ANALYSIS OF COMPRESSION CREEP DEFORMATION OF 7050 ALUMINUM LARGE SCALE OPEN DIE FORGINGS DURING THE SOLUTION HEAT TREATMENT PROCESS

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by

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Abstract

A stress, ranging from 104.17 to 166.67 psi, was applied to 0.5 in diameter cylindrical samples of 7050 aluminum using a manufactured fixture that applies stress using an indenter with a diameter of 0.127 in. The stress range used replicates the stresses produced on large scale forgings weighing up to 4000 lbs. We chose a maximum, medium and low stress as our stress parameters. The samples were placed into the fixture for stability then placed in a furnace heated to 890°F which is the solution heat treatment temperature for 7050 aluminum. The heat treatment times varied between 4 and 24 hours. The creep deformation produced from the different parameters of time and stress was analyzed using a profilometer. The amount of deformation for each sample was in the range of 0.001 to 0.007 in. These results coincide with the large scale with a difference of about 1896 to 1. The amount of deformation and time was plotted to generate creep curves for the various stresses produced. The creep curves can then be used to develop the conditions when the large scale forgings would experience creep deformation and therefore be able to prevent the deformation in the future.

Keywords: Compression Creep Deformation, Precipitation Strengthening, Open Die Forging, 7050 Aluminum, Aluminum Alloy, Solution Heat Treatment, Profilometer, Manufacturing, Materials Engineering.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background

1.1.1 Weber Metals, Inc

Weber Metals, Inc was founded in 1945 by Edmond L. Weber in Paramount, CA. Weber served the needs of the growing West Coast aerospace industry with major customers including Douglas Aircraft Company and The Boeing Company. Today, this customer base is still a significant source of Weber business. Weber is a full line aluminum and titanium forging supplier offering products for commercial aerospace, military aerospace, space programs, jet engine components, and electronics/semiconductor industry.[1] **Figure 1** shows an examples of creep deformation the occurs in open die forgings.

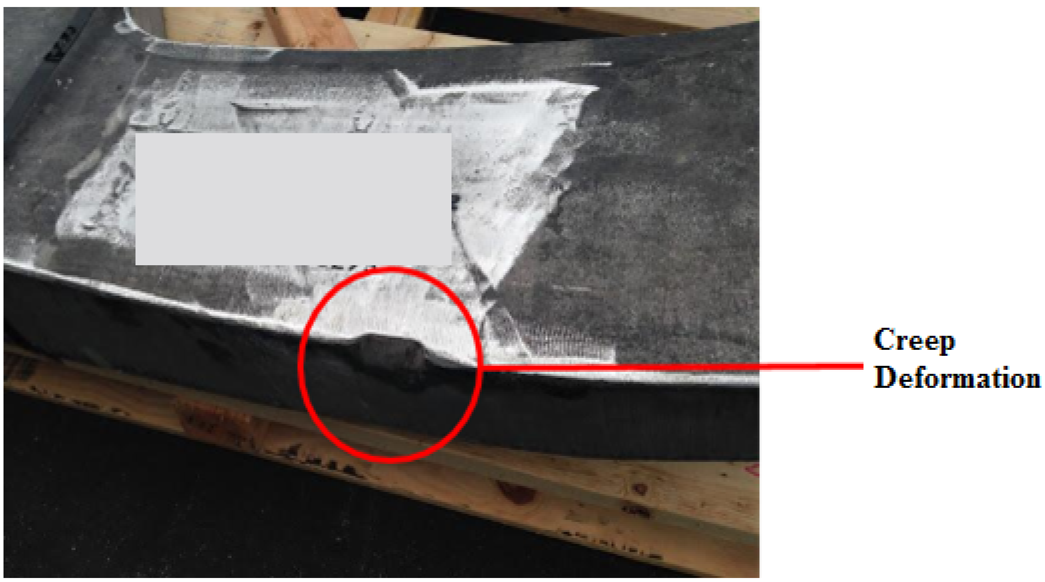

Figure 1-This image shows the area where the aluminum slabs are experiencing creep deformation. The result is an indentation caused during the solution heat treatment step.[2]

1.1.2 Problem Statement

Weber Metals produces large 7050 Al open die forgings (also known as hand forgings) that are solution heat treated on steel racking at temperatures around 890°F. During the solution heat treatment cycle, the forging rests on isolated points of contact and creep into the steel racks produces indentations in the forging. After solution heat treating and quenching, internal stresses are produced and therefore need to be stress relieved. Non-uniform stress relief is the result of

having these indentations in the forging. The non-uniform stress then requires more processing to achieve uniform stress throughout the forged material. The goal of our project is to determine if the creep deformation is linear by producing a creep curve of 7050 aluminum samples in compression. The parameters involved are time, temperature, the points of contact of the forging, and stress. The points of contact and temperature will be kept constant while the time and stress applied will vary. Our project will give Weber Metals the parameters to correlate how creep deformation can be prevented in these large forgings.

1.2 Aluminum Alloys

Alloying elements are added to aluminum to increase its strength and various other properties. There are two categories of aluminum alloys; non-heat-treatable and heat-treatable. Within those categories there are cast and wrought aluminum alloys. Our project involves heat-treatable wrought alloys of the 7xxx series.

1.2.1 Heat-Treatable Aluminum Alloys

Aluminum alloys can benefit from age hardening (precipitation hardening) if they have the right alloying elements that allow for extra strengthening, **Figure 2** shows the primary alloying elements of aluminum.

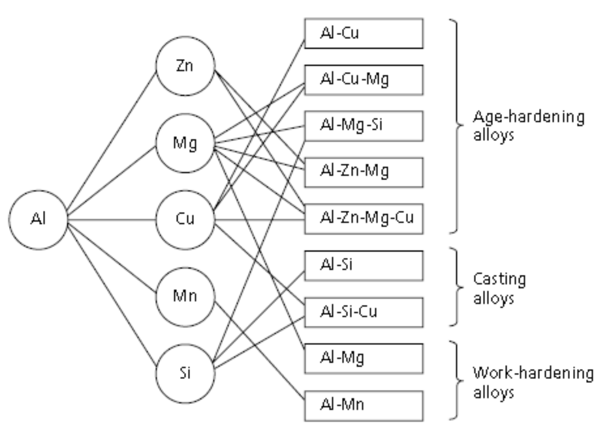

Figure 2-The primary alloying elements of aluminum are zinc, magnesium, copper, manganese, and silicon.[3]

Manganese is used because it greatly increases the strength of aluminum. Silicon decreases the melting point and increases the fluidity and strength of aluminum. Copper is alloyed which

increases the solubility and strengthening of age hardening. Magnesium and when combined with other alloying elements greatly increases the overall strength of aluminum when alloyed. Alloying with zinc substantially increases the strength of pure aluminum.[4]

7xxx Series

The 7xxx series samples we will be testing are 7050 aluminum. 7xxx series aluminum has superior strength that also comes from precipitation hardening. The main alloying elements are zinc (range of 4-6 wt%) and magnesium (range of 1-3 wt%). Zinc and magnesium control the aging process by maximizing the age-hardening potential where the precipitating phases are typically $MgZn_2$.[5]

1.2.2 Temper Designations

The temper designations of an alloy indicate how the alloy was heat-treated or aged. The temper designation for 7050 Al is T74. This indicates that the alloy is solution heat-treated and artificially aged to achieve high strength, stress corrosion, and exfoliation corrosion resistance.[6]

1.2.3 Aluminum Alloy Applications

The 7xxx series is important for applications requiring high strength such as aerospace, space exploration, military and nuclear applications. It is also used for structural parts in building applications as well as high strength sports' attributes (ski poles, tennis rackets).[5]

1.3 Forging

Forging is in the metalworking process classification of bulk, or massive, forming operations. Distinguishing features of the bulk-forming category include a deforming material which undergoes large plastic deformation, resulting in an appreciable change in shape or cross section; and the portion of the work piece undergoing plastic deformation is generally much larger than the portion undergoing elastic deformation; therefore, elastic recovery after deformation is negligible.[7]

Forging allows for the formation of complex shapes with superior mechanical properties. Wrought alloys are initially cast as ingots or billets and cold worked mechanically into the

desired form in preparation to be forged and it is important to prepare the forgings by preheating them. **Figure 3** shows an example of the forging process and the material shown is titanium.[8]

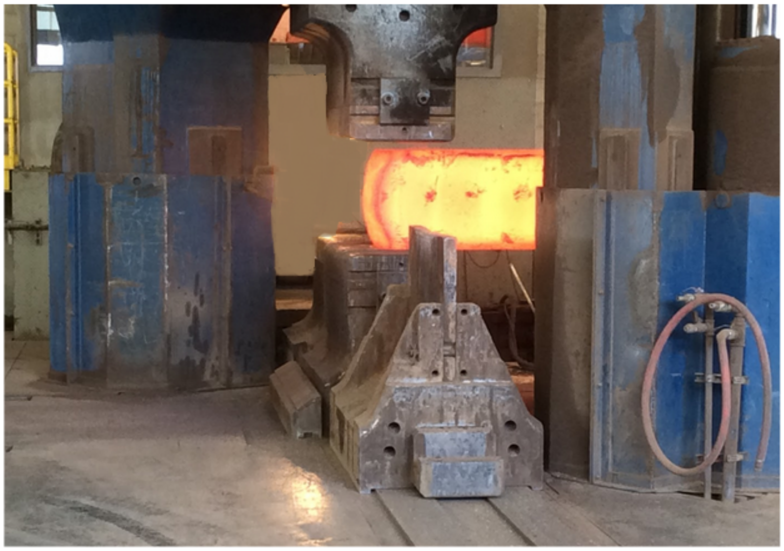

Figure 3- An open-die press with a titanium forging located at Weber Metals in Paramount, CA.[9]

1.3.1 Forging of Aluminum Alloys

There are different methods in which aluminum alloys can be forged such as open-die and closed-die forging, **Figure 4**. Open die forging is ideal when working with large parts. Open-die presses have room to allow for movement of large parts and the ability to deform them into plates and simple shapes.[7]

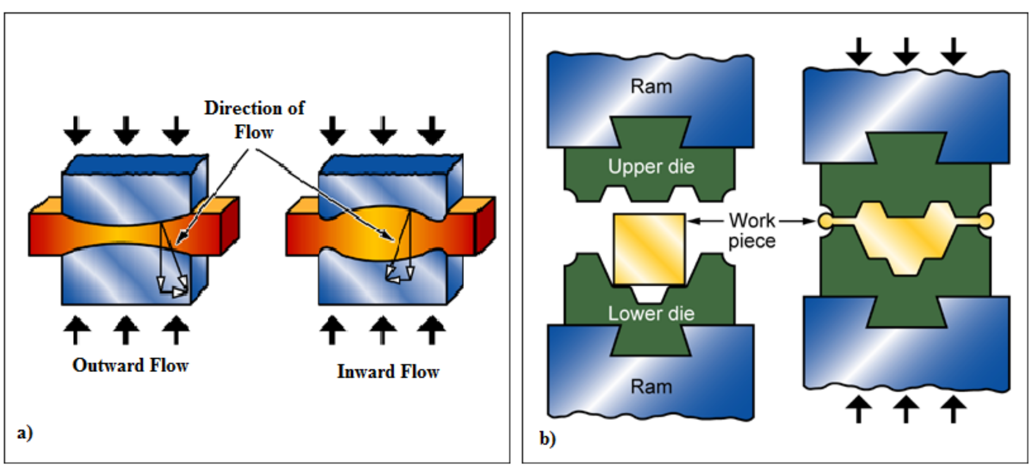

Figure 4-Figure a) is a schematic of open die forging and Figure b) shows a schematic of a work-piece being formed by closed-die forging.[10]

Aluminum alloy forgings produced in closed-die forgings, are usually produced to more highly refined final forging configurations than hot-forged carbon or alloy steels. The pressure requirements in forging depend primarily on the chemical composition of the alloy being forged, the forging process being employed, the forging strain rate, the type of forging being manufactured, the lubrication conditions, and the forging and die temperature. Flow stress represents the low limit of forging pressure requirements, however, actual forging pressures are usually higher.[11]

1.3.2 Strengthening Mechanisms

Once a part has been forged, it is solution heat treated, quenched, and aged in order to increase the strength of the aluminum alloy. The largest amount of strength achieved from forging comes from the age hardening of the material. The intermetallic phases grow from prolonged exposure to heat and they act as barriers to the movement of dislocations therefore increasing its strength. The ability of these phases to block dislocation movement depends on their size and dispersion within the matrix. It is considered a precipitation strengthening process because precipitates grow from the solid solution.[12]

1.4 Precipitation Hardening Treatment Process

The heat treatment of aluminum involves three steps: solution heat-treat, quench, and aging. This process is used to increase the strength of aluminum by the formation of precipitates that block the movement of dislocations.

1.4.1 Solution Heat-Treating

The heat-treatment involves heating the alloy to a high temperature for a specified amount of time to achieve a solid solution. This softening mechanism is used to bring solute additions trapped in second phases back into solid solution in preparation for aging.[3] It is essential to use a phase diagram to determine the phases that will be present and the correct temperature to produce the phases. **Figure 5** shows the aluminum magnesium phase diagram. This phase diagram can be used for 7050 aluminum alloys because magnesium is a main alloying element.

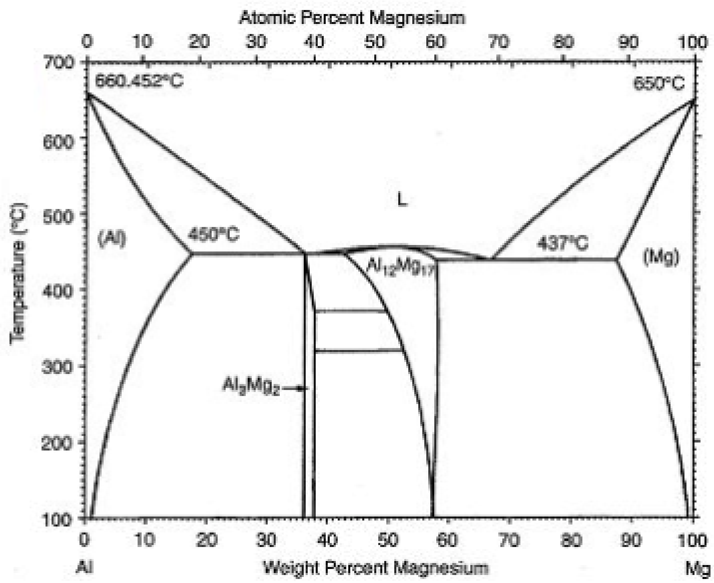

Figure 5-Al-Mg phase diagram showing the intermetallic phases that form precipitates during the aging process in order to strengthen the material.[13]

The solution heat treat temperature and time depends on the alloying elements as well as the thickness of the material. Aluminum alloy 7050 is typically solution heat treated for minimum 4 hours 890°F.

1.4.2 Quenching

Quenching is where the metal is taken directly from the furnace and immediately placed in a quenching medium. The medium can range from oil, polymer or water and can vary in temperature. Stresses can be introduced internally from being quenched in a colder quenching medium because of differential thermal expansion. When solution heat-treating, it is necessary to immediately quench the metal so that the atoms stay in place and do not have enough time to diffuse out of solution which would occur if it were slow cooled.[8] Aqueous solutions of polymer quenchants are now being used and they achieve the slow quench rates of oil quenchants. Polymer quenchants tend to be more sensitive to agitation than are mineral oils. Increasing the agitation increases the cooling rate and reduces the polymer film thickness. However, decreasing the agitation can produce non-uniform film thickness. Also, the effective quench rate of the polymer solutions is affected by temperature.[14]

1.4.3 Aging Treatment

There are two ways to age aluminum: natural aging and artificial aging. Natural aging is where the alloy is aged at room temperature which generally takes a long time. Artificial aging is a quicker process because the aluminum alloy is aged at higher temperatures. The hardening of aluminum is determined by Guinier-Preston (GP) zones and the rate of formation of these zones is rapid in the beginning of the aging process but the rate decreases with time. At higher temperatures the GP zones form faster and reach the maximum amount more quickly. Temperature and aging time can greatly affect the yield strength of the alloy. The alloy will reach the maximum yield strength at the proper aging time and then start to decrease in strength after that time. This is known as overaging.[3]

1.5 Creep Deformation

Creep is an inelastic deformation that occurs continuously and slowly over time when structure is loaded to a stress below its yield stress under a temperature higher than about 30% of its melting temperature. The amount of creep deformation that occurs is highly dependent on the time and heat treatment temperature the material experiences.[15] Creep deformation is a time dependent, temperature accelerated plastic deformation.

1.5.1 Creep Testing

To test creep, a load is applied to a material that is kept at a constant temperature. The amount the material plastically deforms and the specific time it deforms is measured. The measurements are plotted to produce a creep curve which shows the rate of creep in the material. The rate of creep is a strong function of the applied stress and temperature and the resistance to this form of deformation is of great importance when materials are used at elevated temperatures.[16]

1.5.2 Stages of Creep

There are three stages of creep: primary creep, secondary or steady state creep, and tertiary creep, **Figure 6**.

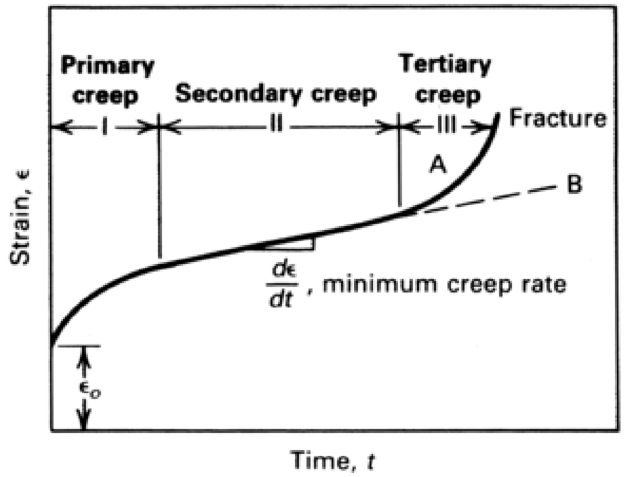

Figure 6- The three stages of creep with relationship to strain and time. Fracture occurs at the end of the third stage.[16]

Primary creep is the first portion of the creep process. Elastic strain increases rapidly in this portion as soon as the creep process begins. The most amount of plastic strain occurs in this stage. If the temperature is high enough this stage might not occur. Once the strain rate starts to decrease and become constant secondary creep begins. This is considered to be the "transition" stage where the creep reaches a minimum value. When the strain rate transitions from constant to exponentially increasing, tertiary creep begins. Voids can be introduced at the grain boundaries in this stage which leads to fracture.[16]

1.5.3 Atomic and Microstructural Changes

Creep induces the formation of dislocations in the microstructure of the material. This can lead to work hardening from a high dislocation density which block the movement of even more dislocations. If creep is occurring at a high enough temperature then the dislocations have enough energy to move right through areas of high dislocation densities. This causes the material to recover over time. New phases precipitating, other phases growing or going back into solution, and grains growing can occur in the microstructure during creep.[16]

1.5.4 Creep Mechanisms

Atoms in solids vibrate at high frequencies (about 10^{13} s^{-1}) about their mean positions. Occasionally (about $1/10^6$ times), the amplitude of the vibration is large enough for the atom to move out of its current location and into a neighboring site. This process is called solid state diffusion. Diffusion is a thermally activated process. Thermal energy provides the necessary

activation energy required to overcome the potential energy barrier preventing atomic displacements. Therefore, solid state diffusion processes are enhanced significantly at high temperatures. Since atomic movements are directly related to microstructural reorganization processes it is then natural to expect the creep phenomena will be directly related to solid state diffusion phenomena, particularly, at the highest temperatures.[14]

If the temperature is relatively low, diffusion is somewhat less important and the creep deformation process at the atomic scale is most influenced by slip and glide phenomena characteristic of low temperature plastic deformation. Therefore, according to the prevailing temperature and stress in a creeping solid, various different microstructural mechanisms determine the observed creep behavior.[14]

1.5.5 Creep in Precipitation Hardened Alloys

In precipitation hardened alloys, the mechanism of creep is believed to consist of glide and diffusion assisted climb with the associated development of a dislocation substructure. Unlike pure aluminum where dislocation-dislocation interactions and the development of a dislocation substructure are significant, in precipitation hardened alloys the dislocation-precipitate interactions are of primary importance. The creep rate will be determined by the rate at which dislocations interact with and ultimately overcome obstacles provided by the precipitates.[16]

Commercial creep resistant aluminum alloys are always based on the Al-Cu system. While the solid state diffusivity of copper in aluminum is similar to the other standard alloying elements, it is the stable nature and fine distribution of the semi-coherent precipitates that can be formed that give rise to its selection. Microstructure stability is of paramount importance for long term application.[16]

1.6 Stress Relief

When metals are quenched in a medium after being heat-treated for a period of time, stresses are introduced internally. The outside of the metal is cooled significantly faster than the inside of the metal which produces internal or residual stresses due to differential thermal expansion. There are many other ways in which residual stresses can be introduced into a material. To relieve

these stresses there are a few viable options. Distortion can occur in the material during processing, such as machining, if not properly stress relieved.

1.6.1 Stress Relief by Slow Cooling

To remove the residual stresses an option is to place the metal in a furnace at a temperature that is lower than the critical temperature and hold it until the stresses have been relieved. Then the metal is removed to slowly cool to not introduce any more stresses. This can be similar to an annealing process which recrystallizes the material which removes some of the strength and increases the ductility. However, stress relief by thermal means is not used with aluminum alloys because it causes the coalescences of precipitates that should be formed during the aging process which overages the alloy.[17]

1.6.2 Stress Relief by Plastic Deformation

When a material has residual stresses a method of plastic deformation by mechanical means is used to relieve them. Plastic flow is induced by plastic deformation to rearrange the residual stresses in a beneficial way. The material is usually plastically deformed by stretching or cold-working. It has been shown that in some cases that 90% of the stresses can be relieved by plastic deformation of the material.[20] Most of the residual stresses are relieved after about 0.5% plastic deformation when the material is in either tension or compression.[19]

2. Experimental Procedure

2.1 Safety

During all testing procedures proper safety procedures were followed. Whenever cutting the samples, safety glasses, closed toed shoes, and long pants were worn while hair was pulled back. This procedure was also followed when using the lathe and operating the high temperature furnace. Safety was the number one concern during all the testing procedures.

2.2 Calculations

Calculations were performed to produce the range of stresses that the forgings experience. We were given a 2500-4000 lb range for the forgings at Weber Metals.

From this weight we calculated the stress for 2500, 3500, and 4000 lb forgings. For the area we used the average contact area of 4 in^2. This area is where the forgings are in contact with the steel rack they are placed on during the solution heat treatment step. Incorporated into this area is the amount of contact areas the rackings are touching the forging, which is on average 6 points of contact. **Table I** shows the calculated stresses at each forging weight.

Table I -Stress Calculation Results for Each Forging Weight

Weight (lbs)	Stress Produced (psi)
2500	104.2
3500	145.8
4000	166.7

2.3 Fixture Design

The scale of the sizing from the large hand forgings to our small scale testing is 1896:1. In order to reproduce the stresses shown in **Table I** we needed to design a fixture that would fit into a 6 in x 6 in furnace that would be able to concentrate the stress from the weight we applied. Our first design was a steel base with two guide posts and a platform that we would place weights on to distribute the load. The guideposts are in place to distribute the load evenly in the events that the weights are leaning to one side. The final design of our fixture used the same ideas with a couple of changes. A schematic is shown in **Figure 7**. Not pictured is a third guidepost at the back end of the fixture. We had initially planned on using circular guideposts but the final design used rectangular guideposts. An indenter is shown which was cylindrical and had a 0.127in diameter, and was used to concentrate the weights onto a small area, which would produce the large amount of stress that is required.

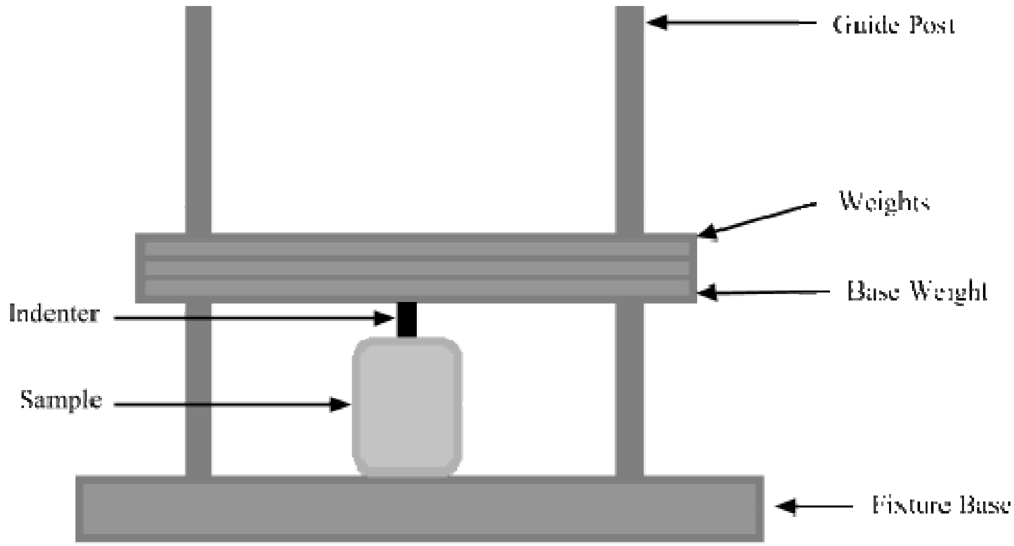

Figure 7-Schematic of the fixture designed for our testing.

Figure 8 shows the final design of the fixture used during testing. The fixture is made of steel.

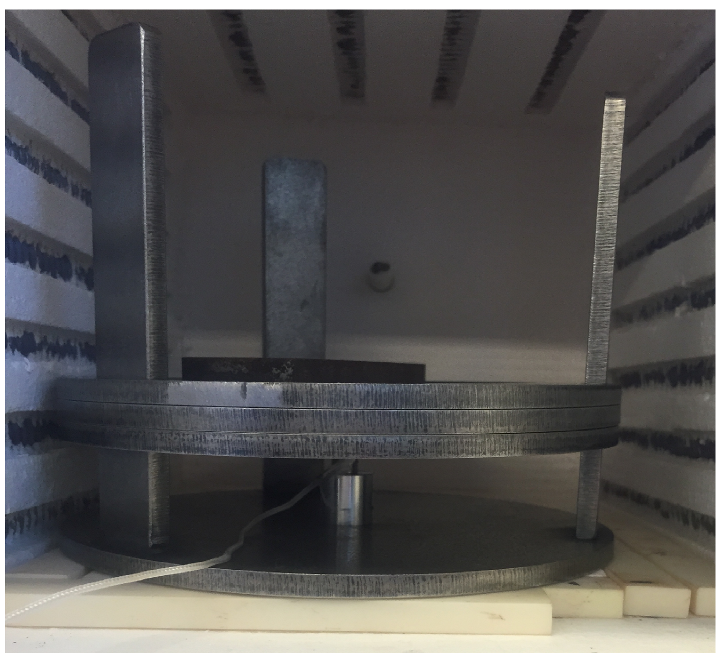

Figure 8- Final fixture design with the manufactured weights and sample in place.

Weights were manufactured to fit on the fixture snugly, were circular, and weighed about 0.9 lbs each. These weights fit on the guideposts, which allowed the weight to be balanced and evenly

distributed. However to produce more precise stresses, other weights were used in addition to the manufactured ones. These weights weighed approximately 0.3 lbs and were rectangular in shape. They were not secured to the fixture so it was important to place the weights directly in the middle which allowed everything to be somewhat balanced.

2.4 Sample Preparation

We received cylindrical tensile bars with a diameter of 0.5 in and a length of 6 in of 7050 aluminum cut from hand forgings for our tests. Using an abrasive saw we made 5 cuts from the gauge length of the tensile bars to get four samples at a rough height of 0.5 in. The samples were then faced on each side using a lathe to ensure that the sample was flat and had parallel faces. The edges of each sample were beveled and the samples were numbered and stored in a plastic bag until they were tested. Before testing, the surface that would be in contact with the indenter was ground using 600, 800 and 1200 abrasive grit paper. This step ensured that the surface finish was smooth from ridges caused from facing operations or any other imperfections.

2.5 Testing Parameters

Our test parameters include the three stresses shown in **Table I**. 1.32 lbs was placed on the fixture to produce the 104psi stress, 1.85 lbs was used for 145 psi, and 2.11 lbs was for 167 psi. With these weights and relating them to the large forgings is a scale of 1897:1. Each test was at the industry standard soak temperature of 890°F. The time varied from 4 hours, which is the minimum industry standard soak time, to 24 hours in order to get a range of creep deformation to develop creep curves. Each test for each parameter was tested twice in order to obtain statistically significant data.

2.6 Measuring the Data

The concentrated stress from the indenter onto the sample produced indentations with a certain depth. The indents measured would show the amount of creep deformation that should occur. The indents on our sample were on the micron scale. We had initially thought we could measure using a depth gauge but accuracy was not attainable using this method because the deformation was so small. We tested with the use of a profilometer to measure the depth of the indent on our samples in the Materials Engineering Department clean room. A profilometer scans the surface of our samples with a stylus that applies a slight load to be able to accurately measure the

topography on the micron scale. Due to its precise measurements we were able to accurately determine the maximum depth of the creep deformation that occurred. However, during multiple tests it was shown in the results that tilting had occurred.

3. Results

3.1 Profilometer Results

When measuring the depth of the indents with the profilometer we expected to see a shape similar to that of the indenter. We assumed that it would scan the surface then dip straight down and measure the flat indent and the go back to the surface of the sample. However, in some of the results tilting was shown, **Figure 9**.

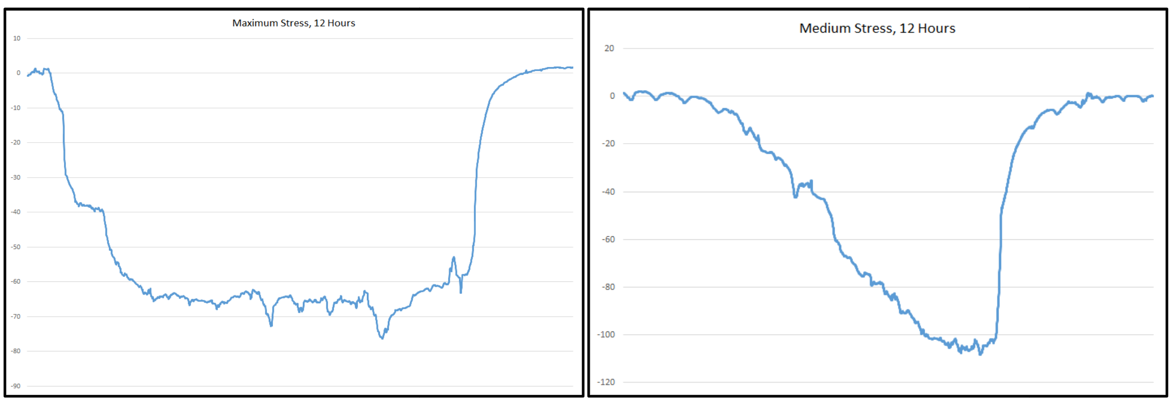

Figure 9- Two examples of the profilometer results. The left figure is of the maximum stress at 12 hours. The right figure is of the medium stress at 12 hours. The y- axis of both figures is indent depth (microns).

3.2 Low Stress Results

For all the stresses we would expect to see an increase in deformation with an increase in time and stress. **Figure 10** is a plot of the measured indent depth of the low stress samples and time. Each plot has two tests for each time parameter to produce statistically significant data. The two tests are shown adjacent to each other and the time is in increasing order from 4 to 24 hours. The blue dots represent the average and the line is the range of data from each sample. What we expected to see with the two tests of each test is averages of similar values. Many of our tests do not appear that way. For example, the difference between the two 20-hour low stress tests and the 24-hour low stress tests. The 24 hour data is close to what we expected. The 20-hour data shows a large variance between the two tests.

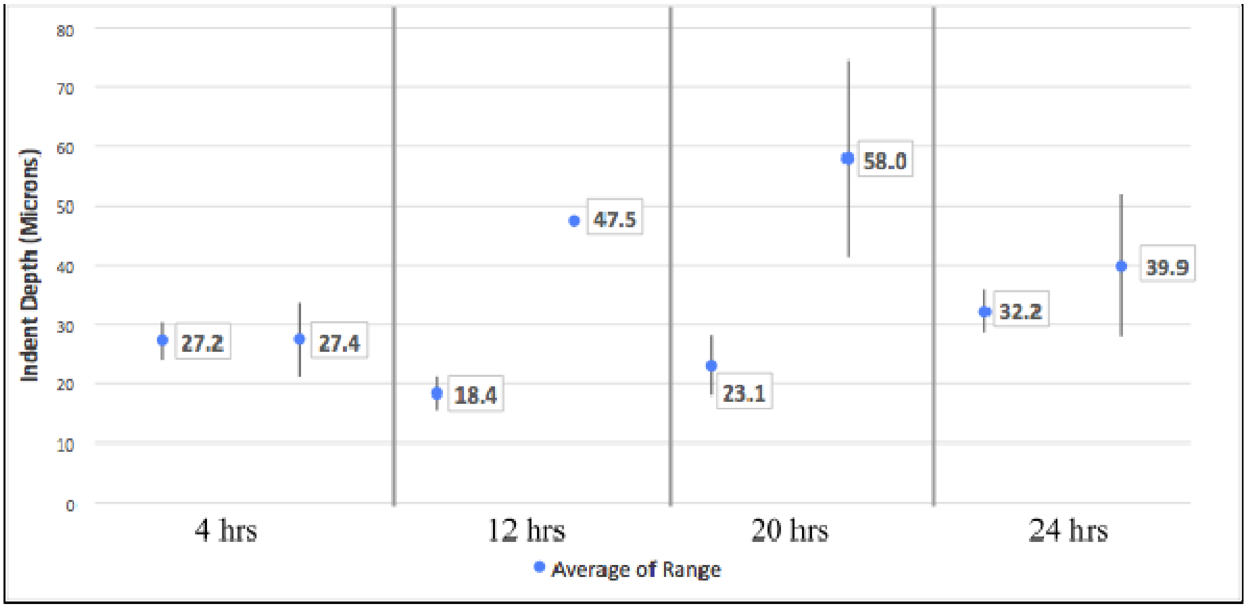

Figure 10- Plot of low stress samples over the time interval of 4 to 24 hours.

3.3 Medium Stress Results

Figure 11 is a plot for the medium stress samples at the varying times. The scaling from graph to graph is not one to one. The data points on the medium pairs seem close, however, the high range of deformation makes it seem as if they are closer than they really are.

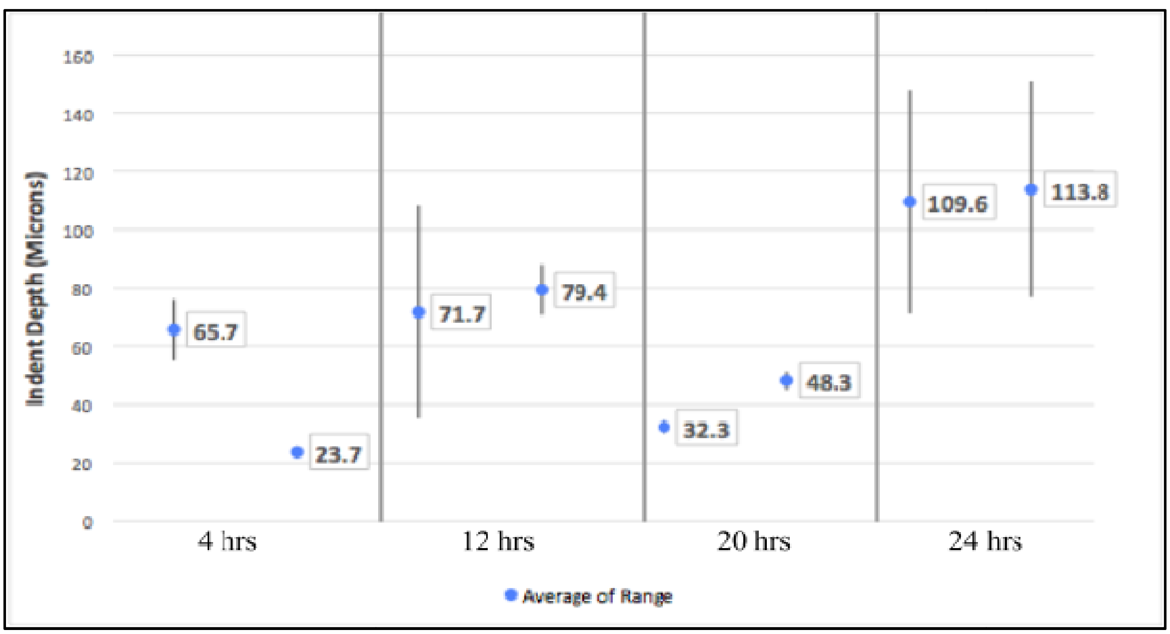

Figure 11- Plot of deformation depth over the time interval for medium stress applied.

3.4 Maximum Stress Results

The results of the maximum stress samples are shown in **Figure 12**. This plot shows a general increase in deformation with time as expected. It also has minimal variance in the range.

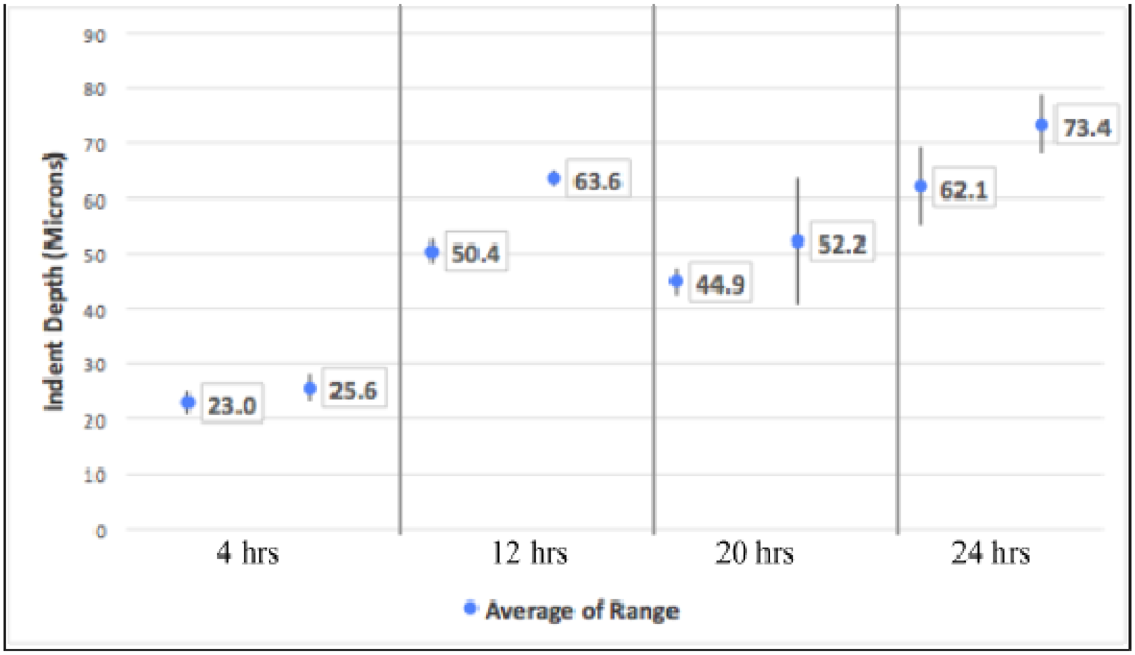

Figure 12- Results from maximum stress testing showing an increase in deformation with an increase in time.

3.5 Overall Results

To compare all of our data we took the averages of each range for each parameter. We plotted those averages for low, medium, and maximum stress shown in **Figure 13**.

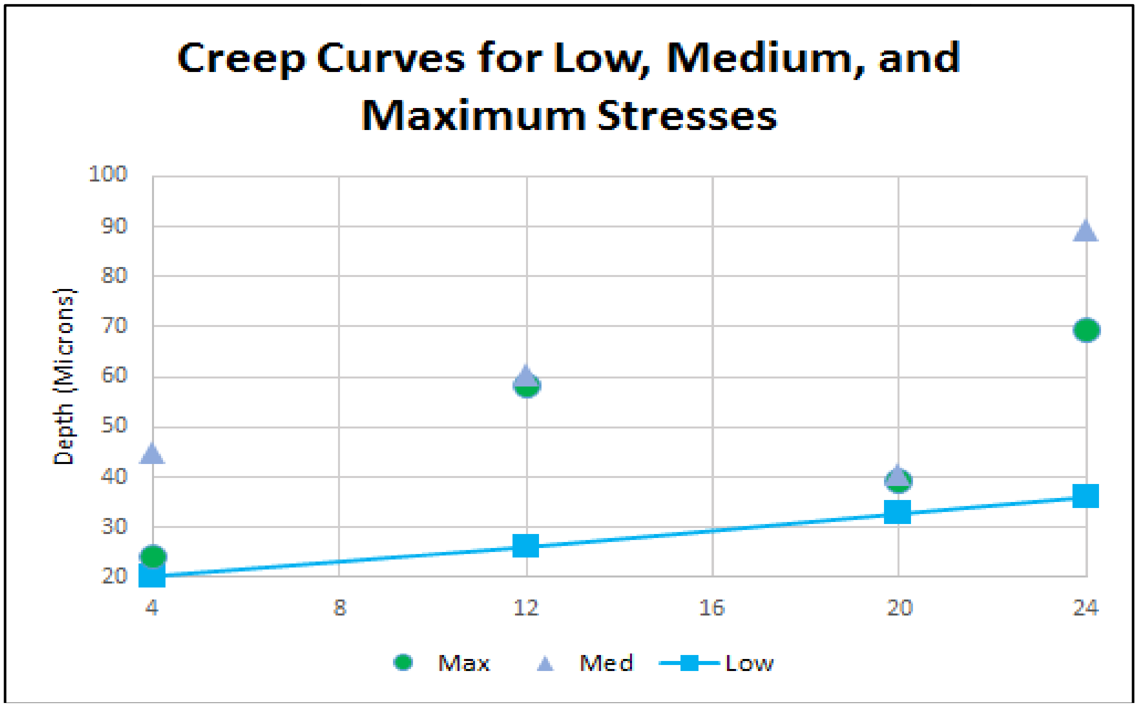

Figure 13-Average of deformation depth for low, medium, and maximum stress over time.

4. Discussion

Low Stress

The trend of the low stress samples shows that there is an increased amount of deformation with an increase in time. This is the correct trend that should be seen which is confirmed by the traditional creep curve in **Figure 6**. However, the trend is linear when compared to the traditional creep curve. This is possibly due to the fact that traditional creep curves are produced at lower temperatures such as that would be seen at application and the tests are performed in tension. All our tests were done at high solution heat treatment temperatures and were done in compression.

There were a few tests that had a small range in the amount of deformation produced. The weights used for the low stress testing setup allowed for the weights to be mostly balanced and evenly distributed. Overall, the fixture was fairly stable in this setup and it can be determined that this data is accurate.

The overall amount of deformation for the low stress was 20-36 microns which when brought to the large scale forgings is 1.47-2.65 in of deformation spread out between the 6 contact points.

Medium Stress

The overall trend of the medium stress samples shows that there is an increased amount of deformation with an increase in time. However, some of the data points do not follow this trend. For example, both the 20-hour data points in **Figure 9** show that there is more deformation than the 12-hour data points which should not occur. There were also a few data points where there was a large range in the amount of deformation. This occurred because the medium stress testing setup was the least stable setup. To produce the correct stress, three smaller weights were balanced on top of the base weight and indenter. It was difficult to precisely balance all the weights on the fixture, which caused the instability of fixture. The instability caused the deformation to be at an angle and not flat which made it difficult to take an average of the amount of deformation that occurred in these samples.

The overall amount of deformation for the medium stress was 44-90 microns which when brought to the large scale forgings is 3.22-6.71 in of deformation spread out between the 6 contact points.

Maximum Stress

The overall trend of the maximum stress samples shows that there is an increased amount of deformation with an increase in time. Some of the data points do not follow this trend. They follow the same trend that the medium stress samples follow; the 20-hour times show more deformation than the 12-hour ones, **Figure 10**. This is caused by the reasons stated earlier as well as that there is more room for error the longer the samples are in the furnace and by the large scaling difference, 1896:1. However, the maximum stress testing setup was the most stable of all the testing and there is little range in the amount of deformation that occurred with each parameter.

The overall amount of deformation for the maximum stress was 24-70 microns which when brought to the large scale forgings is 1.78-5.12 in of deformation spread out between the 6 contact points.

In **Figure 13**, it is shown that overall the medium stress samples show more deformation than the maximum stress samples, which should not occur. This is caused by the instability of the fixture during the medium testing setup. When the weights would even slightly tilt, the force is being concentrated onto a smaller area of the indenter, which in turn increases the amount of stress applied. An increase in stress should cause an increase in the amount of deformation.

5. Conclusions

1. The results are inconclusive do small scale testing setup, 1896:1, compared to the large scale.
2. Some of the results did not follow the expected amount of deformation for the various stresses, which was attributed to the instability of the fixture used for testing.
3. The general trend of increased deformation with an increase in time is what we expected, however the results varied and need further testing. At this point, we can give the approximate parameters to Weber Metals so that they can prevent creep deformation in their large-scale open die hand forgings during solution heat treatment.

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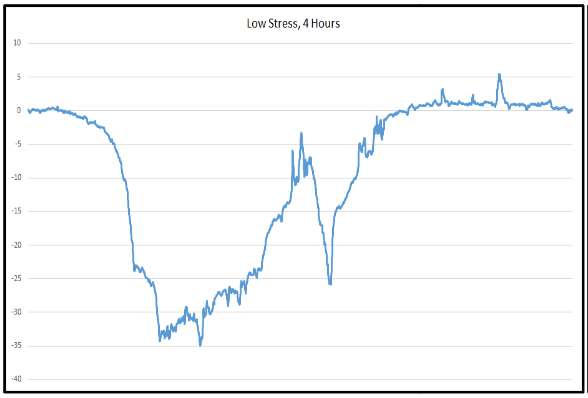
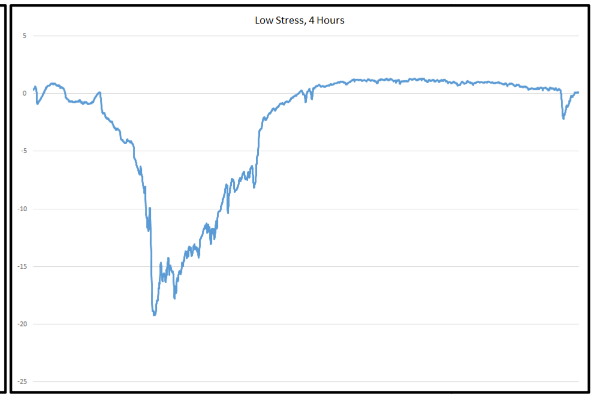
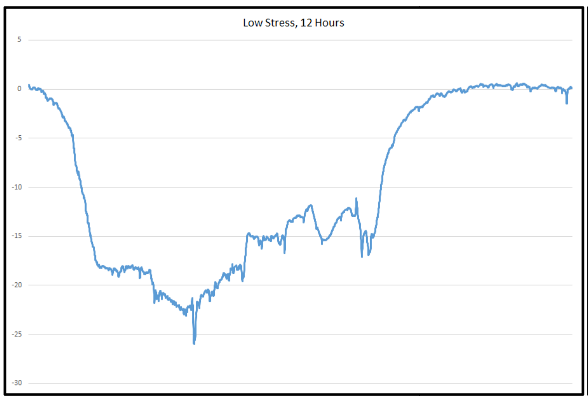
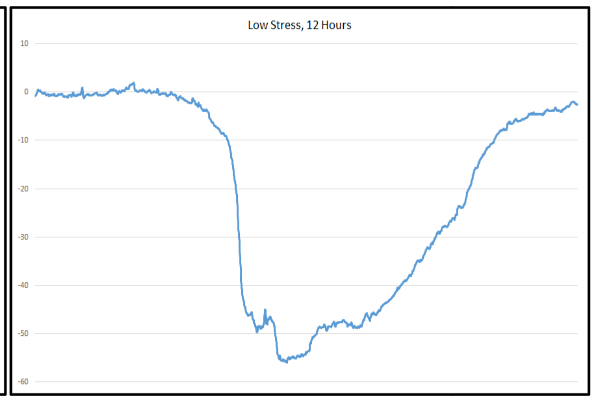
Appendix: Profilometer Scans for Each Sample

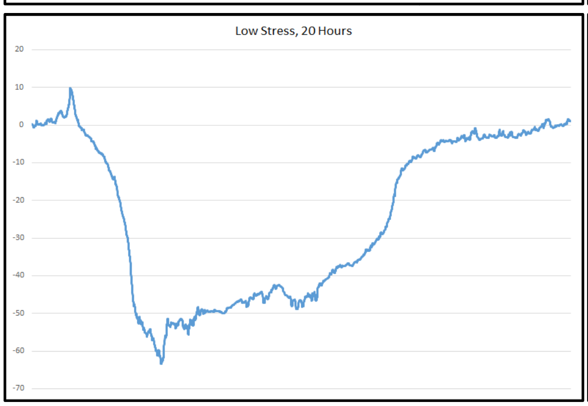
Raw data of profilometer scans for low stress in order from 4 hours to 24 hours. The y-axis is depth of indent in micrometers. The x-axis is the scan length across the sample. All graphs do not have equal scaling.

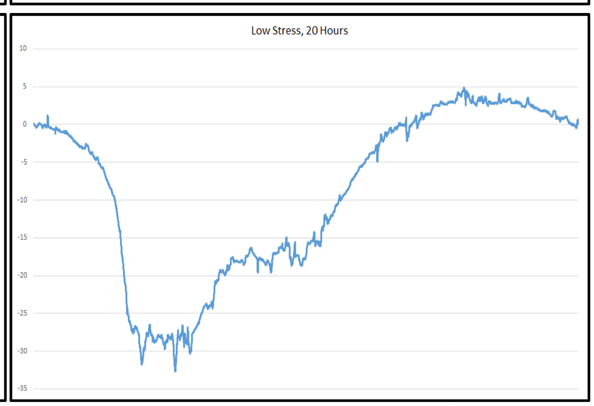


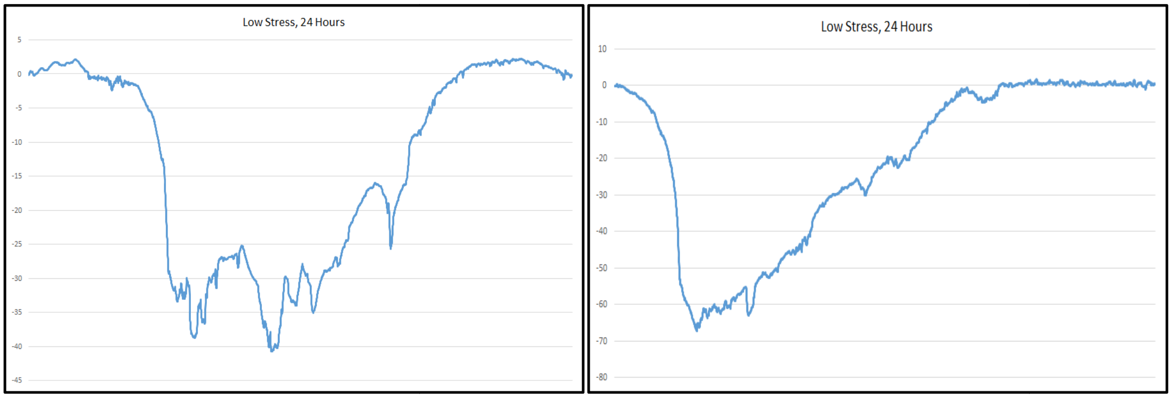




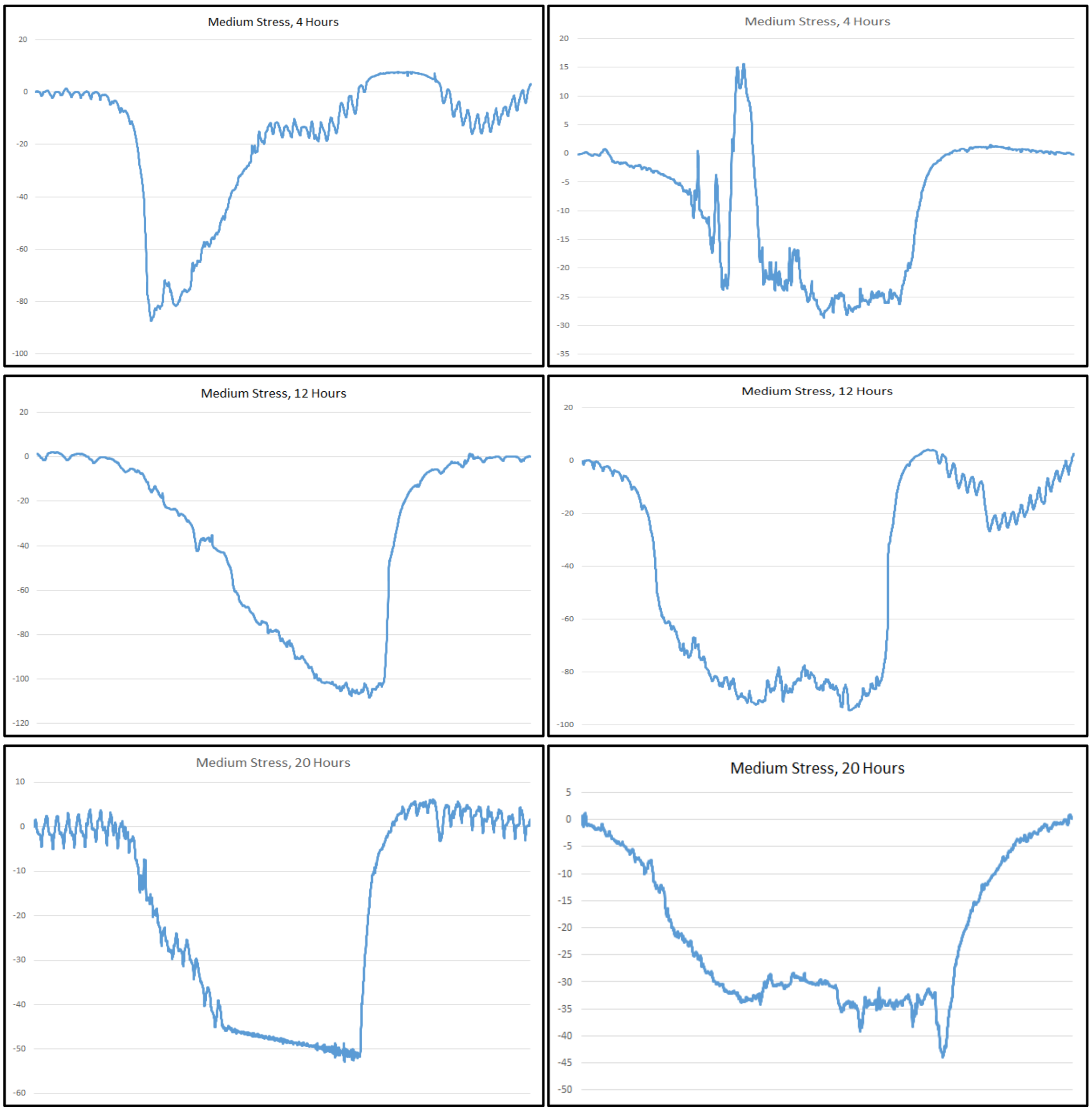


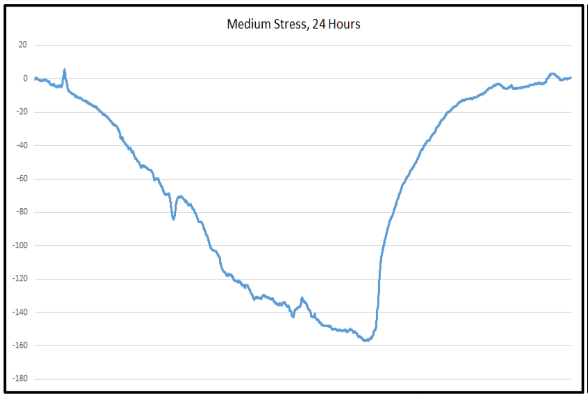


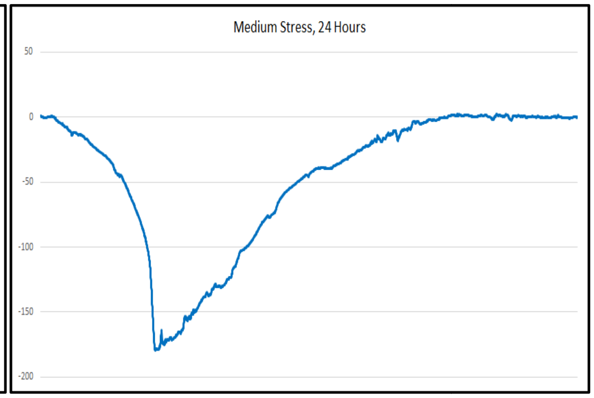




Raw data of profilometer scans for medium stress in order from 4 hours to 24 hours. The y-axis is depth of indent in micrometers. The x-axis is the scan length across the sample.







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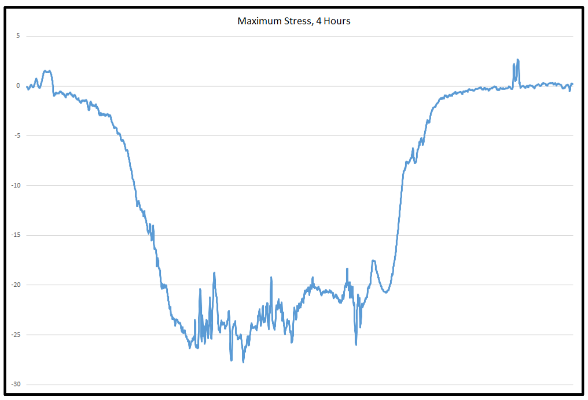
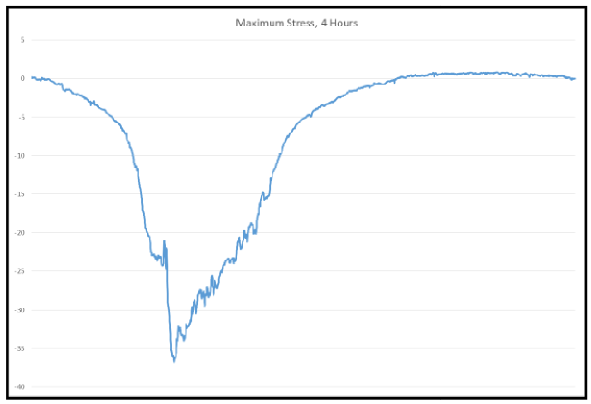
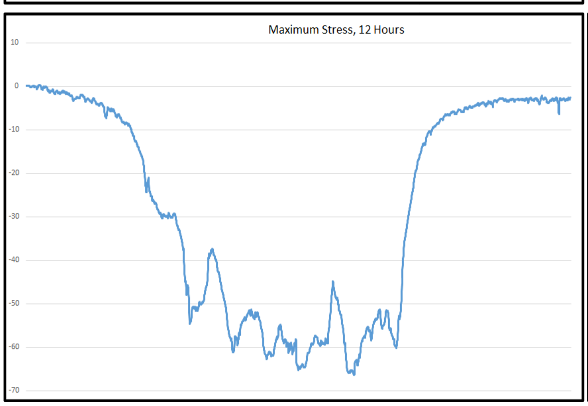
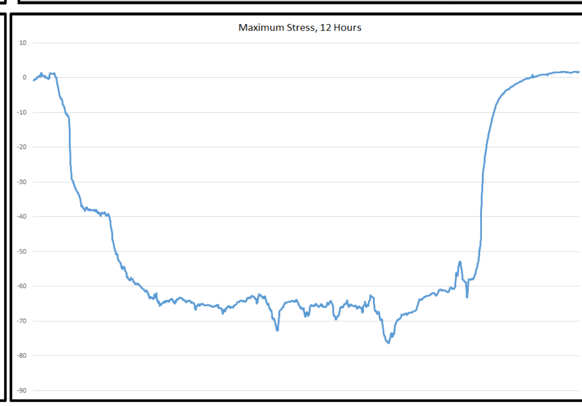
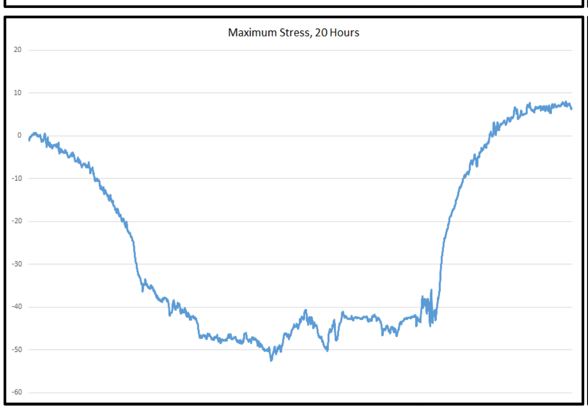
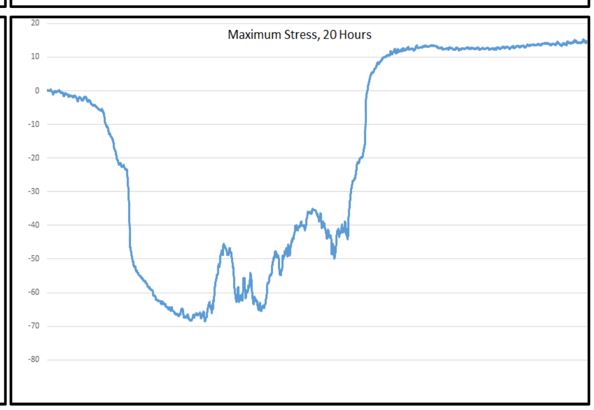




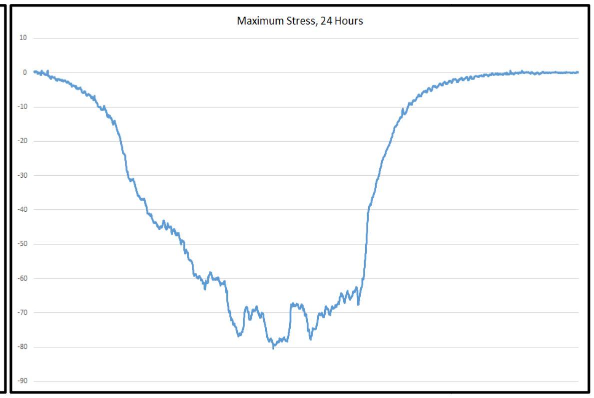









Maximum Stress, 24 Hours
10
0
-10
-20
-30
-40
-50
-60
-70
-80


Maximum Stress, 24 Hours
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90