an increase in strength across all four alloys. The increase occurs from 2 hours until about 8 hours when the strength then begins to fall. The overall change in yield strength in this temperature is small but a slight decrease is seen in all four alloys after 64 hours.



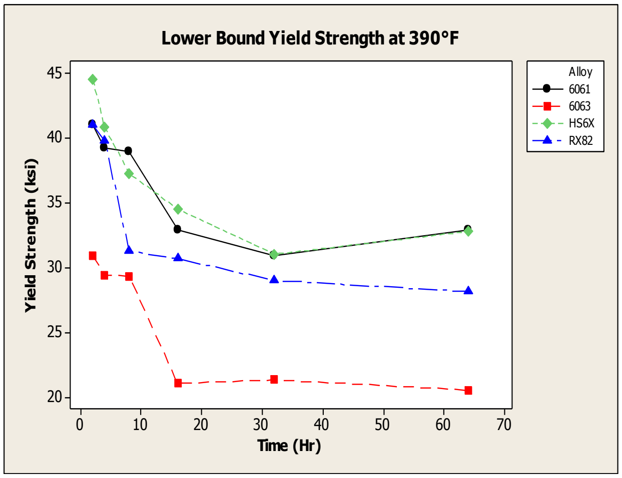
(a)



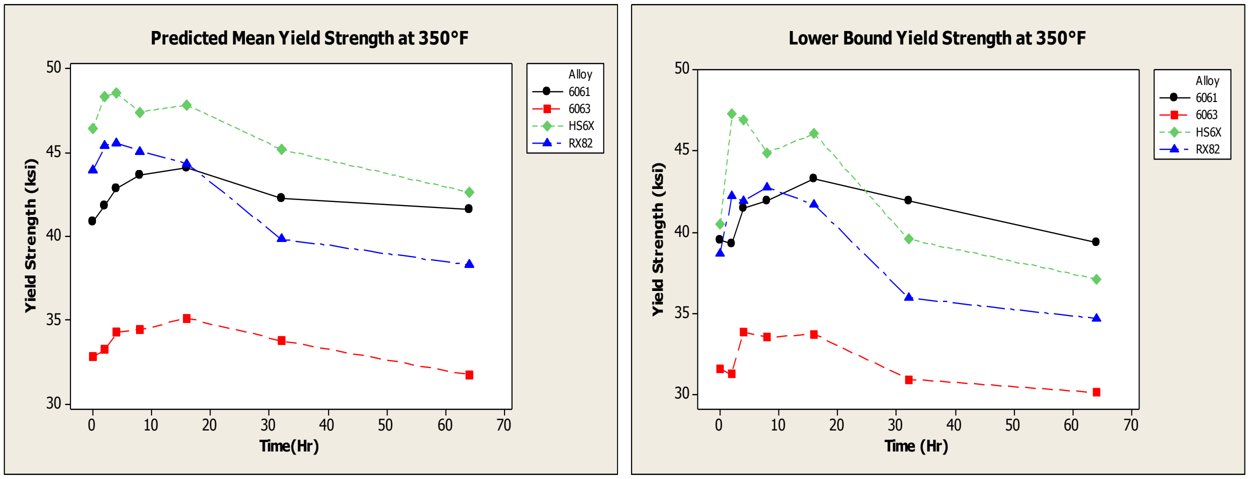
(b)



(c)



(d)



(e) **(f)**

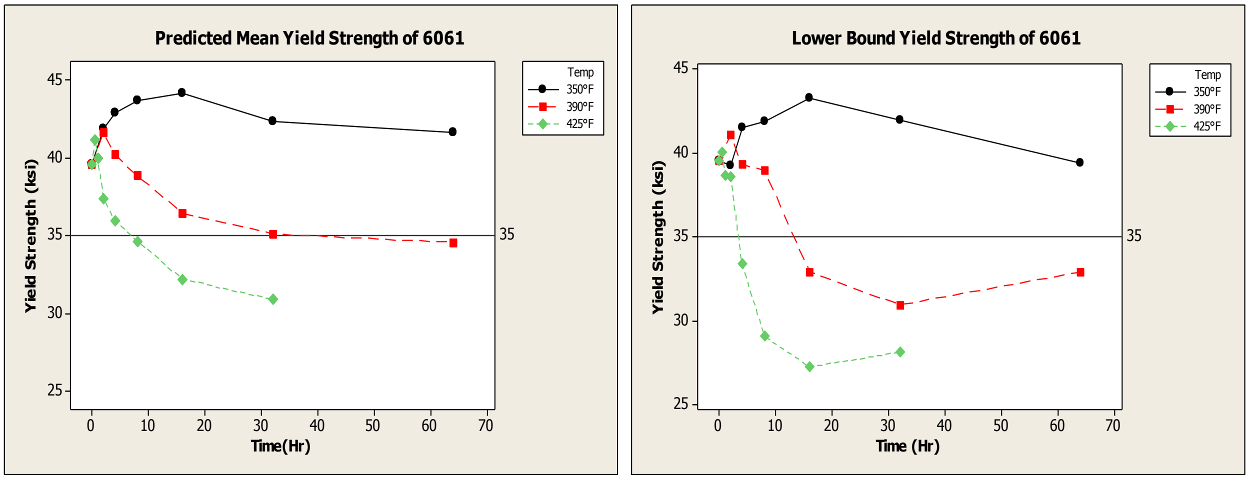
Figure 12 – Minitab outputs of all four alloys at each temperature. Each value listed on the graphs represents five data points, each corresponding to a single tensile test. **(a)** Predicted mean values of all four alloys at 425°F **(b)** lower bound values of all four alloys at 425°F **(c)** predicted mean values of all four alloys at 390°F **(d)** lower bound values of all four alloys at 390°F **(e)** predicted mean values of all four alloys at 350°F **(f)** lower bound values of all four alloys at 350°F.

3.4 Varying Alloy

The second set of graphs shown in **Figure 13** plots the yield strength of each individual alloy at all three heat treatment temperatures. These graphs are good for visualizing the effect each heat treatment has on a single alloy. There are two graphs for each set of data, one showing the predicted mean values, and the other showing lower bound values. These graphs also include minimum yield strength values of each alloy as set by Sapa Extrusions and the aluminum industry. For all four alloys, calculation of the lower bound values lead to more data points falling below these minimum acceptable values. A similar trend is observed for all four alloys across the different times. The 425°F heat treatment has the largest effect on strength, while the 390°F leads to a smaller decrease and the 350°F leads to a minimal amount of change. HS6X has a much smaller threshold between expected and minimum acceptable yield strength. This leads to more values falling below the minimum boundary for the HS6X alloy.

3.4.1 6061 Alloy

The response of the benchmark 6061 alloy to each heat treatment can be seen in **Figure 13**. The average yield strength of 6061 is 40 ksi while the minimum value set by the aluminum industry for this alloy is 35 ksi, a threshold of 5 ksi. At 350°F, an increase in yield strength is observed over the first 16 hours of heat treatment. The 390°F and 425°F heat treatments both resulted in a slight increase in strength over a short amount of time followed by a rapid decrease in strength with the higher temperature having a larger slope. Four heat treatments resulted in predicted mean yield strength values falling below the minimum acceptable yield strength. The heat treatments were 425°F for all times equal to or greater than eight hours, as well as 390°F for 32 hours. For the predicted lower bound calculations, three more values fell below the minimum strength for a total of seven heat treatments resulting in a yield strength below 35 ksi. For both the 390°F and 425°F, a leveling off in yield strength is observed at longer times.



(a) **(b)**

Figure 13 - Minitab outputs of the benchmark 6061 alloy with all three heat treatment temperatures at various times **(a)** gives the predicted mean values while **(b)** shows calculations of lower bound values with a 99.9% confidence level. Each value on the graph represents five data points which correspond to an individual tensile test. The graph also shows the minimum yield strength of 35 ksi as set by the aluminum industry.

3.4.2 6063 Alloy

The 6063 alloy has lower yield strength than the other alloys, but may be more desirable in certain applications due to its improved machinability. **Figure 14** presents the values collected and modified through Minitab. The average yield strength of 6063 is 31 ksi while the minimum value set by the aluminum industry for this alloy is 25 ksi, a threshold of 6 ksi. Similar to the 6061 alloy, the 350°F treatment resulted in an increase in yield strength over the first 16 hours. For this alloy, the 425°F and the 390°F both resulted in an immediate drop in strength, even at the shortest times. Six heat treatments resulted in predicted mean yield strength values falling below the minimum acceptable yield strength. These heat treatments are 425°F for all times equal to or greater than eight hours, as well as 390°F for 16, 32, and 64 hours. The predicted lower bound calculations produced one more value falling below the minimum strength at 425°F for four hours. For both the 390°F and 425°F a leveling off in yield strength is observed at longer times. There are some discontinuities in the curves which may be attributed to scatter in the data.

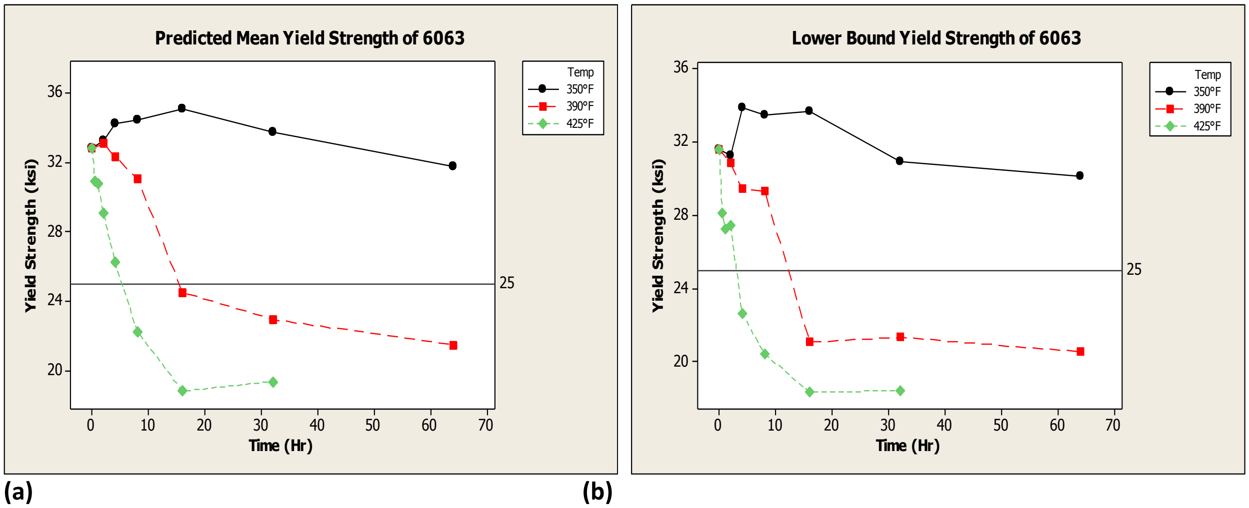


Figure 14 - Minitab outputs of 6063 alloy with all three heat treatment temperatures at various time. **(a)** gives the predicted mean values while **(b)** shows calculations of lower bound values with a 99.9% confidence level. Each value on the graph represents five data points which correspond to an individual tensile test. Each graph also includes the minimum yield strength of 25 ksi as set by the aluminum industry for this alloy.

3.4.3 Proprietary RX82 Alloy

Sapa's RX82 is a high strength structural alloy with improved formability. The average yield strength of RX82 is 44 ksi, while the minimum value set by Sapa for this alloy is 38 ksi, a threshold of 7 ksi. The 350°F heat treatment resulted in a slight increase in strength over the first four hours, after which a considerable drop is observed. In the predicted mean values, the 425°F and the 390°F treatments both resulted in an immediate decline in strength, even at the shortest times. This is followed by a plateau in yield strength at about 16 hours for both temperatures. Nine heat treatments resulted in predicted mean yield strength values falling below the minimum acceptable yield strength. These values are 425°F for all times equal to or greater than four hours, as well as 390°F for eight hours and up. The predicted lower bound calculations produced four more values falling below the minimum strength with two at 425°F for 30 minutes, as well as an hour, and two at 350°F for 32 and 64 hours. The predicted mean and lower bounds are shown in **Figure 15**.

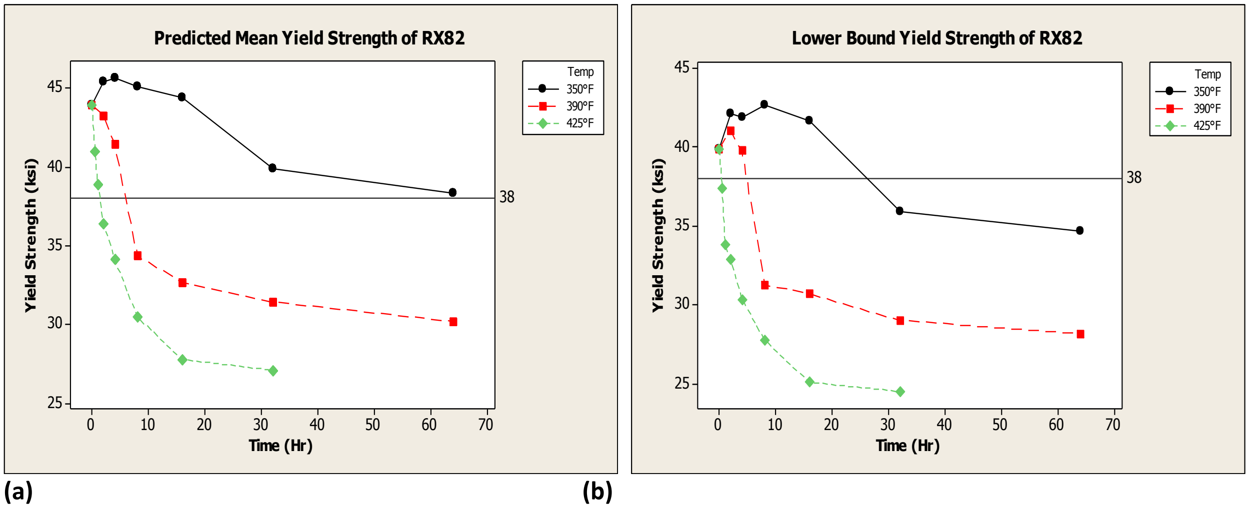
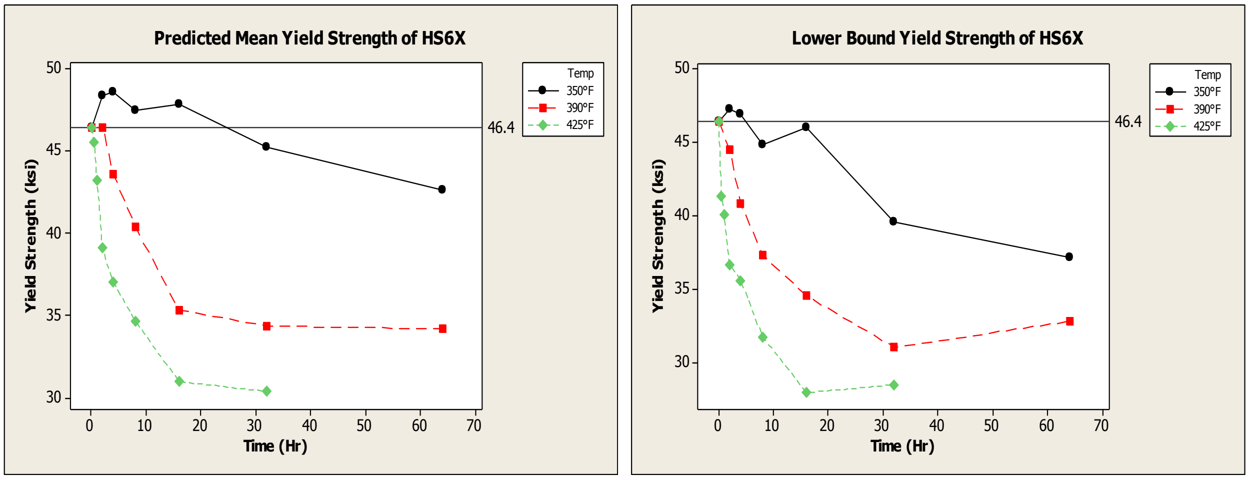


Figure 15 - Minitab outputs of Sapa's proprietary RX82 alloy with all three heat treatment temperatures at various times. **(a)** gives the predicted mean values while **(b)** shows calculations of lower bound values with a 99.9% confidence level. Each value on the graph represents five data points which correspond to an individual tensile test. Each graph also includes the minimum yield strength of 38 ksi as set by Sapa Extrusions.

3.4.4 Proprietary HS6X Alloy

Sapa's HS6X is the highest strength 6xxx series alloy on the market to date. The average yield strength of HS6X is an impressive 48.6 ksi while the minimum value set by Sapa for this alloy is 46.4 ksi, a threshold of only 2.2 ksi. The 350°F heat treatment resulted in a slight increase in strength over the first four hours, after which a slow and steady drop is observed. The eight hour heat treatment at 350°F does not follow the curve and may be attributed to increased variability in that specific data set. In the predicted mean values, the 425°F and the 390°F heat treatments both resulted in an immediate decline in strength, even at the shortest times. For both the predicted and lower bound values every heat treatment at 390°F and 425°F result in a yield strength below the minimum value (**Figure 16**). The predicted lower bound calculations produced a total of 17 values falling below the minimum required strength. It also should be noted that the strength of the as-received alloy was not quite up to the 48.6 ksi average. This may be due to the fact that the samples used in this experiment came from a preliminary batch of the HS6X alloy that was not yet approved for distribution.



(a) **(b)**

Figure 16 - Minitab outputs of Sapa's proprietary HS6X alloy with all three heat treatment temperatures at various times. **(a)** gives the predicted mean values while **(b)** shows calculations of lower bound values with a 99.9% confidence level. Each value on the graph represents five data points which correspond to an individual tensile test. Each graph also includes the minimum yield strength of 46.4 ksi as set by Sapa Extrusions.

3.5 Treatments Resulting in Minimum Values

To reiterate the results, **Table III** shows each alloy, the three temperatures, and the time at which the alloy first fell below the minimum strength. The 6061and 6063 alloys both fall below their respective minimum values at 390°F after 16 hours and 425°F after four hours, and do not fall below the minimum for any time at 350°F. The HS6X falls below its minimum yield strength after the following heat treatments: 450°F at 30 min, 390°F at two hours, and 350°F at eight hours. The RX82 falls below its minimum yield strength after the following heat treatments: 450°F at 30 min, 390°F at eight hours, and 350°F at 32 hours.

Table III – Time and Temperatures at which Yield Strength Falls Below Minimum Values

	350°F	390°F	425°F
6061 Minimum: 35 ksi		16 hrs	4 hrs
6063 Minimum: 25 ksi		16 hrs	4 hrs
HS6X Minimum: 46.4 ksi	8 hrs	2 hrs	30 min
RX82 Minimum: 38 ksi	32 hrs	8 hrs	30 min

4. Discussion

4.1 Ostwald Ripening

In the lower temperature heat treatments at short times, all four alloys experienced a slight increase in strength. This shows that they may have been aged to just below the peak age during the initial precipitation hardening treatment. There are three factors in this experiment that can cause the yield strength to lower: time, temperature, and alloy. An increase in temperature has the greatest effect on the change in yield strength. There is a general trend that, as the heat treatment temperature increases, the time it takes to drop below the minimum yield strength decreases. This can be observed for all of the alloys and is attributed to the fact that diffusion is temperature driven. It can be noted that the two proprietary alloys fall below the minimum yield requirement much faster than the 6061 and 6063 alloys. This is because HS6X alloy had a much smaller threshold for minimum yield strength and the RX82 alloy showed more variance in yield strength, which lead to a greater drop in lower bound values. The proprietary alloys are more heavily alloyed making them more susceptible to losses in strength due to reheating.

In the 425°F heat treatments, all four alloys experienced a plateau in yield strength at which point no further decreases in strength were observed. This occurs at about 16 hours of reheating and is attributed to the Mg_2Si precipitates reaching a maximum size. As heat is added to the system over time, the overall size of the precipitates begins to increase and the number of precipitates declines. This is known as Ostwald ripening and is a thermodynamically-driven spontaneous process in which smaller precipitates begin to dissolve and redeposit onto larger crystals thus decreasing the overall surface area of the precipitates. Atoms on the surface of a particle are less stable than those on the interior; therefore as the overall surface area of the precipitates decreases so does the energy of the system. Since larger precipitates are less effective at impeding the movement of dislocations, the strength of the alloy decreases. As the precipitates continue to grow, the distance between them increases. Eventually they are so far apart that, for all intents and purposes, diffusion no longer occurs. This is the point at which a leveling off in yield strength is observed. **Figure 17** is is a schematic that represents the precipitate's change in size.

The percent decrease in yield strength was calculated by comparing the lower bound of the untreated alloys and the lower bound of the minimum values observed. **Table IV** compiles the percent decrease calculations for each of the alloys and each of the reheating times. The 6061 alloy experienced the smallest percent decrease in strength in every heat treatment. 6061 typically has twice the amount of magnesium and silicon than the 6063 alloy. Since there are more precipitates in the age hardened 6061, higher yield strength is achieved. The increased number of precipitates may lead to a smaller decrease in strength because there is less distance between the precipitates. The shorter distance between precipitates in the 6061 alloy allows for diffusion to continue over longer periods of time. In 6063 however, the smaller amount of Mg_2Si may lead to a greater decrease in strength over the same amount of time because maximum precipitate size will be reached sooner. A comparison to the proprietary alloys in this manner is not possible as the amount of alloying elements is unknown.

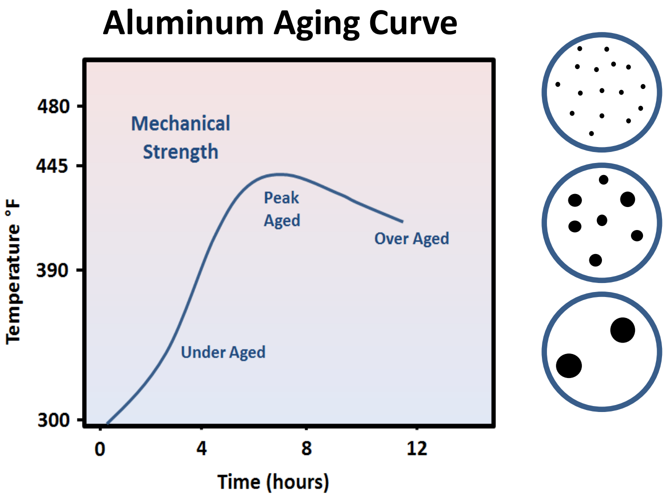


Figure 17 - Aging curve and precipitate size.

Under Aged – The precipitates are finely dispersed, but do not provide much added strength to the aluminum alloy

Peak Aged – The precipitates are at a size that allows for a combination of shearing and bowing as a method to impede dislocation movement throughout the alloy. This provides the ideal amount of strength to the alloy

Over-Aged – With increased time and temperature, the precipitates continue to grow to an undesired size.

.

Table IV – Percent Decrease in Yield Strength with Over-aging

	Alloy			
Over-aging Temperature	**6061**	**6063**	**HS6X**	**RX82**
350°F	0.3%	5.0%	20.0%	13.0%
390°F	22.0%	35.0%	33.0%	30.0 %
425°F	31.0%	40.0%	40.0%	39.0%

4.2 Ductility is not the same as Elongation

Tensile tests are commonly done in industry because they are a quick and inexpensive way to gather data, such as strength, stiffness, and tensile elongation. A common misconception is that a material with high elongation is a ductile material. This is not always the case. Although high elongation sometimes correlates to a high ductility, they are not the same. Specifically, for a tensile test, percent elongation is not a good indicator of ductility as elongation is not uniform over the entire gage length. The reduction of area at the fracture may be a better indicator of ductility. Ductility is commonly defined as a material's ability to withstand plastic deformation without rupture. **Figure 18** demonstrates this by comparing two aluminum alloys with the same strength and percent elongation after quasi-static testing. Image **A** shows a desirable failure, which consists of uniform folds with little to no rupture. Image **B** shows an undesirable failure, with extensive rupture throughout the part.[2]

A continuation of this project that would be useful information for both Sapa Extrusions and the automotive industry would be to run compression tests on these materials to determine the ductility of these alloys after reheating. Ductility is a desirable property for an automotive frame because ductile materials are good at absorbing energy. A considerable reduction in ductility would lead to an unusable part costing the company money and time. Equating percent elongation to ductility is a common misconception, even for professionals in the auto industry, and it is important to understand the difference when making a significant material selection.

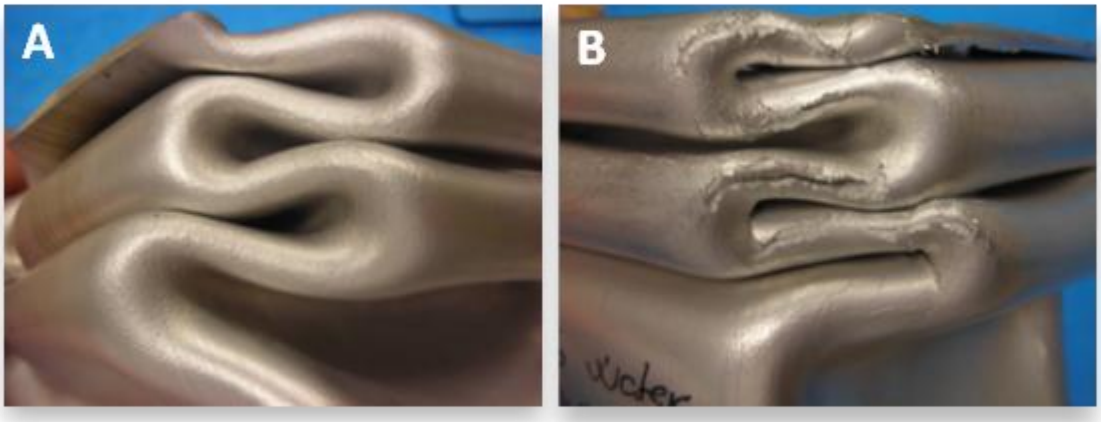


Figure 18 – **(A)** shows an aluminum alloy with high ductility, whereas **(B)** shows an alloy with the same elasticity and elongation, but a different ductility. The alloys are exposed to the same quasi-static test, yet the response to the test is different.[2]

5. Conclusions

1. Given the current time and temperature of GM's paint oven cycle, there is no danger for over-aging and an associated strength loss in any of the four aluminum alloys.
2. With the currently set minimum strengths of the two proprietary alloys, caution must be taken if there is a line stoppage in the paint oven cycle. HS6X for example, will fall below the minimum strength requirement in only 2 hours.
3. For the 6061 and 6063 alloys, the yield strength did not go below the lower bound value at 350°F, at 390°F it took 16 hours, and at 425°F it took 4 hours.
4. For the HS6X alloy, the yield strength fell below the lower bound after 8 hours at 350°F, at 390°F it took 2 hours, and at 425°F it took 30 minutes.
5. At 350°F, the RX82 alloy took 32 hours for the yield strength to fall below the lower bound, at 390°F it took 8 hours, and at 425°F it took 30 minutes.

6. References

[1] Design Manual: Success with Aluminium Profiles. S.l.: Sapa Profiler AB, 2009. Print.

[2] Victor, Jeff. "Metallurgy." Sapa Profile Academy. City of Industry. 12 Nov. 2014. Lecture

[3] Zhu, Hanliang, Malcolm Couper, and Arne Dahle. "Effect of Process Variables on Mg-Si Particles and Extrudability of 6xxx Series Aluminum Extrusions." JOM, 63.11 (2011): 66-71.

[4] Saha, P. "Fundamentals of Extrusion." Aluminum Extrusion Technology. Materials Park, OH: ASM International, 2000. 1-23. Print.

[5] Amberg, Dustin. "Extrusion Production." Sapa Profile Academy. City of Industry. 12 Nov. 2014. Lecture.

[6] Heat Treating of Aluminum Alloys, Heat Treating, Vol 4, ASM Handbook, ASM International, 1991, p 841–879

[7] Image from a website: <http://sastramech.blogspot.com/2013/05/fine-particle-strengthening.html>

[8] Sheasby, P. , Pinner, R. , & Wernick, S. (2001). The Surface Treatment and Finishing of Aluminium and Its Alloys. Materials Park, Ohio : Stevenage: ASM International : Finishing Publications.

[9] Scamans, G. , Andrews, P. , Butler, C. , Hall, A. , Thompson, G. , et al. (2013). Surface treatment of aluminium automotive sheet: Mythology and technology. Surface and Interface Analysis, 45(10), 1430-1434.

[10] Siddiqui, Rafiq A., Hussein A. Abdullah, and Khamis R. Al-Belushi. "Influence of Aging Parameters on the Mechanical Properties of 6063 Aluminium Alloy." Journal of Materials Processing Technology 102.1-3 (2000): 234-40. Web.

[11] ASTM Standard B557, 2014, “Standard Test Methods for Tension Testing Wrought and Cast Aluminium- and Magnesium-Alloy Products,” ASTM International, West Conshohocken, PA, 2014.

[12] Devore, Jay L., and Nicholas R. Farnum. *Applied Statistics for Engineers and Scientists*. Pacific Grove, CA: Duxbury, 1999. Print.

Appendix A – Aluminum Temper Designations

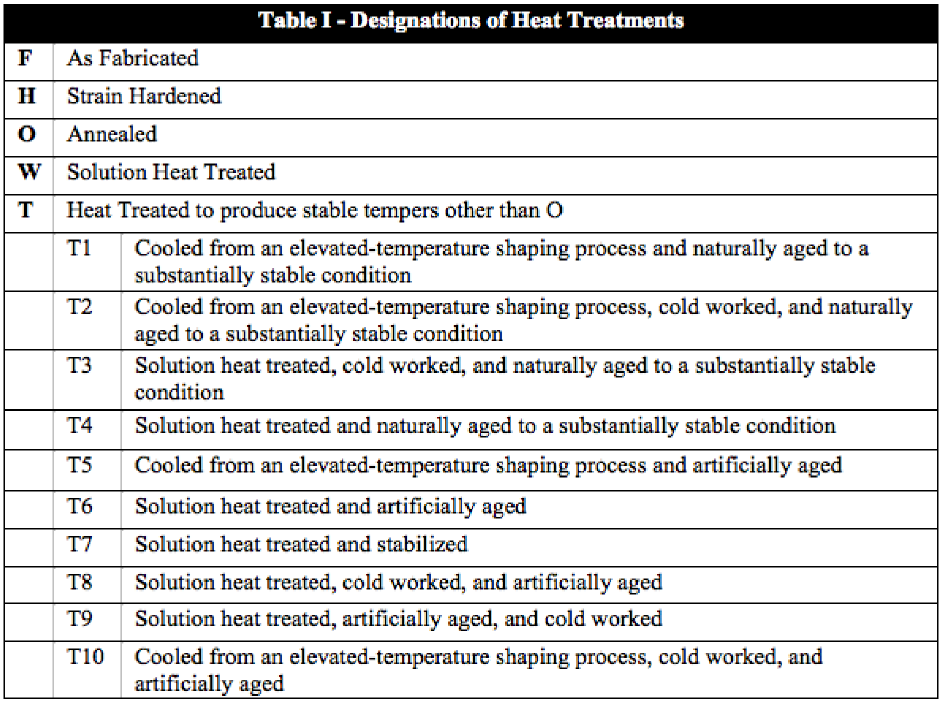


Table I - Designations of Heat Treatments		
F	As Fabricated	
H	Strain Hardened	
O	Annealed	
W	Solution Heat Treated	
T	Heat Treated to produce stable tempers other than O	
	T1	Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition
	T2	Cooled from an elevated-temperature shaping process, cold worked, and naturally aged to a substantially stable condition
	T3	Solution heat treated, cold worked, and naturally aged to a substantially stable condition
	T4	Solution heat treated and naturally aged to a substantially stable condition
	T5	Cooled from an elevated-temperature shaping process and artificially aged
	T6	Solution heat treated and artificially aged
	T7	Solution heat treated and stabilized
	T8	Solution heat treated, cold worked, and artificially aged
	T9	Solution heat treated, artificially aged, and cold worked
	T10	Cooled from an elevated-temperature shaping process, cold worked, and artificially aged

Appendix B – Tensile Test Data

425 for 30 mins

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from Yield Stress	Average % Difference from Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.52	40.99	2.17	43.45	8.94	-0.30%	3.29%	-0.64%	3.14%	41.13	43.52
2	6061-2	10.13	41.41	2.18	43.52	9.39	-1.33%	3.14%				
3	6061-3	11.28	40.68	2.14	42.81	8.17	0.46%	4.72%				
4	6061-4	9.33	41.16	2.18	43.65	9.41	-0.72%	2.85%				
5	6061-5	9.19	41.4	2.21	44.17	10.29	-1.31%	1.69%				
6	6063-1	8.91	30.76	1.72	34.48	11.49	6.21%	7.42%	5.79%	6.94%	30.90	34.66
7	6063-2	8.99	30.27	1.7	33.98	11.66	7.70%	8.76%				
8	6063-3	10.73	30.01	1.68	33.55	10.99	8.49%	9.92%				
9	6063-4	8.69	31.71	1.78	35.62	12.08	3.31%	4.36%				
10	6063-5	9.48	31.74	1.78	35.66	12.15	3.22%	4.25%				
11	HS6X-1	10.33	45.34	2.34	46.9	7.39	0.25%	2.84%	-0.09%	2.13%	45.496	47.242
12	HS6X-2	10.94	45.14	2.34	46.7	7.96	0.69%	3.25%				
13	HS6X-3	9.35	44.07	2.3	45.9	8.99	3.05%	4.91%				
14	HS6X-4	9.73	47.4	2.47	49.34	9.27	-4.28%	-2.22%				
15	HS6X-5	9.27	45.53	2.42	47.37	9.99	-0.16%	1.86%				
16	RX82-1	10.33	42.09	2.19	43.79	7.97	4.20%	3.46%	5.17%	5.37%	41.664	42.924
17	RX82-2	9.46	41.06	2.1	42.05	6.39	6.55%	7.29%				
18	RX82-3	9.98	41.18	2.12	42.39	7.55	6.27%	6.54%				
19	RX82-4	8.93	39.63	2.29	40.81	9.29	9.80%	10.03%				
20	RX82-5	9.63	44.36	2.28	45.58	8.25	-0.97%	-0.49%				

425 for 1 Hour

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	10.08	39.85	2.09	41.88	8.46	2.49%	6.79%	0.64%	5.23%	40.604	42.58
2	6061-2	9.05	40.4	2.11	42.19	8.79	1.14%	6.10%				
3	6061-3	9.48	39.51	2.07	41.41	7.99	3.32%	7.83%				
4	6061-4	9	41.44	2.17	43.43	9.47	-1.40%	3.34%				
5	6061-5	9.58	41.82	2.2	43.99	9.05	-2.33%	2.09%				
6	6063-1	10.38	30.52	1.7	33.98	11.36	6.94%	8.76%	6.24%	8.48%	30.748	34.086
7	6063-2	9.96	29.13	1.63	32.62	10	11.18%	12.42%				
8	6063-3	10.4	31.06	1.73	34.57	11.13	5.29%	7.18%				
9	6063-4	8.88	31.25	1.72	34.4	10.98	4.71%	7.64%				
10	6063-5	9.05	31.78	1.74	34.86	11.01	3.10%	6.40%				
11	HS6X-1	10.33	43.14	2.26	45.19	7.51	5.09%	6.38%	4.74%	6.28%	43.302	45.24
12	HS6X-2	8.88	43.48	2.26	45.23	9.09	4.34%	6.30%				
13	HS6X-3	10.34	41.84	2.2	43.98	7.66	7.95%	8.89%				
14	HS6X-4	10.17	44.19	2.31	46.1	8.78	2.78%	4.50%				
15	HS6X-5	8.9	43.86	2.28	45.7	8.85	3.51%	5.32%				
16	RX82-1	9.17	39.51	2.06	41.2	8.92	10.07%	9.17%	11.57%	9.33%	38.854	41.124
17	RX82-2	9.32	36.95	1.97	39.38	8.29	15.90%	13.18%				
18	RX82-3	10.11	37.73	2.02	40.34	7.85	14.13%	11.06%				
19	RX82-4	9.95	40.2	2.12	42.41	8.46	8.50%	6.50%				
20	RX82-5	10.11	39.88	2.11	42.29	9.38	9.23%	6.76%				

425 for 2 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.1	40.19	2.1	42.05	8.32	1.65%	6.41%	2.19%	6.49%	39.97	42.014
2	6061-2	9.57	40.16	2.11	42.18	7.87	1.73%	6.12%				
3	6061-3	9.53	39.69	2.08	41.66	7.94	2.88%	7.28%				
4	6061-4	9.49	40.38	2.13	42.55	8.53	1.19%	5.30%				
5	6061-5	9.44	39.43	2.08	41.63	8.3	3.51%	7.34%				
6	6063-1	9.13	28.7	1.61	32.15	12.61	12.49%	13.68%	11.02%	12.22%	29.058	32.518
7	6063-2	9.18	29.05	1.63	32.59	9.93	11.42%	12.50%				
8	6063-3	8.85	29.3	1.64	32.73	10.39	10.66%	12.12%				
9	6063-4	9.58	29.68	1.66	33.3	16.34	9.50%	10.59%				
10	6063-5	8.85	28.56	1.59	31.82	10.39	12.92%	14.56%				
11	HS6X-1	9.28	40.33	2.17	43.31	8.05	11.27%	10.28%	14.02%	12.71%	39.082	42.136
12	HS6X-2	9.38	38.81	2.09	41.85	8.57	14.62%	13.30%				
13	HS6X-3	9.12	38.8	2.09	41.89	8.98	14.64%	13.22%				
14	HS6X-4	9.03	38.91	2.1	42.02	8.83	14.40%	12.95%				
15	HS6X-5	9.87	38.56	2.08	41.61	7.12	15.17%	13.80%				
16	RX82-1	9.77	37.59	2.01	40.27	9.08	14.44%	11.22%	17.16%	13.82%	36.398	39.09
17	RX82-2	9.72	37.07	1.98	39.54	8.45	15.63%	12.83%				
18	RX82-3	9.54	36.36	1.96	39.13	8.55	17.24%	13.73%				
19	RX82-4	9.46	35.96	1.93	38.55	8.38	18.15%	15.01%				
20	RX82-5	10.28	35.01	1.9	37.96	7.95	20.32%	16.31%				

425 for 4 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield	Average % Difference from average Tensile	Average Yield Stress	Average Tensile Stress
1	6061-1	9.03	36.8	1.97	39.46	8.61	9.95%	12.17%	11.64%	13.38%	36.108	38.918
2	6061-2	9.51	36.88	1.97	39.47	8.57	9.75%	12.15%				
3	6061-3	9.64	35.27	1.91	38.27	7.76	13.69%	14.82%				
4	6061-4	9.32	35.28	1.92	38.32	7.93	13.67%	14.71%				
5	6061-5	10.09	36.31	1.95	39.07	14.61	11.15%	13.04%				
6	6063-1	9.46	25.86	1.48	29.66	10.7	21.15%	20.36%	19.91%	18.91%	26.266	30.202
7	6063-2	9.75	27.32	1.56	31.21	11.91	16.70%	16.20%				
8	6063-3	9.49	24.69	1.46	29.1	17.65	24.72%	21.87%				
9	6063-4	9.38	26.49	1.52	30.33	10.52	19.23%	18.56%				
10	6063-5	9.58	26.97	1.54	30.71	10.52	17.76%	17.54%				
11	HS6X-1	9.73	37.31	2.05	41.09	9.08	17.92%	14.87%	18.59%	15.38%	37.004	40.844
12	HS6X-2	9.26	36.88	2.03	40.52	9.21	18.86%	16.06%				
13	HS6X-3	9.77	37.27	2.06	41.26	9.18	18.01%	14.52%				
14	HS6X-4	9.91	36.35	2.02	40.37	9.25	20.03%	16.37%				
15	HS6X-5	9.95	37.21	2.05	40.98	8.97	18.14%	15.10%				
16	RX82-1	10.32	35.87	1.96	39.18	8.27	18.36%	13.62%	22.38%	16.59%	34.104	37.834
17	RX82-2	10.17	34.06	1.9	38.1	9.67	22.48%	16.00%				
18	RX82-3	9.97	32.97	1.82	36.48	8.65	24.96%	19.57%				
19	RX82-4	10.45	34.03	1.91	38.18	10.11	22.55%	15.83%				
20	RX82-5	9.67	33.59	1.86	37.23	9.51	23.55%	17.92%				

425 for 8 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.14	33.35	1.85	37.07	8.89	18.39%	17.49%	21.35%	19.54%	32.14	36.1525
2	6061-2	9.14	31.76	1.79	35.86	9.16	22.28%	20.19%				
3	6061-3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	6061-4	8.92	31.33	1.77	35.47	8.94	23.33%	21.05%				
5	6061-5	9.44	32.12	1.81	36.21	9.06	21.40%	19.41%				
6	6063-1	8.89	22.6	1.37	27.45	12.56	31.09%	26.30%	32.25%	27.14%	22.218	27.136
7	6063-2	9.65	21.47	1.32	26.49	11.27	34.53%	28.87%				
8	6063-3	9.15	22.11	1.36	27.13	12.67	32.58%	27.16%				
9	6063-4	9.65	22.81	1.38	27.66	10.27	30.45%	25.73%				
10	6063-5	9.71	22.1	1.35	26.95	12.79	32.61%	27.64%				
11	HS6X-1	9.22	33.17	1.91	38.13	9.41	27.03%	21.01%	23.80%	18.51%	34.636	39.336
12	HS6X-2	8.92	35.19	1.98	39.53	9.48	22.58%	18.11%				
13	HS6X-3	9.77	35.1	2	39.95	9.24	22.78%	17.24%				
14	HS6X-4	9.4	34.81	1.97	39.47	9.36	23.42%	18.23%				
15	HS6X-5	9.74	34.91	1.98	39.6	9.21	23.20%	17.96%				
16	RX82-1	9.64	29.95	1.74	34.82	9.85	31.83%	23.23%	30.69%	21.72%	30.454	35.504
17	RX82-2	10.2	30.47	1.79	35.8	10.38	30.65%	21.07%				
18	RX82-3	9.68	31.72	1.82	36.45	9.07	27.80%	19.64%				
19	RX82-4	9.79	29.71	1.74	34.72	9.09	32.38%	23.45%				
20	RX82-5	9.26	30.42	1.79	35.73	11.04	30.76%	21.23%				

425 for 16 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	8.93	28.4	1.69	33.79	9.4	30.50%	24.79%	29.35%	24.20%	28.872	34.058
2	6061-2	8.75	28.66	1.7	33.91	8.99	29.87%	24.53%				
3	6061-3	9.43	28.69	1.7	33.91	10.04	29.79%	24.53%				
4	6061-4	10.09	28.96	1.7	34.1	9.58	29.13%	24.10%				
5	6061-5	9.75	29.65	1.73	34.58	9.27	27.45%	23.04%				
6	6063-1	9.55	18.88	1.24	24.79	11.35	42.43%	33.44%	42.74%	33.85%	18.78	24.636
7	6063-2	9.14	18.87	1.24	24.86	13.26	42.46%	33.25%				
8	6063-3	8.59	18.59	1.22	24.37	13.66	43.32%	34.57%				
9	6063-4	9.04	18.86	1.23	24.67	11.72	42.49%	33.76%				
10	6063-5	9.24	18.7	1.22	24.49	12.9	42.98%	34.24%				
11	HS6X-1	9.77	31.16	1.83	36.56	9.82	31.45%	24.26%	31.87%	24.00%	30.968	36.686
12	HS6X-2	10.23	31.48	1.87	37.39	8.95	30.74%	22.54%				
13	HS6X-3	9.49	31.67	1.86	37.22	9.12	30.33%	22.89%				
14	HS6X-4	9.57	31.06	1.85	37	9.1	31.67%	23.35%				
15	HS6X-5	10.24	29.47	1.76	35.26	9.45	35.17%	26.95%				
16	RX82-1	9.77	26.78	1.66	33.19	10.64	39.05%	26.83%	36.82%	25.50%	27.758	33.792
17	RX82-2	9.66	28.3	1.71	34.27	9.23	35.59%	24.45%				
18	RX82-3	10.39	28.27	1.71	34.26	10.05	35.66%	24.47%				
19	RX82-4	9.59	27.05	1.65	32.97	9.71	38.43%	27.31%				
20	RX82-5	10.68	28.39	1.71	34.27	9.68	35.38%	24.45%				

425 for 32 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.46	29.03	1.71	34.11	9.69	28.96%	24.08%	28.43%	23.73%	29.246	34.268
2	6061-2	9.41	29.71	1.72	34.44	9.04	27.30%	23.35%				
3	6061-3	9.23	29.46	1.73	34.59	9.1	27.91%	23.01%				
4	6061-4	8.92	29.07	1.7	34.06	9.22	28.87%	24.19%				
5	6061-5	10.46	28.96	1.71	34.14	9.43	29.13%	24.02%				
6	6063-1	10.54	19.61	1.27	25.38	12.12	40.21%	31.85%	41.04%	32.49%	19.338	25.144
7	6063-2	9.04	19.42	1.26	25.17	16.03	40.79%	32.42%				
8	6063-3	9.41	19.55	1.27	25.44	13.27	40.39%	31.69%				
9	6063-4	9.62	19.11	1.24	24.84	14.58	41.73%	33.30%				
10	6063-5	9.19	19	1.24	24.89	11.44	42.07%	33.17%				
11	HS6X-1	9.92	30.8	1.83	36.58	8.94	32.24%	24.22%	33.21%	25.06%	30.36	36.172
12	HS6X-2	9.09	29.67	1.77	35.48	9.04	34.73%	26.50%				
13	HS6X-3	8.34	30.49	1.82	36.49	9.83	32.92%	24.40%				
14	HS6X-4	10.19	29.92	1.78	35.58	8.99	34.18%	26.29%				
15	HS6X-5	9.45	30.92	1.84	36.73	8.98	31.98%	23.91%				
16	RX82-1	9.32	27.6	1.69	33.83	9.33	37.18%	25.42%	38.40%	26.42%	27.066	33.376
17	RX82-2	8.46	27.87	1.7	34.04	10.68	36.57%	24.95%				
18	RX82-3	9.44	26.39	1.64	32.79	12.57	39.94%	27.71%				
19	RX82-4	10.12	26.18	1.62	32.46	9.67	40.41%	28.44%				
20	RX82-5	9.97	27.29	1.69	33.76	9.67	37.89%	25.57%				

390 for 2 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.14	42.28	2.22	44.35	9.63	-3.46%	1.29%	-5.20%	0.06%	42.99	44.902
2	6061-2	9.19	42.53	2.22	44.4	9.22	-4.07%	1.18%				
3	6061-3	9.76	43.34	2.26	45.15	9.18	-6.05%	-0.49%				
4	6061-4	9.74	43.31	2.26	45.18	9.89	-5.98%	-0.56%				
5	6061-5	9.4	43.49	2.27	45.43	9.19	-6.42%	-1.11%				
6	6063-1	9.29	32.8	1.85	36.19	11.38	-0.01%	2.83%	-0.90%	2.04%	33.09	36.486
7	6063-2	9.17	32.41	1.82	35.69	11.12	1.18%	4.17%				
8	6063-3	9.53	33.78	1.86	37.2	10.89	-3.00%	0.12%				
9	6063-4	9.48	33.75	1.86	37.3	11.08	-2.91%	-0.15%				
10	6063-5	9.88	32.71	1.8	36.05	11.36	0.26%	3.21%				
11	HS6X-1	9.27	46.02	2.38	47.56	9.43	-1.24%	1.47%	-2.12%	0.78%	46.418	47.894
12	HS6X-2	9.63	45.95	2.37	47.37	7.74	-1.09%	1.86%				
13	HS6X-3	9.72	47.17	2.43	48.63	8.74	-3.77%	-0.75%				
14	HS6X-4	9.15	46.81	2.41	48.28	8.47	-2.98%	-0.02%				
15	HS6X-5	9.83	46.14	2.38	47.63	8.85	-1.51%	1.33%				
16	RX82-1	9.95	42.95	2.25	44.07	8.31	2.24%	2.84%	1.71%	2.16%	43.186	44.38
17	RX82-2	9.81	43.04	2.21	44.16	8.7	2.04%	2.64%				
18	RX82-3	9.93	42.45	2.18	43.58	7.59	3.38%	3.92%				
19	RX82-4	10.12	44.08	2.28	45.63	9.1	-0.33%	-0.60%				
20	RX82-5	10.27	43.41	2.22	44.46	7.98	1.20%	1.98%				

390 for 4 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.39	40.9	2.14	42.87	8.29	-0.08%	4.58%	-1.81%	3.43%	41.606	43.39
2	6061-2	9.59	42.49	2.21	44.12	9.22	-3.97%	1.80%				
3	6061-3	9.42	41.94	2.18	43.69	8.52	-2.63%	2.76%				
4	6061-4	9.29	41	2.14	42.82	8.43	-0.33%	4.70%				
5	6061-5	9.2	41.7	2.17	43.45	8.26	-2.04%	3.29%				
6	6063-1	8.9	31.36	1.72	34.48	10.94	4.38%	7.42%	1.40%	4.54%	32.336	35.552
7	6063-2	8.72	32.57	1.79	35.77	10.88	0.69%	3.96%				
8	6063-3	8.95	32.13	1.76	35.23	10.59	2.03%	5.41%				
9	6063-4	9.4	33.61	1.84	36.88	10.97	-2.48%	0.98%				
10	6063-5	10.08	32.01	1.77	35.4	10.52	2.40%	4.95%				
11	HS6X-1	9.28	43.16	2.26	45.25	7.48	5.05%	6.26%	4.09%	5.74%	43.594	45.498
12	HS6X-2	9.31	43.66	2.28	45.55	7.96	3.95%	5.63%				
13	HS6X-3	8.66	43.74	2.27	45.49	7.76	3.77%	5.76%				
14	HS6X-4	9.34	42.64	2.24	44.78	7.28	6.19%	7.23%				
15	HS6X-5	9.39	44.77	2.32	46.42	7.53	1.51%	3.83%				
16	RX82-1	9.49	41.53	2.15	43.05	8.5	5.48%	5.09%	6.90%	5.65%	40.904	42.794
17	RX82-2	9.86	41.49	2.16	43.19	7.39	5.57%	4.78%				
18	RX82-3	10.01	41.64	2.17	43.39	8.67	5.23%	4.34%				
19	RX82-4	10.08	40.94	2.13	42.66	7.34	6.82%	5.95%				
20	RX82-5	10.08	38.92	2.08	41.68	8.7	11.42%	8.11%				

390 for 8 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	8.87	40.08	2.1	42.03	8.36	1.92%	6.45%	1.43%	6.02%	40.28	42.23
2	6061-2	9.27	40.22	2.12	42.33	8.16	1.58%	5.79%				
3	6061-3	8.92	40.63	2.12	42.35	9.09	0.58%	5.74%				
4	6061-4	8.94	40.7	2.13	42.66	8.64	0.41%	5.05%				
5	6061-5	9.04	39.78	2.09	41.76	8.74	2.66%	7.06%				
6	6063-1	9.29	31.65	1.75	34.91	10.55	3.49%	6.27%	5.31%	7.79%	31.05	34.34
7	6063-2	9.44	31.36	1.73	34.67	10.48	4.38%	6.91%				
8	6063-3	8.95	30.73	1.7	33.94	10.59	6.30%	8.87%				
9	6063-4	8.63	30.41	1.68	33.59	10.41	7.28%	9.81%				
10	6063-5	9.47	31.12	1.73	34.6	10.55	5.11%	7.10%				
11	HS6X-1	8.83	40.49	2.16	43.22	9.49	10.92%	10.46%	11.09%	10.42%	40.41	43.24
12	HS6X-2	8.77	37.92	2.06	41.23	8.23	16.58%	14.58%				
13	HS6X-3	9.46	39.65	2.13	42.67	8.15	12.77%	11.60%				
14	HS6X-4	9.49	43.04	2.27	45.46	8.09	5.31%	5.82%				
15	HS6X-5	9.15	40.97	2.18	43.63	8.8	9.87%	9.61%				
16	RX82-1	9.47	35.08	1.91	38.12	8.26	20.16%	15.96%	20.65%	15.88%	34.86	38.16
17	RX82-2	10.12	37.02	1.98	39.69	8.55	15.74%	12.50%				
18	RX82-3	9.07	33.37	1.85	36.92	8.36	24.05%	18.60%				
19	RX82-4	10.39	35.02	1.93	38.68	9.04	20.29%	14.72%				
20	RX82-5	9.68	33.83	1.87	37.37	9.74	23.00%	17.61%				

390 for 16 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.79	34.86	1.9	37.96	9.64	14.70%	15.51%	11.28%	13.03%	36.26	39.08
2	6061-2	8.49	36.22	1.96	39.14	9.06	11.37%	12.89%				
3	6061-3	9.21	36.3	1.96	39.11	8.16	11.17%	12.95%				
4	6061-4	9.36	37.6	2	40.05	8.95	7.99%	10.86%				
5	6061-5	9.65	36.31	1.96	39.12	9.41	11.15%	12.93%				
6	6063-1	9.88	24.14	1.43	28.55	14.18	26.39%	23.34%	25.29%	22.54%	24.50	28.85
7	6063-2	9.7	26.11	1.5	30.07	14.74	20.39%	19.26%				
8	6063-3	10.61	23.78	1.42	28.45	17.66	27.49%	23.61%				
9	6063-4	9.66	23.72	1.41	28.22	17.91	27.67%	24.23%				
10	6063-5	8.83	24.76	1.45	28.96	10.39	24.50%	22.24%				
11	HS6X-1	9.43	35.69	2	39.99	9.12	21.48%	17.15%	22.34%	18.06%	35.30	39.55
12	HS6X-2	9.34	35.17	1.97	39.42	9.26	22.63%	18.33%				
13	HS6X-3	9.44	35.23	1.97	39.31	9.24	22.49%	18.56%				
14	HS6X-4	10.93	35.24	1.97	39.44	9.58	22.47%	18.29%				
15	HS6X-5	9.81	35.18	1.98	39.6	9.68	22.60%	17.96%				
16	RX82-1	9.13	33.37	1.87	37.44	8.75	24.05%	17.46%	25.64%	18.66%	32.67	36.89
17	RX82-2	9.27	31.96	1.81	36.1	10.32	27.26%	20.41%				
18	RX82-3	10.38	32.61	1.86	37.13	9.83	25.78%	18.14%				
19	RX82-4	9.67	32.32	1.82	36.36	9.02	26.44%	19.84%				
20	RX82-5	9.84	33.1	1.87	37.43	9.33	24.66%	17.48%				

390 for 32 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.46	34.79	1.9	38.07	10.37	14.87%	15.27%	17.33%	17.08%	33.78	37.26
2	6061-2	8.53	34.49	1.88	37.59	8.35	15.60%	16.34%				
3	6061-3	10.11	33.23	1.84	36.8	9.24	18.69%	18.09%				
4	6061-4	9.69	33.54	1.85	37.06	8.77	17.93%	17.52%				
5	6061-5	9.37	32.87	1.84	36.77	9.36	19.57%	18.16%				
6	6063-1	9.89	22.87	1.37	27.46	11.83	30.27%	26.27%	30.14%	25.96%	22.91	27.58
7	6063-2	9.07	23.3	1.4	27.92	18.39	28.95%	25.03%				
8	6063-3	9.31	22.51	1.36	27.2	12.97	31.36%	26.97%				
9	6063-4	9.01	23.45	1.4	28.08	12.92	28.50%	24.61%				
10	6063-5	9.96	22.43	1.36	27.22	12.16	31.61%	26.91%				
11	HS6X-1	9.6	34.21	1.94	38.7	10.37	24.74%	19.83%	24.44%	19.51%	34.34	38.85
12	HS6X-2	9.32	36	2.02	40.41	9.03	20.80%	16.28%				
13	HS6X-3	9.93	33.71	1.91	38.29	8.86	25.84%	20.68%				
14	HS6X-4	9.43	34.09	1.93	38.58	9.72	25.00%	20.07%				
15	HS6X-5	10.54	33.71	1.91	38.28	9.2	25.84%	20.70%				
16	RX82-1	9.41	31.56	1.82	36.47	9.83	28.17%	19.60%	28.55%	20.57%	31.39	36.03
17	RX82-2	11.91	31.55	1.82	36.35	9.38	28.19%	19.86%				
18	RX82-3	9.68	31.02	1.77	35.45	9.16	29.40%	21.84%				
19	RX82-4	10.63	32.34	1.84	36.87	9.23	26.39%	18.71%				
20	RX82-5	8.78	30.5	1.75	34.99	9.59	30.58%	22.86%				

390 for 64 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.63	31.59	1.78	35.69	9.45	22.70%	20.57%	22.32%	20.07%	31.75	35.91
2	6061-2	9.98	31.43	1.79	35.85	8.62	23.09%	20.21%				
3	6061-3	9.33	31.33	1.78	35.51	8.69	23.33%	20.97%				
4	6061-4	10.18	32.2	1.82	36.33	9.4	21.21%	19.14%				
5	6061-5	9.22	32.18	1.81	36.19	9.07	21.25%	19.45%				
6	6063-1	8.68	21.01	1.31	26.26	12.21	35.94%	29.49%	34.60%	28.54%	21.45	26.61
7	6063-2	9.76	21.41	1.33	26.65	13.55	34.72%	28.44%				
8	6063-3	9.67	21.53	1.33	26.5	13.16	34.35%	28.85%				
9	6063-4	10.41	21.65	1.33	26.69	12.57	33.99%	28.34%				
10	6063-5	9.29	21.65	1.35	26.97	13.15	33.99%	27.59%				
11	HS6X-1	9.98	34.46	1.95	39.02	8.79	24.19%	19.16%	24.81%	19.38%	34.18	38.92
12	HS6X-2	8.93	34.47	1.96	39.24	8.94	24.17%	18.71%				
13	HS6X-3	9.62	33.87	1.94	38.77	8.89	25.49%	19.68%				
14	HS6X-4	9.81	33.63	1.92	38.38	8.85	26.01%	20.49%				
15	HS6X-5	9.64	34.45	1.96	39.17	9.37	24.21%	18.85%				
16	RX82-1	9.96	30.12	1.78	35.55	9.26	31.45%	21.62%	31.35%	21.60%	30.16	35.56
17	RX82-2	9.24	30.41	1.79	35.71	9.3	30.79%	21.27%				
18	RX82-3	10.15	29.39	1.75	35	10.48	33.11%	22.84%				
19	RX82-4	10.32	30.72	1.8	35.99	11.82	30.08%	20.65%				
20	RX82-5	NA	NA	NA	NA	NA						

350 for 2 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	8.93	28.4	1.69	33.79	9.4	30.50%	24.79%	29.35%	24.20%	28.87	34.06
2	6061-2	8.75	28.66	1.7	33.91	8.99	29.87%	24.53%				
3	6061-3	9.43	28.69	1.7	33.91	10.04	29.79%	24.53%				
4	6061-4	10.09	28.96	1.7	34.1	9.58	29.13%	24.10%				
5	6061-5	9.75	29.65	1.73	34.58	9.27	27.45%	23.04%				
6	6063-1	9.55	18.88	1.24	24.79	11.35	42.43%	33.44%	42.74%	33.85%	18.78	24.64
7	6063-2	9.14	18.87	1.24	24.86	13.26	42.46%	33.25%				
8	6063-3	8.59	18.59	1.22	24.37	13.66	43.32%	34.57%				
9	6063-4	9.04	18.86	1.23	24.67	11.72	42.49%	33.76%				
10	6063-5	9.24	18.7	1.22	24.49	12.9	42.98%	34.24%				
11	HS6X-1	9.77	31.16	1.83	36.56	9.82	31.45%	24.26%	31.87%	24.00%	30.97	36.69
12	HS6X-2	10.23	31.48	1.87	37.39	8.95	30.74%	22.54%				
13	HS6X-3	9.49	31.67	1.86	37.22	9.12	30.33%	22.89%				
14	HS6X-4	9.57	31.06	1.85	37	9.1	31.67%	23.35%				
15	HS6X-5	10.24	29.47	1.76	35.26	9.45	35.17%	26.95%				
16	RX82-1	9.77	26.78	1.66	33.19	10.64	39.05%	26.83%	36.82%	25.50%	27.76	33.79
17	RX82-2	9.66	28.3	1.71	34.27	9.23	35.59%	24.45%				
18	RX82-3	10.39	28.27	1.71	34.26	10.05	35.66%	24.47%				
19	RX82-4	9.59	27.05	1.65	32.97	9.71	38.43%	27.31%				
20	RX82-5	10.68	28.39	1.71	34.27	9.68	35.38%	24.45%				

350 for 2 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	8.98	41.55	2.28	45.58	12.27	-1.67%	-1.45%	-2.37%	-0.54%	41.83	45.17
2	6061-2	8.99	40.73	2.27	44.56	12.66	0.33%	0.82%				
3	6061-3	9.5	42.16	2.26	45.24	11.31	-3.17%	-0.69%				
4	6061-4	9.95	42.71	2.28	45.57	11.15	-4.51%	-1.42%				
5	6061-5	9.02	42.02	2.25	44.91	11.06	-2.82%	0.04%				
6	6063-1	9.45	33.29	1.88	37.59	13.11	-1.51%	-0.93%	-1.32%	-0.11%	33.23	37.28
7	6063-2	8.17	32.33	1.86	36.52	13.29	1.42%	1.94%				
8	6063-3	9.47	33.18	1.86	37.11	12.05	-1.17%	0.36%				
9	6063-4	9.1	33.87	1.89	37.83	11.9	-3.27%	-1.57%				
10	6063-5	9.18	33.47	1.87	37.37	12.17	-2.06%	-0.34%				
11	HS6X-1	10.18	48.74	2.55	51.03	10.39	-7.23%	-5.72%	-6.41%	-4.22%	48.37	50.31
12	HS6X-2	9.22	48.37	2.53	50.51	9.28	-6.41%	-4.64%				
13	HS6X-3	10.1	48.63	2.53	50.52	9.01	-6.98%	-4.66%				
14	HS6X-4	9.78	48.03	2.49	49.7	8.28	-5.66%	-2.96%				
15	HS6X-5	9.88	48.07	2.49	49.78	10.51	-5.75%	-3.13%				
16	RX82-1	9.84	44.88	2.31	46.19	9.3	-2.15%	-1.83%	-3.37%	-2.69%	45.42	46.58
17	RX82-2	10.45	46.55	2.39	47.83	8.68	-5.95%	-5.45%				
18	RX82-3	9.43	44.26	2.26	45.14	7.75	-0.74%	0.48%				
19	RX82-4	10.18	46.13	2.34	46.77	6.07	-4.99%	-3.11%				
20	RX82-5	9.71	45.27	2.35	46.95	9.97	-3.04%	-3.51%				

350 for 4 Hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.07	42.93	2.27	45.43	11.33	-5.05%	-1.11%	-4.86%	-1.20%	42.85	45.47
2	6061-2	9.19	42.56	2.27	45.49	11.37	-4.15%	-1.25%				
3	6061-3	10.47	42.61	2.25	45.08	11.27	-4.27%	-0.33%				
4	6061-4	9.24	42.66	2.26	45.19	10.59	-4.39%	-0.58%				
5	6061-5	9.59	43.51	2.31	46.16	10.99	-6.47%	-2.74%				
6	6063-1	8.47	34.23	1.89	37.84	11.84	-4.37%	-1.60%	-4.44%	-1.81%	34.25	37.92
7	6063-2	8.71	34.08	1.88	37.53	11.74	-3.92%	-0.77%				
8	6063-3	9.31	34.36	1.9	38.09	12.02	-4.77%	-2.27%				
9	6063-4	9.36	34.29	1.9	37.97	11.43	-4.56%	-1.95%				
10	6063-5	9.76	34.3	1.91	38.16	11.42	-4.59%	-2.46%				
11	HS6X-1	9.43	48.39	2.5	50.06	8.1	-6.46%	-3.71%	-6.84%	-3.80%	48.56	50.11
12	HS6X-2	9.12	48.05	2.47	49.39	6.9	-5.71%	-2.32%				
13	HS6X-3	8.85	48.38	2.49	49.75	8.75	-6.43%	-3.07%				
14	HS6X-4	10.22	48.99	2.53	50.59	9.43	-7.78%	-4.81%				
15	HS6X-5	9.93	49.01	2.54	50.74	9.3	-7.82%	-5.12%				
16	RX82-1	11.05	46.25	2.35	47.03	6.33	-5.27%	-3.69%	-3.79%	-2.26%	45.60	46.38
17	RX82-2	10.15	45.86	2.33	46.58	6.8	-4.38%	-2.69%				
18	RX82-3	9.72	46.88	2.37	47.43	4.42	-6.70%	-4.57%				
19	RX82-4	9.6	44.52	2.29	45.78	8.39	-1.33%	-0.93%				
20	RX82-5	9.73	44.5	2.26	45.1	6.51	-1.28%	0.57%				

350 for 8 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	8.95	43.49	2.26	45.18	9.64	-6.42%	-0.56%	-6.88%	-1.10%	43.68	45.43
2	6061-2	9.4	44.07	2.29	45.89	9.9	-7.84%	-2.14%				
3	6061-3	9.95	44.34	2.3	46.05	8.3	-8.50%	-2.49%				
4	6061-4	9.72	43.11	2.24	44.82	9	-5.49%	0.24%				
5	6061-5	9.06	43.37	2.26	45.19	9.46	-6.13%	-0.58%				
6	6063-1	9.02	34.44	1.88	37.52	10.87	-5.01%	-0.74%	-5.01%	-0.76%	34.44	37.53
7	6063-2	8.79	34.25	1.87	37.34	11.05	-4.43%	-0.26%				
8	6063-3	9.15	34.33	1.87	37.44	11.07	-4.68%	-0.53%				
9	6063-4	8.8	34.28	1.87	37.35	11.39	-4.52%	-0.28%				
10	6063-5	9.45	34.89	1.9	37.99	10.73	-6.38%	-2.00%				
11	HS6X-1	9.2	48.62	2.5	49.94	7.61	-6.96%	-3.46%	-4.33%	-0.99%	47.42	48.75
12	HS6X-2	9.85	46.71	2.41	48.19	9.13	-2.76%	0.17%				
13	HS6X-3	9.02	47.16	2.43	48.51	8.62	-3.75%	-0.50%				
14	HS6X-4	9	47.1	2.42	48.35	8.16	-3.62%	-0.17%				
15	HS6X-5	9.6	47.53	2.44	48.76	9.78	-4.56%	-1.02%				
16	RX82-1	10.4	45.63	2.32	46.48	8	-3.86%	-2.47%	-2.61%	-1.79%	45.08	46.17
17	RX82-2	9.9	45.21	2.31	46.26	8.04	-2.90%	-1.99%				
18	RX82-3	10.16	44.18	2.29	45.76	8.97	-0.56%	-0.89%				
19	RX82-4	10.6	44.62	2.29	45.84	8.17	-1.56%	-1.06%				
20	RX82-5	9.62	45.77	2.33	46.52	7.5	-4.17%	-2.56%				

350 for 16 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.83	44.09	2.29	45.8	9.44	-7.89%	-1.94%	-7.96%	-1.90%	44.12	45.78
2	6061-2	9.57	43.92	2.28	45.68	10.18	-7.47%	-1.67%				
3	6061-3	9.22	43.85	2.28	45.51	8.99	-7.30%	-1.29%				
4	6061-4	10.1	44.39	2.3	45.99	9.32	-8.62%	-2.36%				
5	6061-5	8.82	44.34	2.3	45.93	9.57	-8.50%	-2.23%				
6	6063-1	9.51	35.32	1.92	38.35	10.35	-7.70%	-2.97%	-7.04%	-2.48%	35.11	38.17
7	6063-2	9.27	35.15	1.91	38.22	10.71	-7.18%	-2.62%				
8	6063-3	9.65	35.2	1.92	38.35	10.93	-7.33%	-2.97%				
9	6063-4	9.41	35.44	1.93	38.51	10.74	-8.06%	-3.40%				
10	6063-5	9.24	34.42	1.87	37.4	10.99	-4.95%	-0.42%				
11	HS6X-1	8.98	47.48	2.44	48.8	9.02	-4.45%	-1.10%	-5.29%	-1.91%	47.86	49.19
12	HS6X-2	10.27	48.17	2.47	49.43	6.89	-5.97%	-2.40%				
13	HS6X-3	10.22	48.02	2.47	49.46	8.78	-5.64%	-2.47%				
14	HS6X-4	9.94	48.45	2.49	49.77	7.26	-6.59%	-3.11%				
15	HS6X-5	9.61	47.18	2.43	48.51	8.69	-3.79%	-0.50%				
16	RX82-1	10.22	44.77	2.3	45.98	8.16	-1.90%	-1.37%	-0.96%	-0.04%	44.36	45.38
17	RX82-2	10.32	44.32	2.27	45.47	7.2	-0.87%	-0.25%				
18	RX82-3	10.01	43.28	2.21	44.22	4.9	1.49%	2.51%				
19	RX82-4	9.47	44.09	2.24	44.78	6.71	-0.35%	1.27%				
20	RX82-5	10.66	45.33	2.32	46.44	8.08	-3.17%	-2.39%				

350 for 32 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.25	42.34	2.19	43.79	9.11	-3.61%	2.54%	-3.52%	2.42%	42.30	43.84
2	6061-2	9.82	42.14	2.19	43.89	8.24	-3.12%	2.31%				
3	6061-3	9.41	42.28	2.19	43.79	8.66	-3.46%	2.54%				
4	6061-4	9.43	42.46	2.2	43.92	8.79	-3.90%	2.25%				
5	6061-5	9.47	42.3	2.19	43.83	8.92	-3.51%	2.45%				
6	6063-1	9.19	33.39	1.82	36.45	9.95	-1.81%	2.13%	-2.96%	1.40%	33.77	36.72
7	6063-2	8.85	33.6	1.82	36.47	9.65	-2.45%	2.08%				
8	6063-3	8.96	34.37	1.87	37.32	10.35	-4.80%	-0.20%				
9	6063-4	9.51	34.77	1.88	37.7	10.04	-6.02%	-1.22%				
10	6063-5	9.98	32.71	1.78	35.68	10.38	0.26%	4.20%				
11	HS6X-1	9.51	47.2	2.44	48.7	7.49	-3.84%	-0.89%	0.58%	2.55%	45.19	47.04
12	HS6X-2	9.71	43.01	2.26	45.27	7.82	5.38%	6.22%				
13	HS6X-3	9.31	45.97	2.38	47.69	8.67	-1.13%	1.20%				
14	HS6X-4	9.82	44.21	2.31	46.1	7.16	2.74%	4.50%				
15	HS6X-5	10.3	45.56	2.37	47.43	7.9	-0.23%	1.74%				
16	RX82-1	9.37	41.46	2.14	42.88	7.94	5.64%	5.46%	9.28%	7.73%	39.86	41.85
17	RX82-2	9.84	38.56	2.04	40.83	8.06	12.24%	9.98%				
18	RX82-3	10.53	40.42	2.11	42.29	7.34	8.00%	6.76%				
19	RX82-4	9.75	39.22	2.07	41.46	8.11	10.73%	8.59%				
20	RX82-5	9.75	39.64	2.09	41.79	7.17	9.78%	7.87%				

350 for 64 hours

Sample #	Test Specimen	Modulus (E-modulus) (Mpsi)	Yield Stress (Offset 0.2 %) (ksi)	Maximum Load (kip)	Tensile stress at Maximum Load (ksi)	Tensile strain at Break (Standard) (%)	% Difference from average Yield Stress	% Difference from average Tensile Stress	Average % Difference from average Yield Stress	Average % Difference from average Tensile Stress	Average Yield Stress	Average Tensile Stress
1	6061-1	9.45	42.71	2.2	44.09	9.23	-4.51%	1.87%	-1.77%	3.87%	41.59	43.19
2	6061-2	9.13	41.36	2.16	43.12	8.53	-1.21%	4.03%				
3	6061-3	9.12	41.18	2.14	42.83	8.99	-0.77%	4.67%				
4	6061-4	8.99	41.43	2.15	42.97	8.74	-1.38%	4.36%				
5	6061-5	9.2	41.26	2.15	42.95	9.12	-0.96%	4.41%				
6	6063-1	9.09	31.39	1.73	34.57	9.75	4.29%	7.18%	3.24%	6.55%	31.73	34.80
7	6063-2	9.23	31.29	1.71	34.18	9.6	4.59%	8.23%				
8	6063-3	8.87	32.26	1.77	35.38	10.21	1.63%	5.00%				
9	6063-4	8.62	32.21	1.76	35.23	10.27	1.79%	5.41%				
10	6063-5	8.75	31.52	1.73	34.66	10.22	3.89%	6.94%				
11	HS6X-1	8.89	43.13	2.26	45.2	7.28	5.11%	6.36%	6.19%	6.78%	42.64	45.00
12	HS6X-2	9.05	45.15	2.35	47.08	8.09	0.67%	2.47%				
13	HS6X-3	9.84	41.09	2.19	43.83	8.29	9.60%	9.20%				
14	HS6X-4	9.1	42.14	2.22	44.47	7.81	7.29%	7.87%				
15	HS6X-5	9.93	41.69	2.22	44.4	8.73	8.28%	8.02%				
16	RX82-1	9.91	37.4	2.02	40.32	8.59	14.88%	11.11%	12.88%	9.88%	38.28	40.88
17	RX82-2	9.77	37.08	1.99	39.78	8.37	15.60%	12.30%				
18	RX82-3	10.22	38.81	2.05	41.08	8.37	11.67%	9.43%				
19	RX82-4	9.73	39.61	2.09	41.88	7.15	9.85%	7.67%				
20	RX82-5	10.17	38.49	2.07	41.33	8.68	12.40%	8.88%				