Residual Stress Measurement of 7050 Aluminum Alloy Open Die Forgings Using the Hole-Drilling Method

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Approval Page

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Abstract

Open die forged 7050 aluminum alloy has residual stresses that can be measured by the hole-drilling method following standard ASTM E837-01. Weber Metals (Paramount, CA) assumes that the stress is uniform throughout the thickness of an open die forged plate. Four different stress relieved 7050 aluminum samples were tested to confirm if the measurements by the hole-drilling method at the surface of a plate is indicative of the stress throughout. The different stress relief methods included: two water quenched samples at temperature ranges of 60°-90°F and 120°-130°F and two samples plastically deformed by forging at room temperature 1% and 3%. For accurate measurements, a strain gauge rosette, CEA-06-062UL-120, was applied to the samples and drilled with a RS-200 Milling Guide by Micro-Measurements. The final three microstrain values at the depth of 0.100 inches were tabulated by the P3 Strain Indicator and Recorder. The strains were then converted into stresses following equations provided by the standard. Before drilling into samples, the method was calibrated with a plate that had a known low level of residual stress between 0-2 ksi. Testing confirmed the residual stress to be 0.65 ksi. Each sample was tested and results confirmed the residual stress to be non-uniform through the cross-section of the forged plates. The two water quenched samples had residual stress in tension at the surface; the two plastically deformed samples had residual stress in compression at the surface. There were no trends for either type of sample for residual stress variation from the surface to the center. Overall, the 3% plastically deformed sample would be the recommended residual stress reducing method before machining.

Keywords: Materials Engineering, Aluminum, 7050, Open Die, Forging, Residual Stress, Hole-Drilling Method, Water Quenched, Plastically Deformed, Age Hardening

1. Introduction

Weber Metals, Inc. (Paramount, CA) is an aluminum and titanium alloy forging company for aerospace and semiconductor industries. For aluminum alloys, Weber Metals specializes in open die stress relieved forgings products to minimize distortion during machining[1].

1.1 Aluminum and Forging

The aerospace industry requires materials with a high strength to weight ratio, corrosion resistance and toughness. Aluminum alloys meet this requirement; typically the 7xxx series wrought aluminum alloy is the structural material of choice (Figure 1). To produce large structural parts the aluminum undergoes a forging process, followed by solution treatment, quenching, and aging to achieve high strength. A commonly forged aluminum alloy for aircraft is 7050 aluminum. This alloy in particular is used due to its high strength, high resistance to exfoliation corrosion and stress-corrosion cracking, high fracture toughness, and fatigue resistance[2].

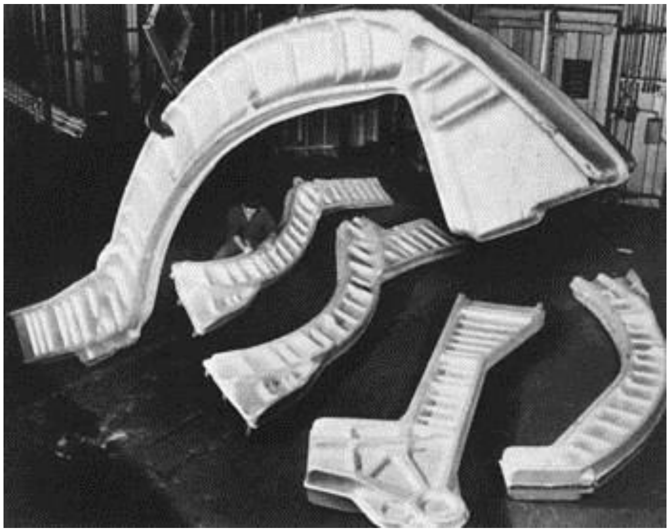

Figure 1. 7050 aluminum alloy aircraft parts formed by closed die forging[2].

The forging process for 7050 aluminum can be accomplished by two methods, either closed or open die forging. Both involve the use of large heated metal dies to shape a hot piece of metal. However, the types of dies used and the positioning of the metal to achieve the final shape differ[3].

Closed die forging involves dies that are cut into the shape that the metal will assume once force is applied. The ingot is placed into the bottom die and the top die is pushed downward. The metal plastically deforms and fills in the mold. The excess metal is pushed out of the die and the component is pulled out of the die in the desired shape (Figure 2). The extra metal can then be machined off the component. Due to the precut mold contained in the dies, more complex shapes can be produced by this process[4].

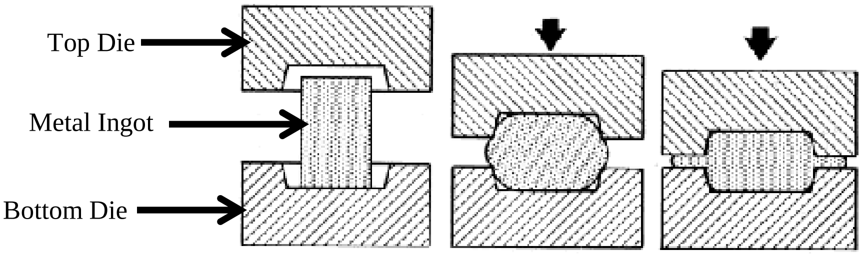

Figure 2. Closed die forging step-by-step process[3].

The dies utilized for open die forging are less intricate. Instead of having a precut mold the dies are flat. To create the correct final shape, the metal is repositioned every time after the top die is forced down[4]. With this method the operator is able to create more basic final shapes, such as plates. Special dies can be used to make rings or holes in the forged pieces (Figure 3). This report will focus on open die forged 7050 aluminum alloy used to produce between 5.5 to 5.75 inch thick plates.

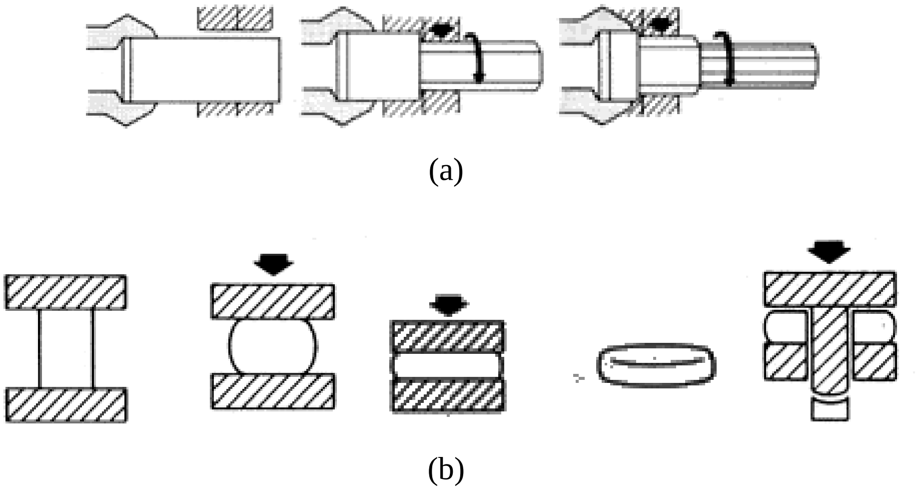

Figure 3. Open die forging process: (a) Forging of a solid cylinder (b) Forging of a ring with special dies[3].

1.2 Residual Stress Formation

After the aluminum alloy is forged it is then solution heat treated, quenched in water, plastically deformed, and aged. The rapid cooling from quenching after the solution heat treatment creates different cooling rate on the outside compared to the inside. This thermal gradient creates residual stresses in the material[5].

Residual stresses remain in a material after all applied forces have been removed. The stress can be harmful or beneficial. Typically, a residual tensile stress at the surface of a part is harmful and can decrease fatigue strength. A residual compressive stress at the surface can increase fatigue strength. A part designed for a specific load may fail early due to fatigue when the service stress is imposed on the already present residual stress. Additionally, residual stress can cause distortion during machining and is the driving force for stress corrosion cracks[6].

The residual stresses that form during quenching are from a thermal gradient. The thermal gradient creates stress related to the alloy's thermal expansion coefficient, elastic modulus, and the temperature difference between the surface and the interior of the metal[7]. The residual stresses that develop are typically large because the surface of the metal rapidly cools during the initial quenching, causing the metal to contract more on the surface than the interior. This creates pressure in the core of the material. The core cannot contract by the same amount thus, creating a condition of tension on the surface and compression in the interior. If the part is thick enough however, the core stays at a higher temperature and cools through a larger temperature range than the outside. This temperature difference allows the core to contract more than the surface, reversing the residual stress pattern. The final resulting residual stress condition is that of compression at the surface and tension at the interior[5,7].

In order to reduce the residual stresses produced, the metal can be quenched in warmer water to decrease the cooling rate. There are other thermal and mechanical methods to relieve residual stresses as well. For the forged and solution heat treated 7050 aluminum, thermal methods of relief are avoided due to the resulting inability to keep the favorable mechanical properties[8]. Therefore, after quenching, parts are plastically deformed at room temperature by either 1%, 3%, 4% or 5% to reduce the amount of residual stresses present. The slight deformation mostly eliminates the residual stresses by preferential plastic deformation; this levels the stresses across the plate and reduces the severity of the residual stresses[9]. However, some low levels of residual stresses will remain after deformation. These need to be measured so that when machining, the residual stresses can be avoided, guaranteeing no distortion of the parts will occur.

1.3 Residual Stress Measurement

Residual stresses are measured to confirm that they have been minimized and to avoid the stresses while machining. There are several different methods for measuring residual stress. The methods can be destructive, semi-destructive, or non-destructive. Since the forged aluminum parts are to be used after the measurement process, only semi-destructive and non-destructive methods can be utilized in this case.

Diffraction is a commonly used non-destructive method. There are several ways residual stress can be measured by diffraction including: electron diffraction, x-ray diffraction (XRD), and neutron diffraction. Electron diffraction and XRD are only able to measure the residual stress of thin samples. Using neutron diffraction allows for deeper penetration of the surface for measurement[10]. However, the most commonly used of the three is XRD. When utilizing the XRD method the position of the diffraction peak will shift as the sample is rotated (Figure 4). The severity of the shift is related to the amount of residual stress present in the sample. Thus, if there are no residual stresses present in a sample there will be no shift[11].

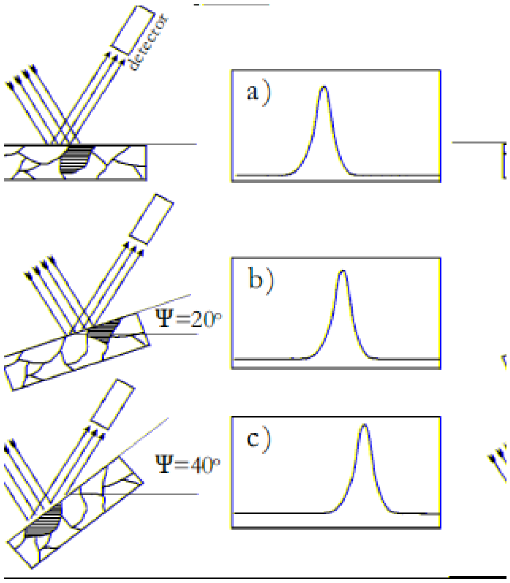

Figure 4. X-ray diffraction measurement of residual stress by the offset of the peak[11].

Semi-destructive methods of measurement include the crack compliance method and the hole-drilling method[10]. Both methods are considered semi-destructive because the damage is localized and in most cases does not affect the mechanical properties of the sample. The crack compliance method involves the measuring of strains through a slot that is incrementally cut through a part. This method allows for measurement of the entire cross section of a part[12]. The hole-drilling method is the most widely used semi-destructive technique, which involves the drilling of a shallow hole and measuring the strain released in the surface around it[13]. While the hole-drilling method only measures the surface of a part, it is portable and a cheaper method than any of the others. This makes the hole-drilling method the technique of choice for measuring residual stresses on the manufacturing floor[14]. The ASTM standard E837-01 outlines the procedure for accurately measuring residual stresses by utilizing strain gauge rosettes.

Strain gauges are able to determine the amount of strain released by a material after drilling in the center of the rosette (Figure 5). The gauge is able to record strain due its strain sensitivity, the ratio of relative electrical resistance change of the conductor to the relative change in length[15]. This strain is then converted to stress by a series of equations listed in the ASTM standard.

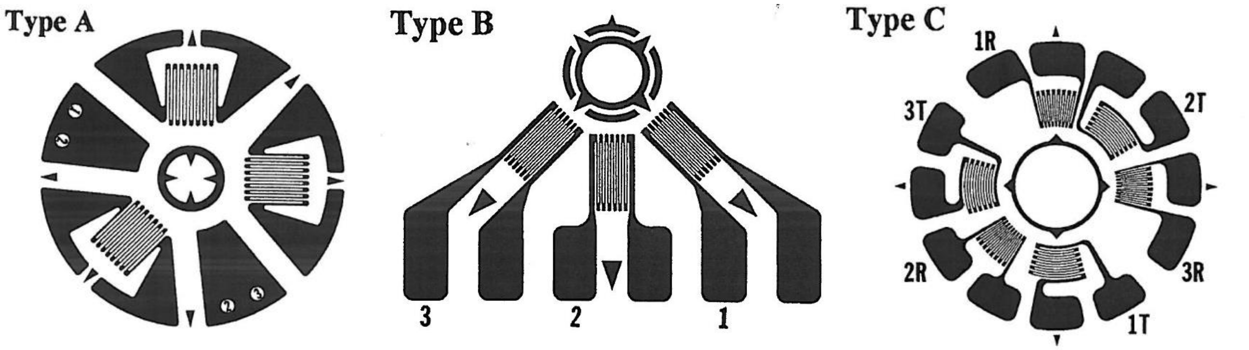

Figure 5. ASTM E837 types of strain gauge rosettes for various situations. Type A: general purpose, Type B: general purpose rosette for measurement near an obstacle, Type C: special purpose for when large strain sensitivity and high thermal stability are required[16].

For measuring strain of the forged 7050 aluminum alloys, the forging company Weber Metals uses a specific residual stress rosette pattern CEA-13-062UL-120 by Micro-Measurements (Raleigh, NC). The pattern is similar to the Type A rosette listed in the ASTM standard. It is used to save time and cost during the installation process because all the solder tabs are on one side of the gauge. This simplifies the lead wire routing (Figure 6)[14].

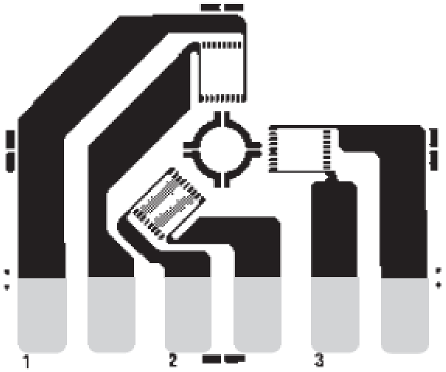

Figure 6. Pattern CEA-13-062UL-120 by Micro-Measurements is an ASTM standard E837 Type A rosette, used by Weber Metals due to having the soldering tabs all on one side to increase efficiency[17].

To eliminate the introduction of plastic deformation in the surrounding drilled area, special drilling techniques must be used. The ASTM standard lists several options, the most easily accessible being the use of a high speed drill (Figure 7). Additionally, the use of a drill with an optical device to center the drill within +/- 0.025 mm avoids errors from misalignment which could produce significant errors in the calculated stress[16].

Figure 7. The RS-200 Milling Guide by Micro-Measurements is an example of a drill that meets the criteria for the ASTM standard E837[13].

1.4 Realistic Constraints

Economics

Measuring residual stress is expensive; the hole-drilling method is the lowest cost option. However, the hole-drilling method still requires costly equipment. The RS-200 Milling Guide by Micro-Measurements is \$7,800 and strain gauges each cost about \$40. Therefore, only fifteen strain gauges were supplied by Weber Metals, limiting the amount of testing for this project.

Besides the high cost for this test, at Weber Metals if a part is machined with a high amount of residual stress then deformation and distortion occurs. The entire heat treating process, solution heat treatment, quenching, plastic deformation and aging, must be repeated. It typically takes about three to four weeks to complete the part process, resulting in loss of time and money for the company. At the same time the distorted part is being processed again, it interferes with the production of new forgings that are at the beginning of the process. This results in high cost from both opportunity cost, the lost revenue from not generating new forgings, and running cost. The running cost is typically a few thousand dollars (Table I). In addition, once the part has been processed through the heat treatment again, it must also be tested again for residual stress, dimensionally and ultrasonically inspected, and finally, tensile tested[18]. By insuring that parts will not need to be re-heat treated the entire forging process will be much more economical.

Table I. Cost for Weber Metals to Re-heat Treat a Forged Part[18]

	Time		**Cost/Pound**	**Range of Weight for Parts (lbs)**	**Range of Cost**
Solution Heat Treatment	12 hours		\$0.27	1000 - 5000	\$270 - \$1350
Aging	First Stage	24 hours	\$0.19	1000 - 5000	\$190 - \$950
	Final Stage	6.5 - 8 hours			
Stress Relief	Small	10 minutes	\$0.50 - \$0.75	1000 - 5000	\$500 - \$3750
	Large	45 minutes			

Manufacturability

A main requirement for the residual stress measurement of each forging is that it must occur on the manufacturing floor. Thus, the hole-drilling method is viable as it is the only portable option. Additionally, Weber Metals was only able to provide four samples for testing the residual stress through the cross-section of the forging. This limited the ability to have multiple tests of the same type of sample to see variation from forging to forging.

1.5 Problem Statement

Residual stresses in open die forged age hardened aluminum alloys result from the rapid cooling during quenching and remain after all the applied stresses are removed. When in service the residual stress is added to the applied stress and can exceed the material's available strength. This can cause a material to fail earlier than its mechanical properties indicate. Thus, residual stresses are a major issue in the aircraft industry due to concerns for predicting longevity. Accurate measurement of residual stresses is desired to confirm the quality of a batch of parts to ensure that failure will not occur once in use. There are multiple ways to measure residual stresses; the most common are x-ray diffraction (XRD) and the hole-drilling method. The XRD method is appropriate for measuring the residual stress of thin samples in a laboratory setting and is not portable. Therefore, for measurement of residual stresses on the manufacturing floor the hole-drilling method is utilized by following ASTM standard E837-01. The assumption Weber Metals makes about the residual stress of an open die forged plate is uniform through the entire cross section will be verified. If variations are present, then the understanding of the residual stress through the cross section of a plate can improve the machining experience of Weber Metal's customers. The first goal of the project will be to develop the ability to measure residual stresses with this method in the Materials Engineering Department at California Polytechnic State University. Next, measurement the amount of expected residual stress in aluminum 7050 alloy open die forgings that have been water quenched at 60°F - 90°F, 120°F - 130°F and deformed by 1% and 3%. After measurement, the factors that indicate the most uniform residual stress throughout the samples will provide a more economical way to produce a forged part that can be accurately measured with the hole-drilling method before machining.

2. Experimental Procedure

The standard ASTM E837-01 was followed for the hole-drilling method in combination with the Weber Metals procedure QWI 7.5-45[19]. There are three main pieces of equipment needed: a strain gauge rosette, a strain indicator/recorder, and a high speed drill.

2.1 Strain Gauge Application

The strain gauge rosette, pattern CEA-13-062UL-120, Weber Metals utilizes is for general purpose measurement. The strain gauge rosette must be applied perpendicular to the grain flow of the material produced by the forging operation, so the three gauges on the rosette are in the correct orientation for measuring the strain during the drilling process. To ensure the rosette adheres, the aluminum surface must be properly prepared[19]. First, the surface is sanded in two steps, with 180 grit sandpaper then 320 grit, to remove the buildup of grease, oils, or oxide layers. Next, a small amount of Keller's etch is applied for five to ten minutes to clean the surface. The Keller's etchant is removed and acetone is applied to wipe the surface clean. Finally, a cotton swab is wiped across the surface to confirm no dirt is leftover.

The strain gauge rosette is then placed and aligned on the surface with a template. A three to four inch piece of PCT-2M gage installation tape then covers and sticks to the strain gauge. The tape is then peeled back at roughly a 45° angle to ensure the strain gauge rosette remains on the tape, fully revealing the back of the strain gauge. Loctite professional super glue is then applied between the base of the pulled back tape and the aluminum (Figure 8).

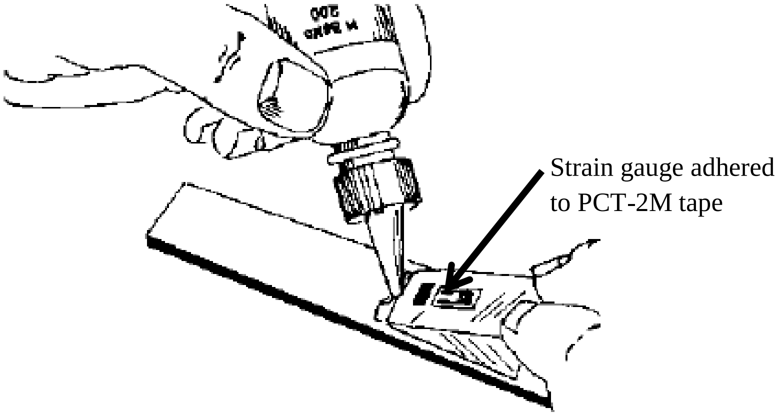

Figure 8. Loctite adhesive is applied at the base of tape and aluminum surface[20].

The tape is quickly lowered and smoothed out to remove air bubbles. A finger applies pressure to ensure a thin, uniform layer of adhesive forms between the strain gauge rosette and the materials' surface (Figure 9).

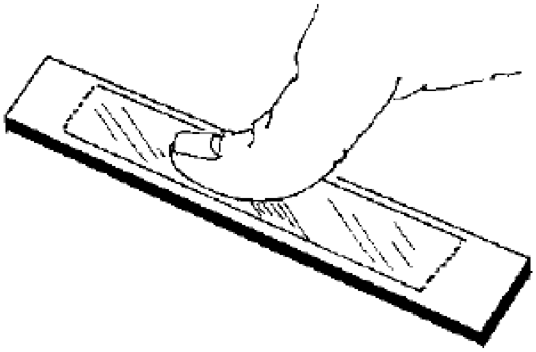

Figure 9. Finger is pressed down to bond the strain gauge to the surface and ensures no bubbles are present in the adhesive[20].

After thirty seconds to one minute the tape is slowly removed from one side at a 30° angle (Figure 10). A piece of tape is then placed over the strain gauge without touching the surface to protect the strain gauge as the Loctite cures for four to five hours. At this time the strain gauge cannot be touched until curing is complete.

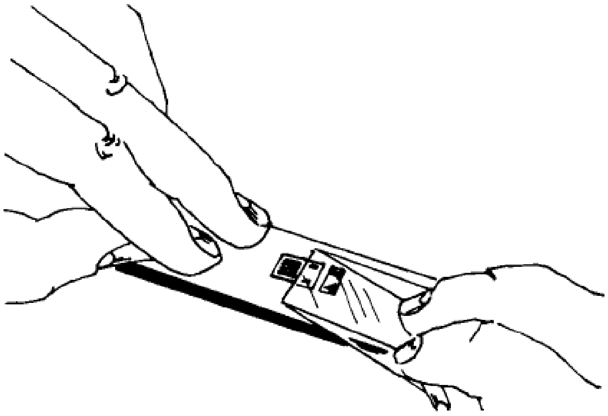

Figure 10. Tape is removed with strain gauge successfully bonded to the surface of the open die forged plate[20].

2.2 Connecting to the P3 Strain Indicator and Recorder

After four to five hours have passed the adhesive has cured. Lead wires are then soldered onto the tabs of the strain gauge (Figure 11). Minimum amounts of solder should be used, as too much can affect the electrical resistance of the strain gauge and distort the readings. There are a total of three strain gauges on a rosette that must be connected to three input channels of the P3 Strain Indicator and Recorder.

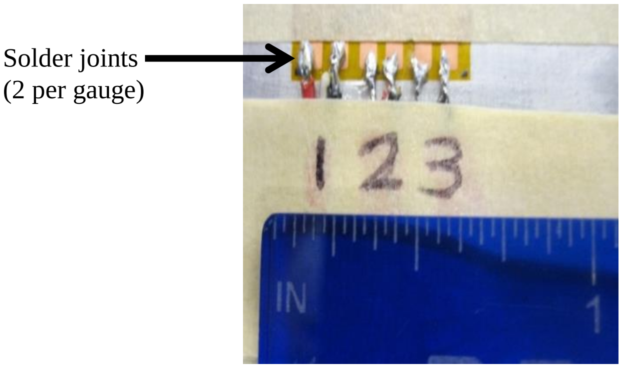

Figure 11. Soldered lead wires onto the strain gauge rosette.

The three sets of lead wires are then connected to the P3 strain indicator and recorder in a quarter bridge circuit (Figure 12). The P3 Strain Indicator and Recorder converts the change in electrical resistance of the strain gauges to microstrains. A memory card is used to record the microstrains every second during the drilling process. When the final depth of 0.100 inches is reached the microstrains are recorded and converted to stress following ASTM E837-01 equations.

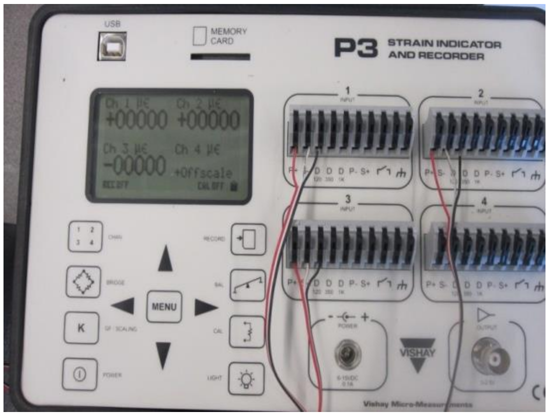

Figure 12. Lead wires connected from the strain gauge rosette to the P3Strain Indicator and Recorder in a quarter bridge set-up. Each input channel can have microstrains read from the screen.

2.3 RS-200 Milling Guide Set Up and Drilling

The RS-200 Milling Guide operates at 80,000 RPM, ensuring that no stresses are introduced to the aluminum during drilling. Before the drilling procedure begins, a microscope is inserted into the milling guide to align the drill (Figure 13).

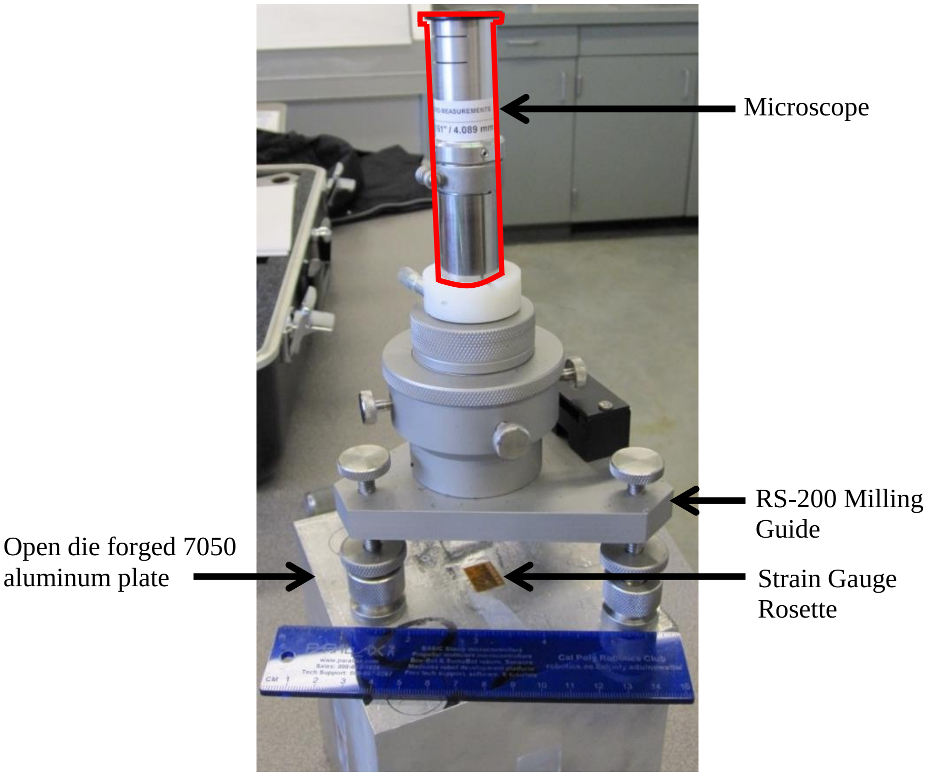

Figure 13. Microscope, outlined in red, is used to align the milling guide with the strain gauge rosette.

When looking through the microscope, cross hairs are used to center the milling guide (Figure 14). Once the microscope successfully aligns the milling guide, the based is locked into place and the microscope removed.

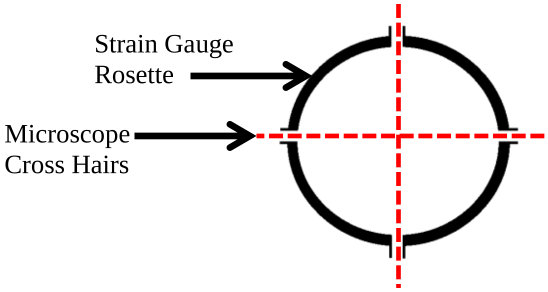

Figure 14. Cross hairs from the microscope are aligned to the above template on the strain gauge to center the drill.

The drill with a carbide cutter is then inserted into the milling guide and lowered to touch the surface of the strain gauge. The drill is then connected to a compressed air source with an output of 40 psi. At this point the set-up of is complete and testing is ready to commence (Figure 15). The surface of the strain gauge is broken and the P3 Strain Indicator and Recorder is balanced to set the mircostrain level at the surface. The micrometer is then used to lower the drill by 0.001 inches every two to four seconds. At the final depth of 0.100 inches the read out from the P3 Strain Indicator and Recorder is recorded and used to calculate the residual stress.

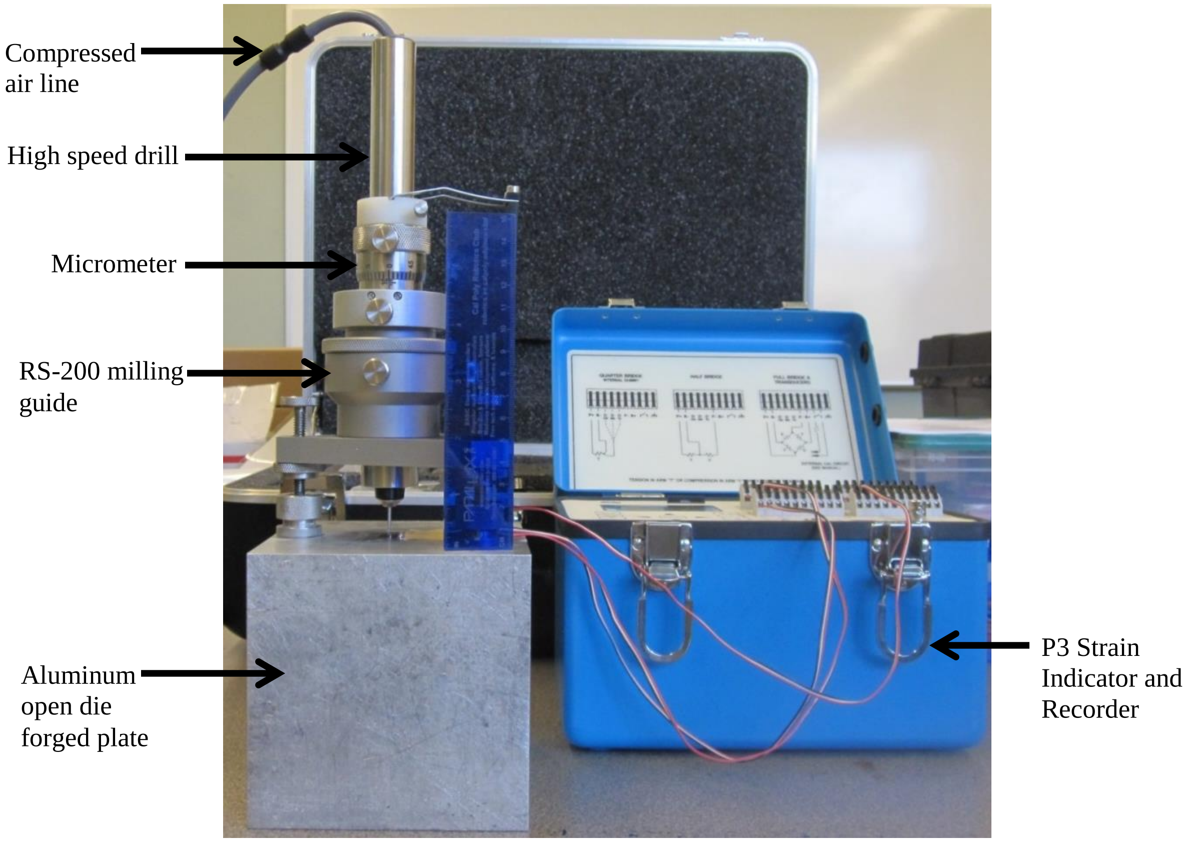

Figure 15. Full set-up of the RS-200 Milling Guide with the strain gauge connected to the P3 Strain Indicator and Recorder.

3. Results

3.1 Conversion from Strains to Stress

The recorded microstrains were converted to maximum, most tensile (+), and minimum, most compressive (-), principal stresses (Equation 1)[16].

$$\sigma_{min}, \sigma_{max} = -\left[p/\bar{a}\,(1+\nu) \pm \sqrt{(q^2 + t^2)}/\bar{b}\right]E \qquad \text{(Equation 1)}$$

Where p, q, and t are combined strains calculated from the recorded strains. The coefficients $\bar{a}$ and $\bar{b}$ are related to the strain gauge geometry. E is Young's modulus of aluminum and ν is Poisson's ratio.

These principal stresses indicated if the residual stress was in compression or tension. The range between the maximum and minimum was recorded ($\sigma_{max} - \sigma_{min}$) as the overall residual stress value of the sample because it best represents the stress during machining.

3.2 Calibration

Before drilling of the samples began, the hole-drilling method was calibrated with a plate that had a known low level of residual stress between 0-2 ksi (Figure 16). Two tests were performed as the first test resulted in higher than expected microstrains.

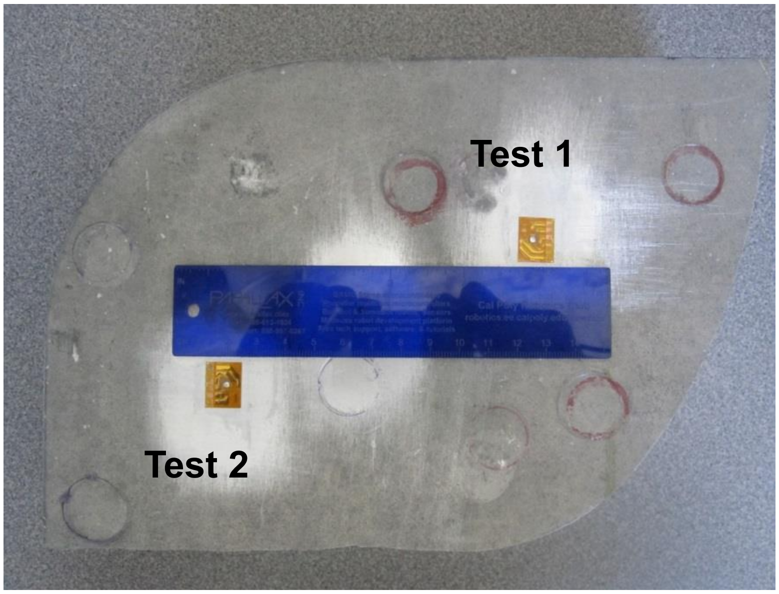

Figure 16. Calibration plate with a low level of residual stress.

After further analysis of the raw data from the first test, a spike from low microstrains at values of about 20-30 με to high microstrains up in the 300-400 με level was noted. It was discovered that a portion of the drill bit fractured during the drilling process. However, the final residual stress range was 1.35 ksi. A second test was performed to confirm the drilling process and resulted in the residual stress of 0.65 ksi (Table II). This confirmed the measurement technique, set-up, and preparation of the strain gauge was correct.

Table II. Microstrain and Residual Stress Values for Calibration Plate

	Microstrain 1 (με)	Microstrain 2 (με)	Microstrain 3 (με)	**Residual Stress (ksi)**
Test 1	-351	-355	-420	1.35
Test 2	21	3	-23	0.65

3.3 Residual Stress Measurement of Aluminum Open Die Forged Plates

Four different samples of 7050 aluminum alloy open die forgings were tested that used different methods for reducing residual stress. Two were water quenched at 60°F - 90°F, 120°F - 130°F after solution heat treatment, and two samples were additionally plastically deformed by 1% and 3% then aged.

After calibration confirmed the technique for the hole-drilling method was correct, testing of each of the four different samples commenced. Each sample was tested on the outer and inner surfaces to determine how the residual stress varied through the cross section of the forging (Figure 17).

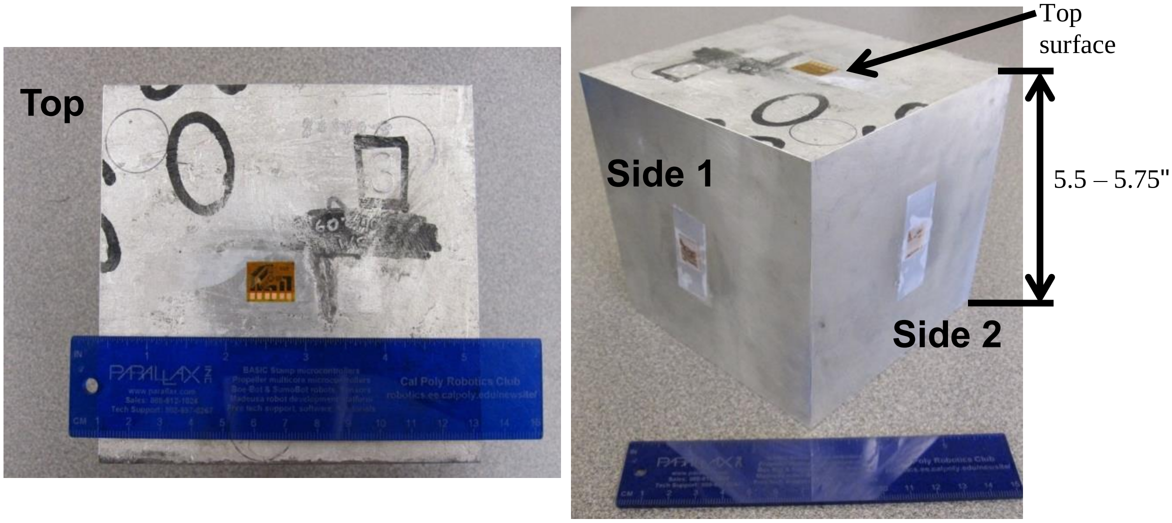

Figure 17. Representative aluminum open die forged plate, all roughly the same dimensions.

Additionally, the two different sides were tested to determine if the grain flow of the aluminum alloy would affect the residual stress. Each sample indicated residual stress variation from the surface to the center, as well as variation due to grain flow (Table III).

Table III. Residual Stress Values for Each of the Faces Tested of the Four Different Samples

Samples		**Residual Stress (ksi)***
Water Quenched 60-90°F	Top	+1.64
	Side 1	-2.82
	Side 2	-0.87
Water Quenched 120-130°F	Top	+1.34
	Side 1	-0.84
	Side 2	+1.87
Plastically Deformed 1%	Top	-2.42
	Side 1	+4.99
	Side 2	-1.23
Plastically Deformed 3%	Top	-3.43
	Side 1	-1.52
	Side 2	-0.17

*$\sigma_{max} - \sigma_{min}$ measured by the hole-drilling method

4. Analysis

For all samples, the three surfaces (top, side 1, and side 2) were measured to understand how residual stress varies through the cross-section of the open die forgings and with the different orientations of the grain in the aluminum alloy. The calculated principal stresses indicate if that residual stress is in tension (+) or compression (-). Both the 60°-90°F and 120°-130°F water quenched samples had residual stress in tension on the outer surface. However, samples that were then plastically deformed by 1% and 3% after the quenching had higher residual stress in compression on the surface.

The 1% and 3% plastically deformed samples will have less warping during machining because the outer surface is not being pulled apart internally, due to the compressive residual stress. Therefore, while the water quenched 120°-130°F has the lowest overall residual stresses, the 3% plastically deformed sample is preferred for reducing residual stress before machining.

There are no confirmed trends of the residual stress increasing or decreasing from the surface to the center for any of the samples. When comparing the two methods of reducing stress there is no trend of the residual stress moving from tension to compression from the surface through the cross-section, or vice versa. In the future, more testing can confirm if there is a typical residual stress profile for each sample. Overall, it was confirmed that the residual stress is non-uniform through the cross-section of an open die forged plate.

5. Conclusions

1. Residual stress is non-uniform through the cross-section of an open die forged 7050 aluminum alloy plate of 5.5 to 5.75 inch thickness.

2. Samples water quenched after solution heat treatment at 60°-90°F and 120°-130°F without being plastically deformed have residual stress in tension on the surface at +1.64 ksi and +1.34 ksi respectively.

3. Samples that were plastically deformed by 1% and 3% have compressive residual stress on the surface at -2.42 ksi and -3.43 ksi respectively.

4. The sample with the lowest overall level of residual stress through the thickness of the plate was the water quenched 120-130°F sample; however, due to the tensile residual stress present on surface, the recommended method to reduce residual stress is to plastically deform the aluminum plate by 3% before machining.

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