

PREDICTION OF RESIDUAL STRESS AND DISTORTION FROM RESIDUAL
STRESS IN HEAT TREATED AND MACHINED ALUMINUM PARTS

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by

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ABSTRACT

PREDICTION OF RESIDUAL STRESS AND DISTORTION FROM RESIDUAL STRESS IN HEAT TREATED AND MACHINED ALUMINUM PARTS

By Robert Jones

Parts machined from relatively large thickness cross sections can experience significant deformations from high residual stresses that develop in the part during the heat treatment used to form the aluminum alloy. Uphill quenching is a process that can create a part with low residual stress and stable dimensions when the process is controlled properly. The uphill quenching process involves a solution heat treat, quench, cool to liquid nitrogen, steam blast, and then age to final temper.

In this thesis two parts were modeled using ANSYS. The first part underwent the uphill quench process in the rough machined state. The second part was modeled in the stock material shape and only underwent a solution heat treat, quench, and age to final temper. After the residual stress in the second part was predicted the excess material was removed by killing the associated elements and the deformation of the final machined part was predicted. For both parts analyzed measurements were made and compared against predictions with fairly good results.

ACKNOWLEDGEMENTS

As an employee of Space Systems/Loral (SSL) I worked on parts that required heat treatment. The thought came to me that an analysis process should be established to select a residual stress mitigation method given certain requirements on the part. Thank you to SSL for allowing me to use information and measurements on these parts, where Proto Manufacturing did residual stress measurement and Newton Heat Treating Company did uphill quenching and I hereby express gratitude to them.

Thank you to Dr. Raymond Yee, Dr. Cecilia Larrosa, and Joseph Cullinan as the San Jose State University thesis advisory committee for coaching the effort for this thesis.

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NOMENCLATURE

CAD - Computer Aided Design

CFD – Computational Fluid Dynamics

E - Modulus of elasticity.

FEA – Finite Element Analysis

ε - Strain at a given point.

ε_p - Integrated plastic strain.

σ - Stress at a given point.

σ_y - Yield stress.

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1.0 INTRODUCTION

Aluminum alloys are commonly used metals in industry due to their desirable strength to weight ratio, relatively low cost, ductility, and machinability. The 6061 aluminum alloy is very commonly used in medium to high strength aerospace applications. Aluminum alloys have been a focus of residual stress research since the 1960s [1]. Residual stress problems can create early fatigue failure, stress corrosion cracking, and dimensional instability. This thesis focuses on predicting the residual stress distribution in a regular heat treated billet and in a rough machined part that is put through the uphill quenching process. This study also predicts the distortion that occurs in a part after being machined from the regular heat treated billet.

It is very common to machine aluminum from forgings, extrusions, or plates into a wide variety of parts with different shapes and sizes. In some applications very tight tolerances are required for the part. Residual stress issues have led to satellite box [2], bulkhead [1], and aircraft landing gear failures [3]. Machine shops can achieve the tight tolerances required of them but in many cases the residual stress in the parts causes the parts to move during machining and after the machine shop pulls the part out of the machine. Aluminum parts have been known to have their dimensions change over time such that they are initially inspected in tolerance and then a short time later are discovered out of tolerance.

For decades the causes of residual stress have been understood but the issues are usually dealt with by implementing a trial and error approach. This approach is expensive and limits the use of the knowledge gained to only parts that are close in configuration to previous parts that were tested. By being able to accurately predict the residual stresses in a part the important parameters that cause residual stress can be identified and quantified. This analysis approach could then be applied to many different kinds of parts and a residual stress mitigation plan could be created at a fraction of the cost for testing. Testing would still be required on a small set of parts to establish confidence in the analytical methods.

Before a machine shop receives an aluminum 6061 stock material piece the material is heat treated. The step in the heat treatment that creates the majority of the residual stress is the quenching of the aluminum [4,5]. During quenching aluminum 6061 starts at a temperature around 470 °C and is dropped into a water or polyalkylene glycol water mixture bath at room temperature [6]. The high temperature difference between the bath and the aluminum causes the bath to boil in the vicinity of the stock material. The outside of the material cools faster than the inside. As the outside of the material cools faster it also becomes much stiffer and contracts. As the outside contracts it plastically deforms the inside. Once the inside starts cooling the inside stiffens and pulls on the outside, plastically deforming the outside. At the end of the quench the stock material reaches force equilibrium but stress remains in the stock material due to thermal gradients. In thinner pieces of material the stresses do not reach the plastic region but significant residual stresses

still exist after quench. When the material with residual stress is removed during machining the part is no longer in force equilibrium and the part deforms to achieve a new equilibrium.

Alloys are a combination of a primary metal with other elements that strengthen the primary element. All metals form into crystals and grains when cooled from the liquid state. The grains form boundaries between other grains. The boundaries are weak points in the metal. When a metal yields the grains slip at the boundaries and move relative to each other.

An alloy is created by heating a metal above its liquidous point and mixing in the alloying elements. The elements dissolve into the metal similar to how salt dissolves into warm water. If the metal cools too slowly the alloying elements clump together and form precipitates in the metal similar to what happens when saturated water cools down and the salt starts to appear. If precipitates form that are too large the alloying elements do not effectively increase the strength of the material. When the metal is cooled rapidly the alloying elements are trapped in the solution, before they can precipitate, and the highest strengths in the metal can be achieved. The alloying elements get trapped between grain boundaries and prevent the grains from slipping thus increasing the strength of the material [7].

After the stock material is quenched, for heat treatable alloys, the full strength of the metal is not truly realized yet. The next step requires the metal to be heated up to a temperature just high enough to allow for the alloying elements to diffuse or

spread out in the metal. A balance is achieved between alloying elements remaining in solid solution and a dispersion of precipitates that creates the peak of strength for the material. Aluminum 6061 achieves the peak of strength in the T6 temper by being heated, or referred to as aging, close to 175 °C for multiple hours [6].

Quenching of heat treatable alloys is a critical step to achieve high strength in the material. The effectiveness of the quench is reduced as the thickness of the material increases. As the part thickness increases the temperature gradient also increases. For larger thicknesses the inside cools slow enough for large undesirable alloying element precipitates to form that do not effectively block grain slipping. Smaller and more widely prevalent precipitates are generally better than larger more sparse precipitates. If a crack forms in the material due to high stresses it is easier for the crack to propagate in such a way as to avoid sparse large precipitates as opposed to a dense field of small precipitates. The residual stress in the material also increases as the thickness of the part increases because of the increase in temperature gradient. Residual stress development slows as the yield point is reached and the part strain hardens [2].

Several different approaches have been taken in the past to mitigate residual stress problems. Table 1 provides an overview of various residual stress mitigation approaches.

Table 1 Various methods for mitigating residual stress issues.

	Method	Advantages	Disadvantages	References
1	Hot water quenching	Reduces residual stress significantly.	Reduces strength potential of ageing significantly.	[2]
2	Overaging	Reduces residual stress slightly and is a relatively simple operation.	Reduces strength significantly and does not reduce residual stress significantly.	[2]
3	Heat treat rough machined part same as billet	Very high strength. Reduced residual stress.	Significant residual stress remains.	[2]
4	Straightening	Deforms part back to desired shape.	Creates residual stress, part can deform later. Causes early fatigue failure or breaking during operation.	[2]
5	High glycol concentration in quench.	Prevents residual stresses from ever forming.	May reduce strength, but in a controllable fashion by varying glycol concentration.	[1]
6	Uphill Quenching	Maximum strength can be achieved with near zero residual stress.	Requires significant process development effort, specialized fixtures, specialized process not common in industry.	[8]
7	Select alternate material or alloy	Some alloys/materials don't develop significant residual stress.	May not work well with other design constraints.	[1]
8	Purchase aluminum in the T651 or T7351 condition.	Stretching can reduce residual stress by ~80%. Compression can reduce residual stress by ~50%.	Generally can't be done to finished part due to part complexity. Can't be done to large parts.	[2]

The warm water quench method greatly slows down the quench time, but it also allows the alloying elements to significantly precipitate into the aluminum. After aging the strength can be easily reduced by over 50%. Warm water quenching is typically not useful for situations requiring high strength and thicknesses larger than one inch. If high strength is not needed often other aluminum alloys can be used that

do not require special process considerations such as the non heat treatable 5000 series of aluminum alloys [2]. Aluminum 7050 is a high strength low residual stress susceptibility alloy but is a more recently developed alloy and the material properties for this alloy are not as prevalent [1]. High levels of glycol concentration can be used on a wide variety of parts in a very controlled fashion but becomes less effective on thicker parts [1].

The method to mitigate residual stress being focused on in this study is the uphill quenching method. Uphill quenching is a five step process. Each step has to be controlled and its effect on the part has to be understood. The five steps are listed below:

1. Solution heat treat
2. Quench
3. Immersion in liquid nitrogen until thermal equilibrium is achieved
4. Steam blast
5. Age to final temper

Uphill quenching, when applied correctly, can achieve the highest strengths possible for a specific sized part because of steps 1-2 and because the part is generally rough machined before step 1. The rough machining step reduces the cross sectional thickness of the part, relative to the original stock material, so that a higher strength

can be achieved from the heat treatment that occurs prior to the liquid nitrogen immersion. Uphill quenching can also achieve near zero residual stress due to the stress reduction that can occur in the steam blast step. The initial quench is a sharp step down in temperature and the steam blast is a sharp step up in temperature. The sharp step up in temperature during the steam blast effectively reverses the effect of the quench. Near the end of the quench the inside cools slower and compresses the outside. Near the end of the steam blast the inside heats slower and stretches the outside.

The effectiveness of uphill quenching has been demonstrated to be a function of the overall temperature difference and heat transfer rate achieved by the uphill quench. The overall temperature difference is achieved by the media used to reach the coldest temperature and the media used to achieve the warmest temperature. Various combinations of liquid have been used and the method with best results that is most widely used is combining liquid nitrogen and steam [8].

The downside to uphill quenching is the variability in results that can be achieved. Steps 1,2, and 5 have been well documented and controlled for decades. Typically uphill quenching becomes more effective when glycol is used in conjunction with step 2. The steam blast is the step with the most variability because the heat transfer from the steam blast is highly dependent on part geometry and the equipment setup used to perform the steam blast. For the best results the steam has to evenly hit all surfaces of the part (same velocity) and increase the temperature of the

entire part as rapidly as possible. This requires special fixtures to be fabricated because in practice the number of nozzles is often limited. For example, if a pocket exists normal to the steam flow then the steam in the pocket moves slower than the steam above the pocket and the heat transfer rate is different.

By being able to model the distortions from a standard machined part and comparing the distortions against the required tolerances and manufacturing capabilities an engineer can determine if uphill quenching, or some other method to mitigate residual stress, is needed. By being able to accurately model uphill quenching in complex geometries engineers will be able to design uphill quenching fixtures and processes as needed for their specific components. Thicker parts may require lower velocity steam but a longer duration to get a more even heat transfer across the part. A special fixture may need to be designed for a part with many pockets to make sure the steam hits the part evenly. There may be some situations where an uneven steam flow may be acceptable.

Much research already exists on predicting residual stress due to the quenching step. Plane strain models have been looked at [9]. Multiple studies exist using finite element analysis to predict residual stress due to quenching [10,11,12] [1]. Citation [13] presents a detailed review of research developments that use simulation/FEA to model heat treating, quenching, and annealing. The effect of glycol in quenching has been researched and heat transfer coefficients derived from measured temperatures of quenched cylinders are available [1,11]. Some analytical

methods exist for predicting residual stress but they are usually accompanied by numerical simulation because of all of the variables involved and are typically only useful for very simple situations [14,15,16]. The effect of machining on residual stress is a well researched area [14,17]. Some recent research has been published showing uphill quenching with boiling water [18,19]. Very little research on predicting residual stress from steam uphill quenching has been published to date.

This study differs from other research that has been done in predicting residual stress in four ways:

1. Modeling the residual stress in a rough machined part that was uphill quenched using steam.
2. Predicting distortion that comes in a finish machined part that was solution heat treated, quenched, and aged in the stock material state.
3. Modeling tapered cylinders with flanges.
4. Modeling the steam so as to be able to predict the heat transfer at each location of the part (instead of averaging the heat transfer) resulting in a more accurate change in temperature prediction.

The configurations that have been analyzed so far include probes, beams, propeller hubs [10], and infinite plates [20]. This paper analyzed a tapered cylinder with flanges and model the fixture used to hold the part during the steam blast. Figure 1 shows the model of the finish machined part that this thesis analyzes for residual

stress due to the uphill quench process. Figure 1 is about .23 m in diameter at the largest outer diameter flange. Figure 2 shows the model of the finished part machined from a solution heat treated, quenched, and aged stock material that this thesis analyzes for residual stress and distortion. Figure 2 is about .10m in diameter at the largest opening.

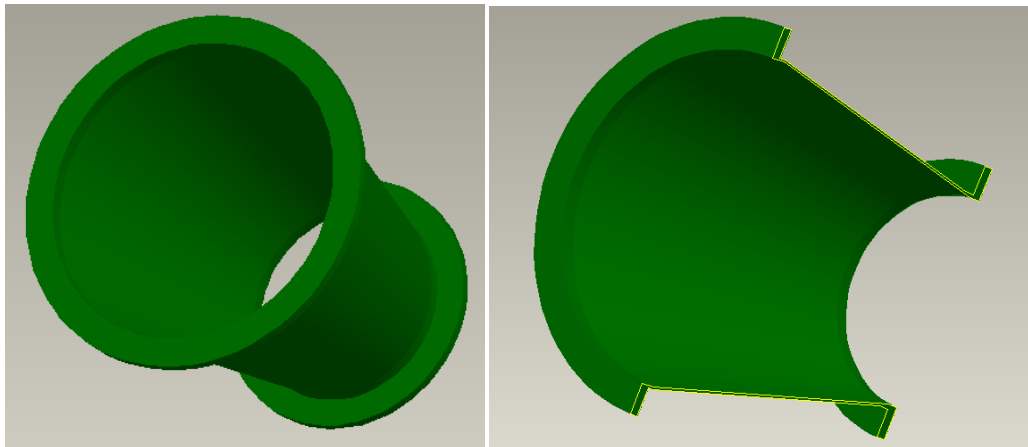


Figure 1 CAD model for finish machined uphill quench part (left) with section view (right).

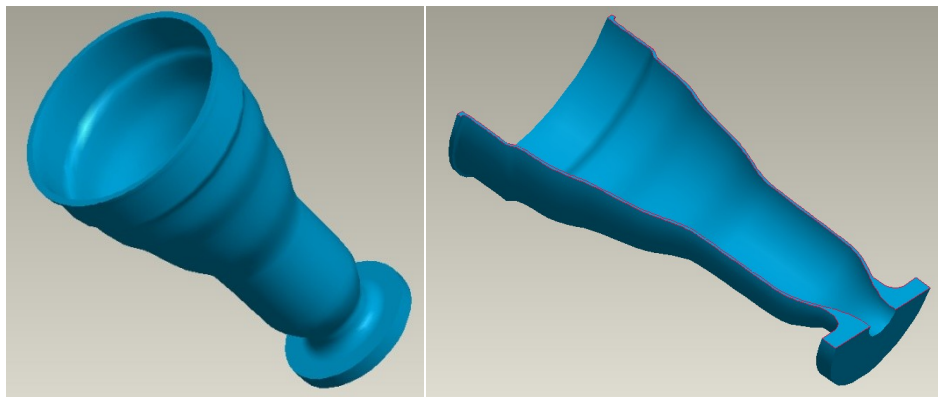


Figure 2 CAD model for finish machined part (left) with section view (right).

Typically the heat transfer to the part is simulated using an average heat transfer coefficient derived from the measured temperature over time on the part.

Another source of residual stress in machined aluminum parts comes from the machining process itself. Most of the research that exists in predicting residual stress from machining concludes that the residual stresses stay near the surface [12,14,15]. This paper assumes that machining residual stresses are near the surface and assumes there is an even, very thin, shell of high tensile stress on all surfaces of the part due to machining. Since all surfaces have a very thin shell of high residual stress this paper assumes that the thin shell of stress has negligible effect on final part distortions.

2.0 METHODOLOGY

The analysis that is shown hereafter is divided into two groups. The first group involves predicting the residual stress from the uphill quenching process for the part shown in Figure 1. Figure 1 does not show the rough material and fixture that is included in the uphill quench analysis. Figure 3 shows the rough material and fixture used for uphill quench analysis. The uphill quench analysis assumes an axially symmetric model where the symmetry axis is the center axis of the finish machined tapered cylinder. The second group involves predicting the residual stress and distortion that occurs in the part shown in Figure 2. Figure 2 does not show the material that is removed from the original stock material that is part of the analysis. Figure 4 shows the material that is removed from the stock material and the final machined part.

The analysis for both groups involves FEA using ANSYS. Modeling the uphill quenching process from beginning to end is a sequential multi-physics problem and is explained in the following sections. The results from each step need to be used as an input in the next step to achieve the final results.

The model used for the uphill quench analysis involves three sub-models. Figure 3 shows a section view of the CAD model used in the uphill quench analysis. One sub-model is the finished machined part, shown in green. The second sub-model is the material on the outside of the final machined part after the rough machining step. The third sub-model is used to model the steam flow over the part. The third sub-model, steam volume, is only used in determining the heat transfer for the uphill quench step. The rough model is about .25 m in diameter at the largest section.

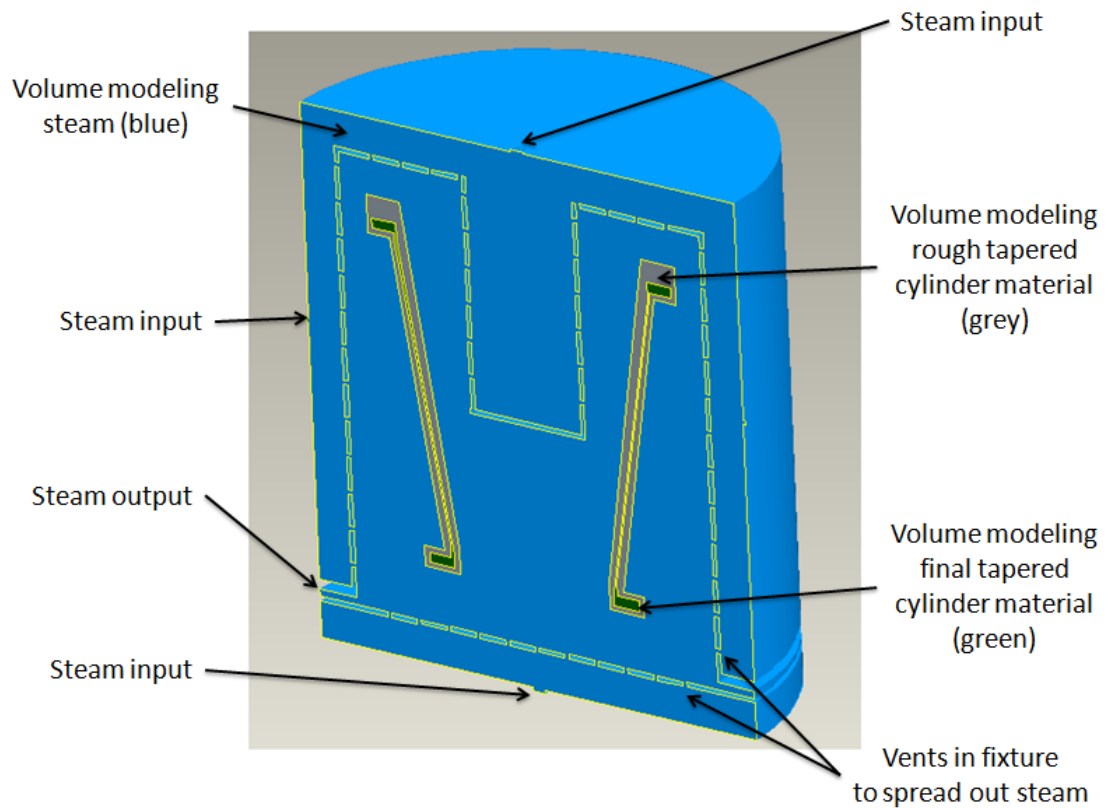


Figure 3 Section view of CAD model for uphill quench analysis.

Figure 4 has a similar model setup for the regular heat treated part as in Figure 3 except with no steam volume. The final machined tapered cylinder in Figure 4 has

a .64 mm axis offset from the rough/billet material cylinder axis. Both analysis models are being modeled after parts that were built and processed before any analysis was conducted. The actual part modeled in Figure 4 was finished machined, inspected and found conforming to a profile tolerance of +/- .025 mm, sat on a table for a couple of weeks, and then re-inspected and found to be out of tolerance. Additionally, the real part was observed to have a noticeable elliptical shape to it instead of being circular. The hypothesis is that the surface roughness on the billet/rough material caused the final machined tapered part to be machined at an axis offset to the original billet. The results section show more specifics about the measurements and the behavior of the model in Figure 4. The billet shown in Figure 4 is .20 m in length.

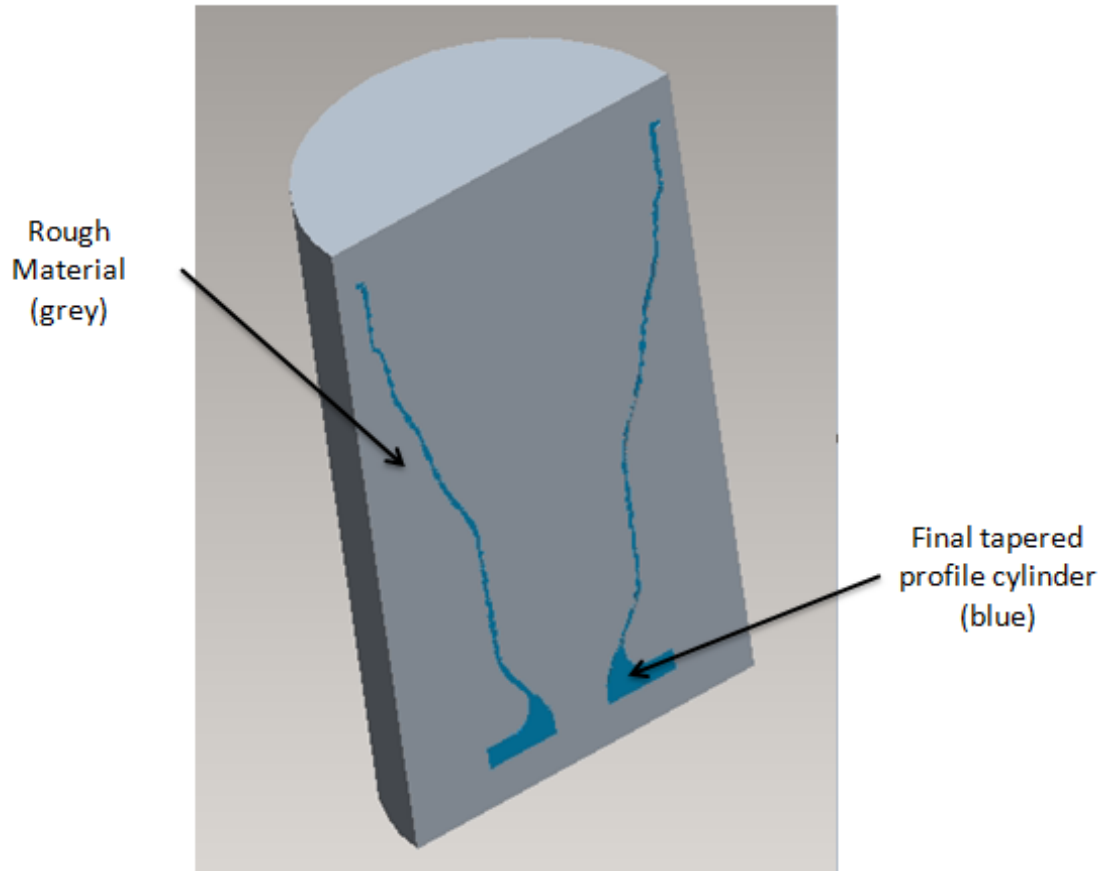


Figure 4 Section view of CAD model for distortion analysis due to normal heat treat and quench.

A rough machining step prior to the uphill quench process is done to acquire a part close in size and shape to the final part. The rough part typically has large residual stress in it so the part deforms during the uphill quench process. If the rough machined part deforms in such a way that no material exists where the final machined part needs to exist then the part has to be scrapped and the machining restarted. Sufficient material needs to be left behind in the rough step to make sure that material will exist where needed for final machining. The amount of material that needs to be

left behind is a function of size of the part and the process that will be used to mitigate residual stress (i.e. solution heat treat or uphill quench). In this situation ~3.8 mm of rough material was left behind on all surfaces except for the larger diameter section. The larger diameter section had additional material left behind to allow for removing tensile test specimens. The rough material part and final material part is bonded together in the analysis and the thermal resistance between the two parts is near zero.

The regular heat treated billet is bonded together in a similar fashion. At the end of the analysis the elements in the billet material, rough material, are killed using the ANSYS EKILL function. The ANSYS EKILL function by default reduces the stiffness of the selected elements by a factor of 10^{-6} and sets the stress in the elements to zero. Killing the elements simulates the removal of the material. The stress in the tapered cylinder, final machined part, section retains the stress that was developed from the quench. Once the elements are killed the tapered cylinder is no longer in force equilibrium and is free to deform to achieve a new equilibrium.

2.1 SOLUTION HEAT TREAT

The solution heat treat is simply heating the aluminum up to the point where the alloying elements dissolve into the metal. The initial heating is usually done in an oven and is generally considered to happen quite slowly, thus causing no initial stress. The aluminum is so compliant at this temperature that it is assumed there is no residual stress in the part. This step merely provides the input for the quench

analysis. The initial condition and boundary condition to the quench analysis are summarized in Table 2.

Table 2 Input for thermal quench analysis.

	Initial Temperature:	Reference:
Initial Temperature:	470 C	[6]
Water Temperature:	100 C	[20]

2.2 QUENCH

To date the most straightforward and well documented approach on predicting residual stress was done by Jeanmart and Bouvaist [20]. Jeanmart and Bouvaist were able to predict and measure residual stress in a plane wall with relatively high accuracy between prediction and measurement. Their approach is closely followed with some alterations.

The values for specific heat, thermal conductivity, and coefficient of thermal expansion across temperature come from page 3-273 in [21] for Aluminum 6061. The values for yield stress and modulus of elasticity come from page 163 in [22] for as quenched Aluminum 6061. The model shown in Figure 3 was quenched in 14.2% glycol. The heat transfer coefficients for 10% glycol from Sarmiento [11] were used. The stock material modeled in Figure 4 was quenched in pure water and the corresponding coefficients from Sarmiento [11] were used. A film of boiling water is formed around the part because the part is much hotter than the quench water. The

steam and boiling water that forms around the part is the main driving factor for the heat transfer to the part during quench.

The mesh used in the quench analysis for the uphill quench model is the same mesh used in the rest of the analysis except for the fluid flow analysis to determine the heat transfer coefficients. Both meshes are axially symmetric. The model used for the distortion analysis shown in Figure 4 only has one mesh for all applicable analysis. The element types for the mesh are summarized below in Table 3.

Table 3 Element types used in uphill quench and distortion models.

ANSYS Element Type	Model	Analysis Type	Description
COMBIN14	Uphill Quench and Distortion	Static	Spring Element
CONTA172	Uphill Quench	Static and Thermal	2D Contact Element
CONTA174	Distortion	Static and Thermal	3D Contact Element
PLANE183	Uphill Quench	Static	2D Mid-side Node Element
PLANE77	Uphill Quench	Thermal	2D Mid-side Node Element
SOLID186	Distortion	Static	3D Mid-side Node Element
SOLID187	Distortion	Static	3D Mid-side Node Element
SOLID87	Distortion	Thermal	3D Mid-side Node Element
SOLID90	Distortion	Thermal	3D Mid-side Node Element
SURF151	Uphill Quench	Thermal	2D Surface Element
SURF152	Distortion	Thermal	3D Surface Element
TARGE169	Uphill Quench	Static and Thermal	2D Contact Element
TARGE170	Distortion	Static and Thermal	3D Contact Element

The contact elements in Table 3 are used to maintain the bonded contact between elements, or have the elements glued together, needed for the analysis.

The fluid flow analysis handles elements differently from thermal and static analysis. In static and thermal analysis the elements have a specific type that is associated with the behavior of the element. The specific type includes the equations used to describe the behavior. For ANSYS Fluent the elements are described by shape, material, and cell zone condition (fluid or solid). The user selects the behavior of the cell zones (such as the steam zone in the uphill quench model) and then ANSYS Fluent assigns the equations for that zone.

Figure 5 shows the mesh used for the uphill quench model using the element types in Table 3. Figure 6 shows the mesh used for the distortion analysis, or regular heat treated billet from Figure 4, with element types from Table 3. The stress and deformations for the distortion analysis model is symmetric about a plane formed by the center axis of the billet and the center axis of the finish machined part. To save on elements only half of the billet and finish machined part are meshed in Figure 6.

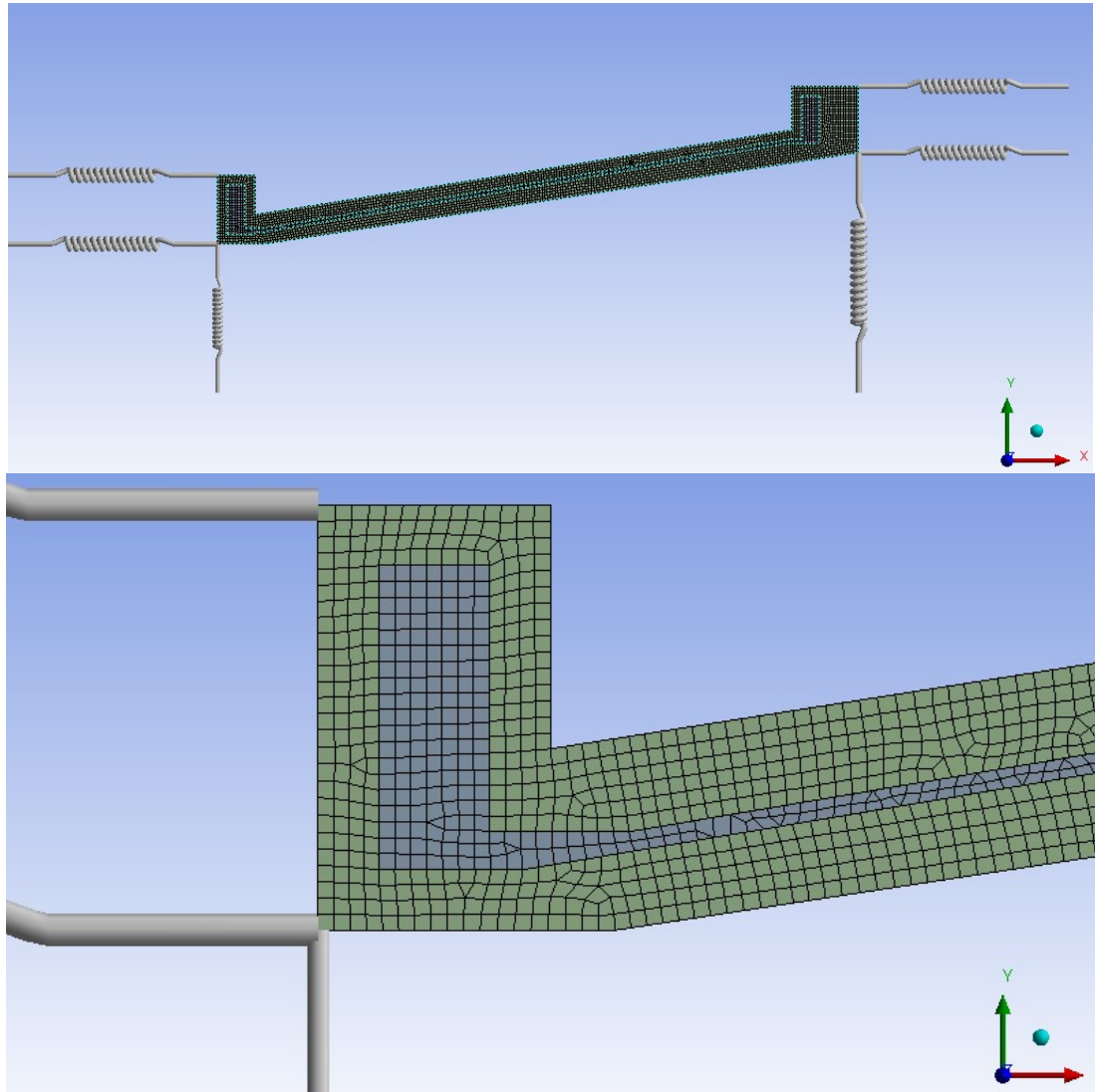


Figure 5 Mesh used in uphill quench static/thermal analysis (above) with close up (below).

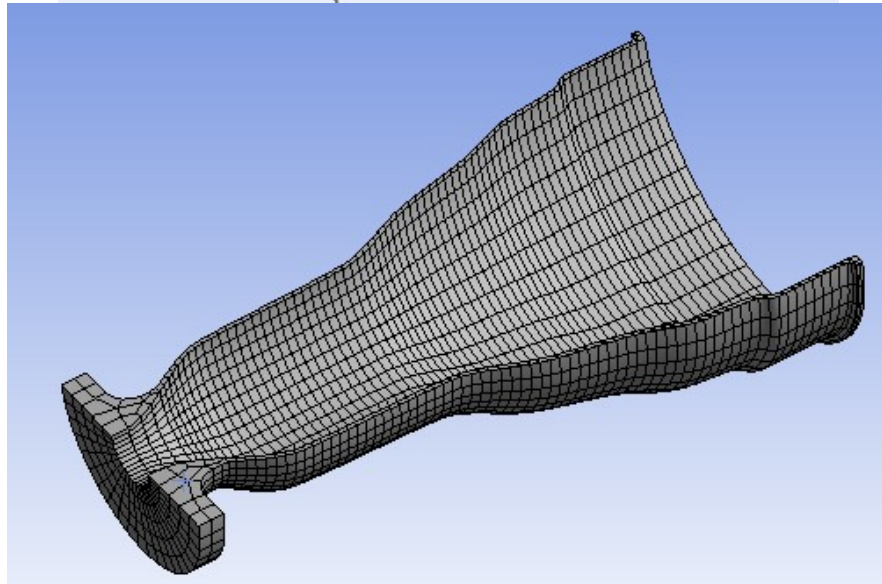
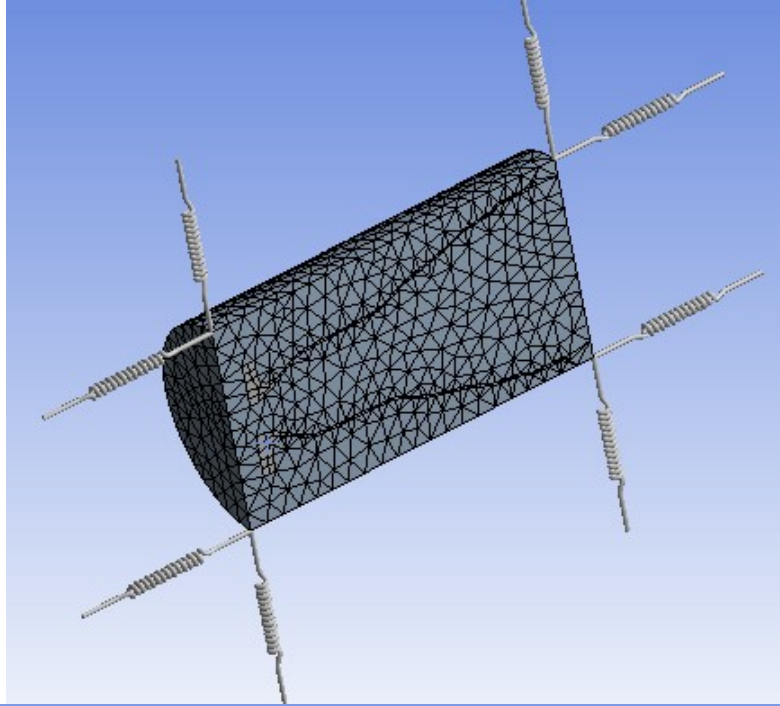


Figure 6 Overall mesh for distortion analysis (above) with final machined model (below).

ANSYS is an H element solver, generally, which adds emphasis to needing smaller elements. Each of the elements are using mid-sized nodes so the stress along the boundary of the element is described with a quadratic relationship, which adds to the accuracy of the results. The spring elements shown in Figure 5 and Figure 6 are soft spring elements designed to allow the part to expand and contract freely. Each spring element is connected to "ground" or in other words is constrained with zero translation on the side opposite of the part under consideration. Spring elements were needed to allow the solver to converge on a non-linear material solution. ANSYS automatically adds soft spring elements when the part is not sufficiently constrained but in this case the solver needed assistance for convergence. The added springs on the left and the right in Figure 5 have 10 N/m stiffness while the springs on the bottom of Figure 5 and the springs in Figure 6 have 25 N/m stiffness. Both spring stiffness values are well below the stiffness of the part and have negligible impact on the results.

The analysis in the quench part is a coupled thermal/stress analysis. Transient thermal analysis is performed until the part temperature matches the boiling temperature of the water. At each step of the transient thermal analysis the thermal gradient across the part is determined and an accompanying thermal strain is calculated. The thermal strain creates a thermal stress within the part. Equations 2.2.1 and 2.2.2 are utilized to represent the stress strain relationship for the material.

$$\sigma = E\varepsilon$$

Equation 2.2.1

$$\sigma = \sigma_y + k(\varepsilon_p)^n$$

Equation 2.2.2

Equation 2.2.1, Hooke's Law, is applied below the yield stress of the material.

Equation 2.2.2, Ramberg-Osgood approximation, is applied above the yield stress of the material. In equation 2.2.2 ε_p is the integrated plastic strain. Plastic strain is nonlinear in nature and path dependant. Once plastic strain is initiated equation 2.2.2 is followed. However, if unloading occurs equation 2.2.1 is followed with a stress offset and the yield stress changes to the stress where unloading occurred. The yield stress changing is a result of strain hardening in the material.

2.3 IMMERSION IN LIQUID NITROGEN

To model the immersion in liquid nitrogen step a heat transfer coefficient from figure 5(c), page 1952, [18] was used. The aforementioned heat transfer coefficient creates very little temperature gradient across the part in this analysis and has been shown to be effective for the part used in Ko [18]. The heat transfer coefficient in Ko is two orders of magnitude smaller than the peak heat transfer coefficient used for initial quench.

2.4 STEAM BLAST

The steam blast step is complete once the part has reached equilibrium with the liquid nitrogen. The part is then placed in a fixture. The fixture's function is to spread the steam evenly across the part. One way to do this is for the fixture to have holes evenly spread across the fixture. The fixture resides within a container. The steam is blasted into the container and passes through the holes in the fixture and hits the part. The holes are sized so that the steam fills the space between the container and the fixture and then moves through the holes in the fixture [23]. Figure 3 shows the model for the steam fixture.

The steam blast step is done in two different analysis steps. The first step is done in ANSYS Fluent, CFD software, modeling the steam flowing around the part. Figure 7 shows the axially symmetric mesh used for the fluid flow analysis. Table 4 summarizes the inputs for the fluid flow analysis.

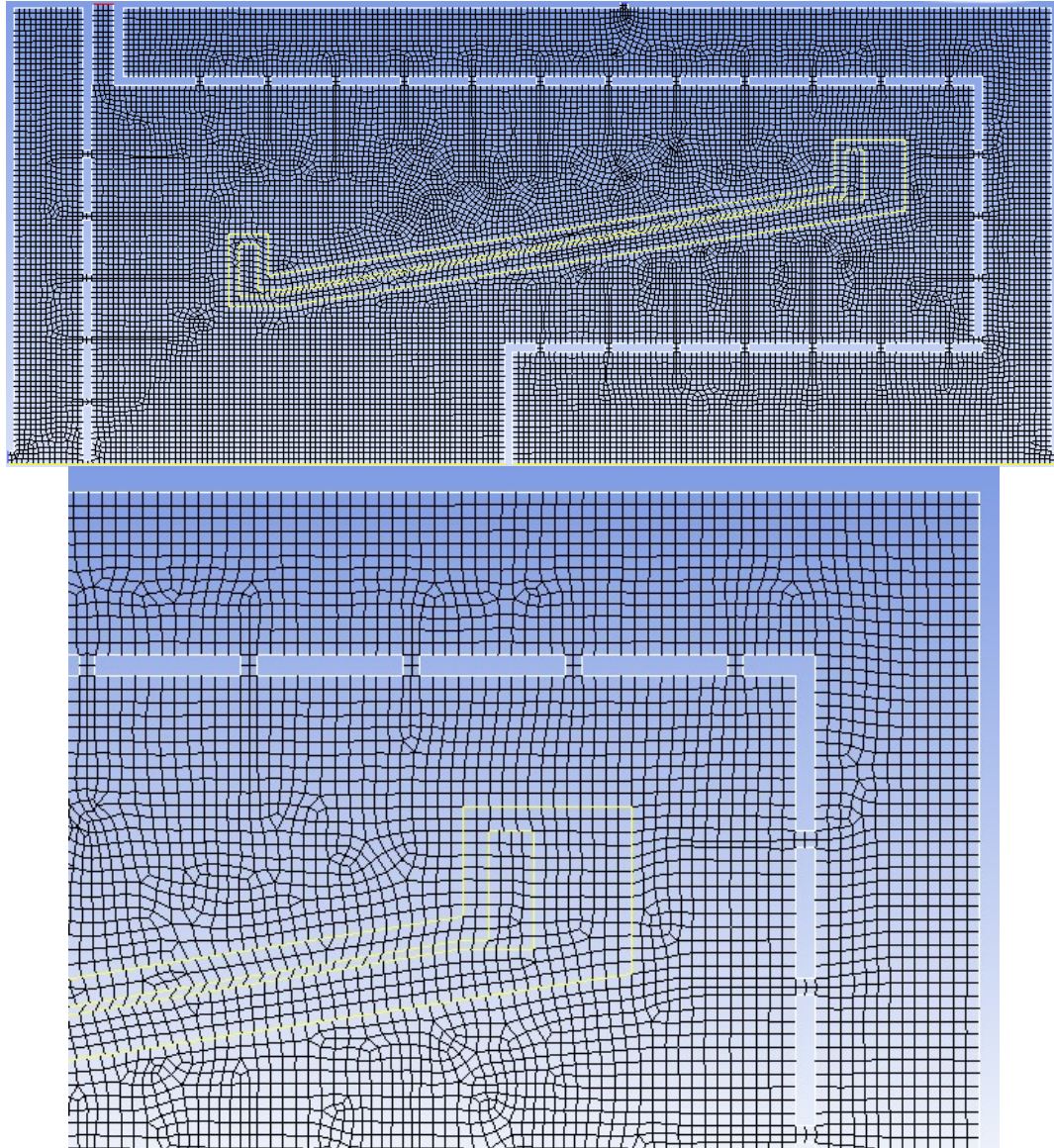


Figure 7 Overall view of mesh used for modeling steam flow (above) with close up view (below).

Table 4 Parameters for steam flow analysis.

	Value	Unit
Steam Input Pressure	928696	Pa
Steam Input Temperature	172	C
Steam Output Pressure	101325	Pa
Steam Output Temperature	22	C

The CFD analysis involved using $k-\omega$ turbulence model. The $k-\omega$ turbulence model is a common model used in CFD analysis and tends to have an easier time achieving convergence than the $k-\varepsilon$ turbulence model.

The flow achieves turbulence because of the high velocity the steam is moving at as well as the fairly complex geometry that the steam has to move through/around. The CFD analysis is used to determine the heat transfer coefficient and the flow temperature near the surface of the part. Once the heat transfer coefficient is determined ANSYS imports the heat transfer coefficient and flow temperature and performs a transient thermal analysis that can then be imported into the final static analysis.

2.5 AGE TO FINAL TEMPER

The final step of aging is used to achieve full strength of the material for aluminum 6061 in the T6 condition. The process of aging occurs in an oven where the temperature is ramped up slowly. The slow temperature change results in little change in residual stress [2]. This step is ignored for the residual stress prediction analysis.

3.0 RESULTS AND DISCUSSION

3.1 BENCHMARK

Before the uphill quench model and the distortion model were analyzed, a benchmark analysis was performed. The simple cylinder analyzed in Ko, [18], was analyzed by this author for uphill quenching in boiling water and the results compared. The purpose of the benchmark was to establish confidence in the model setup by trying to repeat the results achieved in Ko. Table 5 summarizes the results of both Ko [18] and this thesis.

Table 5 Benchmark results compared.

Author:	Interior (MPa):	Exterior (MPa):	Interior (MPa):	Exterior (MPa):
Ko [23]	120	-71.8	79.8	-42.8
Jones	107	-79	93.6	-48.2
% Difference:	10.8	10.0	17.3	12.6

The results were relatively close as shown in Table 5. One of the challenges from using Ko, [18] as a benchmark was it wasn't clear where the material properties used by Ko came from. It is significant to note that the general shape/trend of the stresses is the same. Compressive stresses were found on the exterior and tensile stresses were found on the interior. A stress reversal was also observed where in the first few seconds of the quench the outside was in tension and the inside in compression. The stress reversal is expected because initially the inside is not changing significantly in temperature while the outside is changing rapidly.

3.2 QUENCH

The temperature fall during the glycol quench for the uphill quench model happened rapidly. Equilibrium temperature was reached in 19.2 seconds. Figure 8 shows the maximum and minimum predicted temperature over time during quench for the uphill quench model. As expected, the exterior changes temperature much more rapidly than the interior.

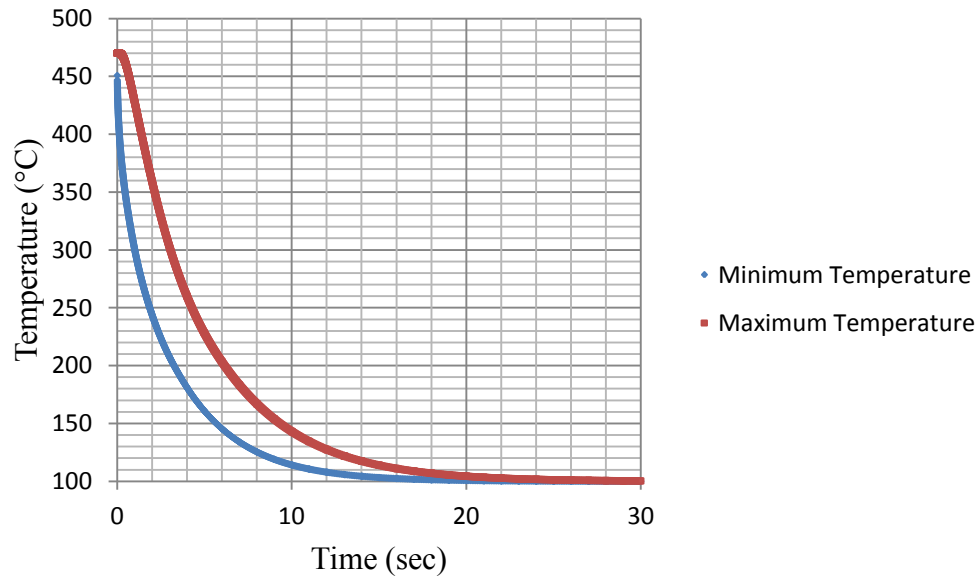


Figure 8 Predicted temperature over time for quench step for the uphill quench model.

The maximum temperature gradient across the uphill quench model is 128 °C and occurs about one second into the quench process. The temperature gradient stays relatively large until about ten seconds into the quench. The temperature gradient

seen in the uphill quench model is similar in magnitude to the 100 °C boiling water quench maximum gradient seen in Jeanmart and Bouvaist, [20]. The temperature gradient seen in the uphill quench model is much smaller than the 225 °C cold water quench maximum gradient seen in Jeanmart and Bouvaist, [20]. This demonstrates that the glycol is slowing the quench as intended.

The distortion model has a much thicker cross section compared to the uphill quench model. The distortion model achieves a maximum temperature gradient of 202 °C five seconds into the quench. The distortion model takes much longer to reach equilibrium due to its increased thickness and mass. Figure 9 shows the maximum and minimum predicted temperatures during quench of the distortion model.

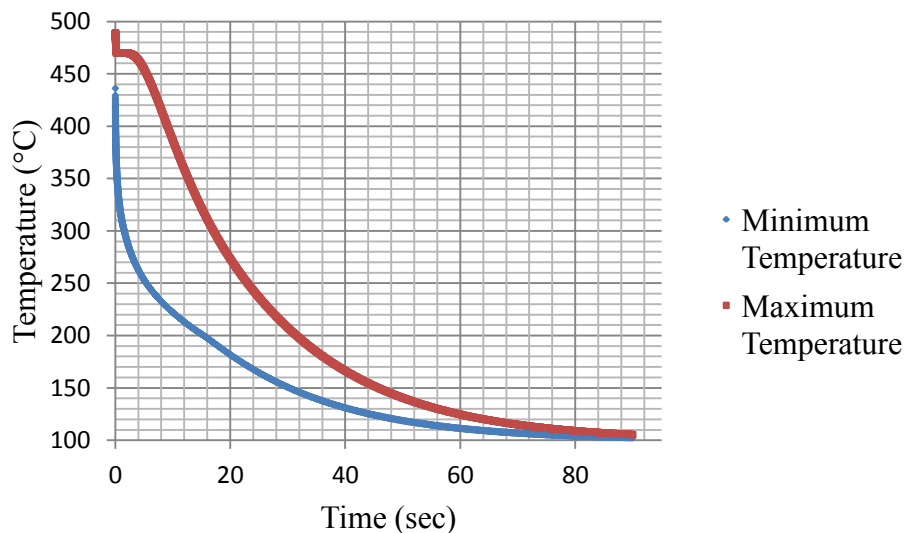


Figure 9 Predicted temperature of the distortion model over time during quench.

3.3 STEAM BLAST

The analysis in fluent shows that the steam was successfully accelerated up to a high velocity. The analysis also indicates that there are regions close to the rough machined part of relatively low velocity in the steam profile. The non-uniform velocity distribution demonstrates some of the complexity of the uphill quench process.

Figure 10 shows that the input regions achieve the highest velocity. The cut outs between the container and the fixture spread out the steam flow. The opening closest to the side input is a source of one of the two fastest flows next to the surface of the rough tapered cylinder. The output portion also has relatively high velocity as the steam is trying to escape. The static pressure drops at the output as the air speeds up to escape.

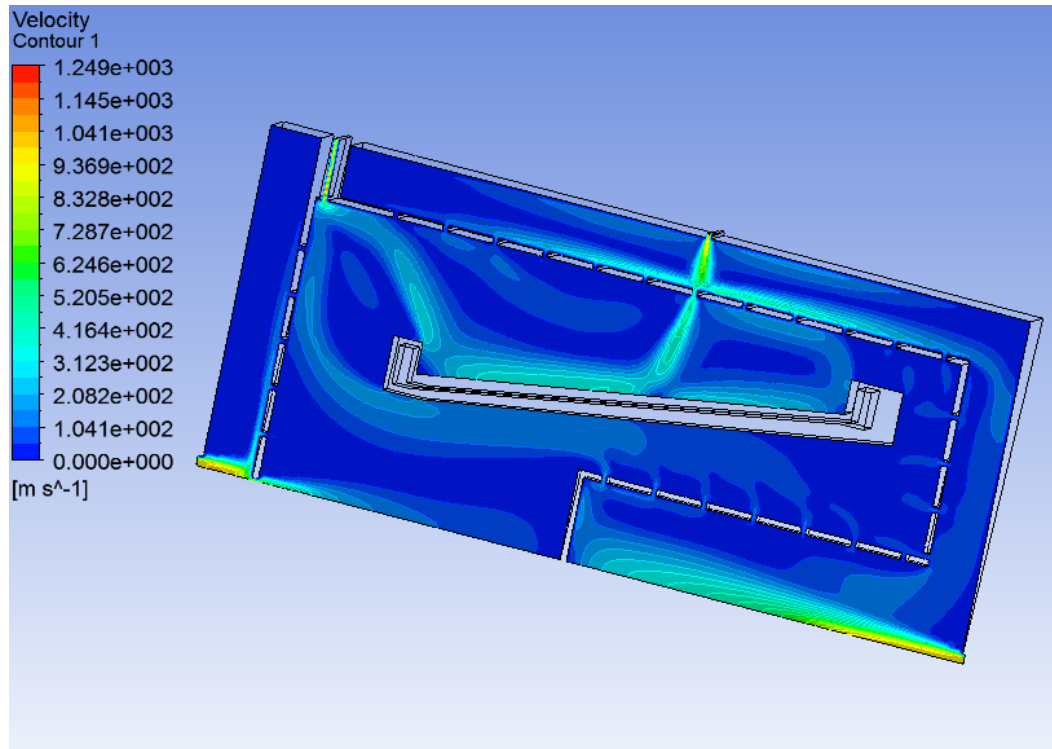


Figure 10 Predicted velocity profile at the end of the steam blast period.

Figure 11 shows that the largest heat transfer coefficient occurs where the steam velocity is the highest, which is to be expected. It is interesting to note that all of the indicated heat transfer coefficients are much lower than the 1510 W/m^2 that Ko, [18], predicts for boiling water uphill quench. Croucher [8,23] indicates that boiling water uphill quenching would produce a less severe temperature gradient than steam driven uphill quenching.

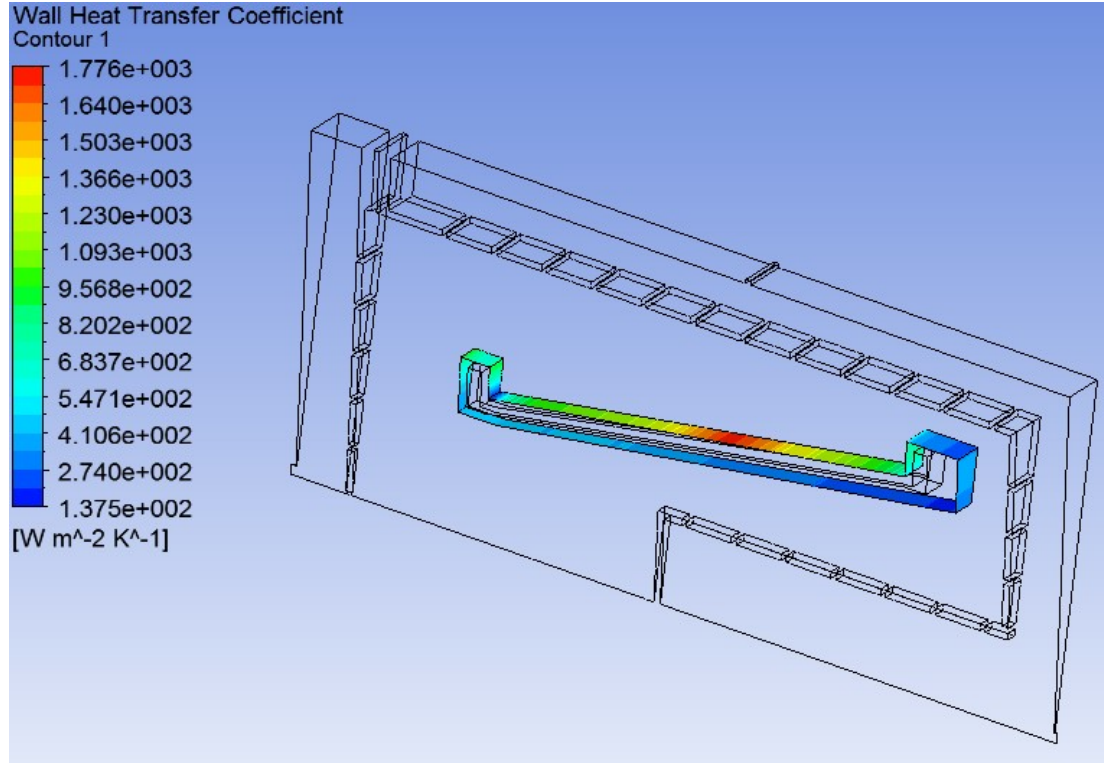


Figure 11 Predicted heat transfer coefficient during the steam blast.

Many of the experiments done between boiling water uphill quenching and steam uphill quenching were done with flat plates. It is very easy with steam to get a much higher convection coefficient for flat plates than what is shown in Figure 11. The steam can be pointed in such a way that the steam runs over the surface of the plate fairly evenly. The complex geometry shown in this research indicates that it may be very difficult with complex geometry to achieve the desired high heat transfer coefficients with steam uphill quenching. Fortunately the temperature of steam can be made much higher than the temperature of boiling water to aid in achieving high heat transfer rates.

Figure 12 shows the predicted maximum and minimum temperatures in the uphill quench model during the steam blast. The predicted temperature gradient for the steam blast reaches 100 °C. This is close to the same temperature gradient as was reached during the quench but has different meaning, which is discussed later.

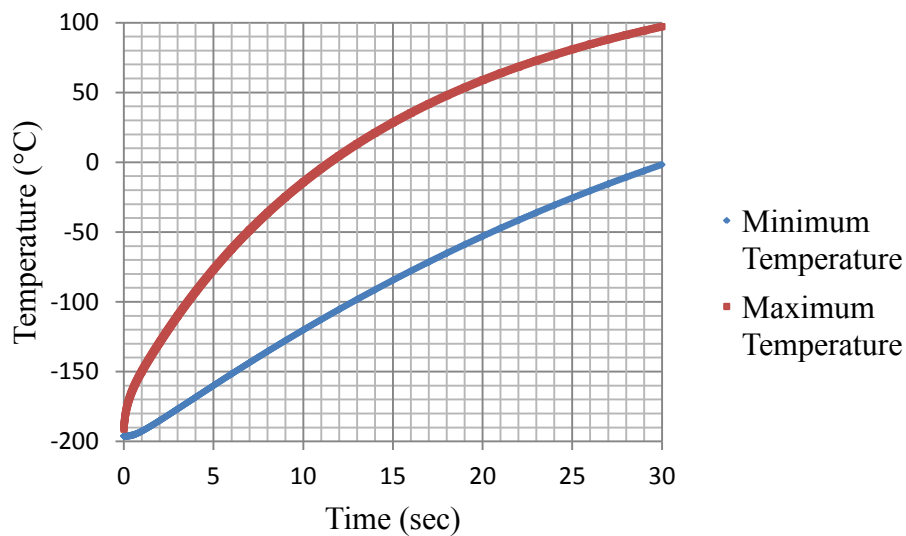


Figure 12 Temperature profile of the uphill quench model during steam blast over time

3.4 RESIDUAL STRESS

The temperature change across the entirety of the uphill quench model for the quench, liquid nitrogen cool, and steam blast/uphill quench was used as a temperature input for the final non-linear material static stress analysis. Figure 13 shows that after quench the residual stress in the part is relatively low compared to many other parts considered in literature, [2] [18]. The exterior residual stress is compressive and

interior residual stress is tensile which is what is generally found after quench. Initially during quench the outside is shrinking while the inside remains unchanged which compresses the inside and puts in tension the outside. Later once the outside has cooled and the inside catches up the tension/compression reverses.

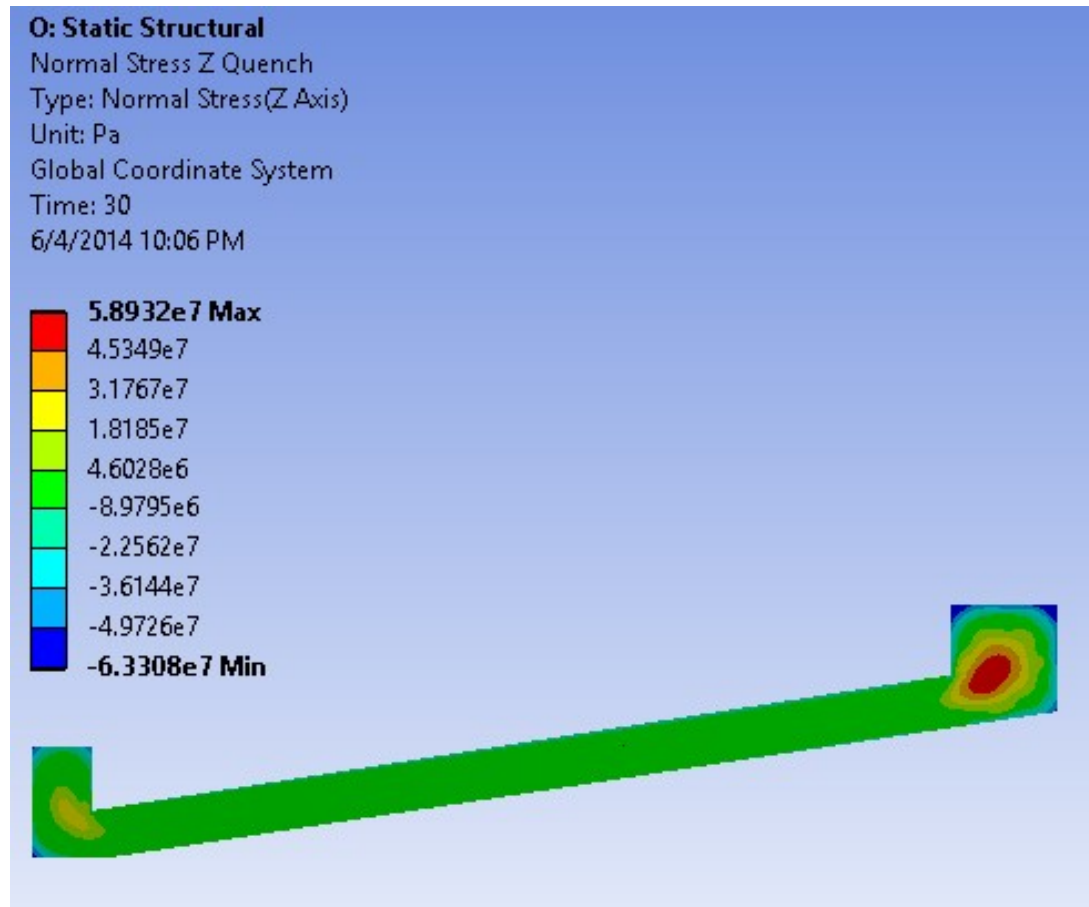


Figure 13 Residual circumferential stress after quench.

Figure 14 shows a relatively small change in residual stress compared to quench residual stress after the steam blast. Since this part was heat treated with a relatively small cross section and with glycol very little residual stress develops in the first place. During uphill quenching the heat transfer is much slower than the initial

quench so the change in residual stress here is expected to be smaller. The more significant change in residual stress comes from the larger diameter section where more mass is present. In the larger mass region a 19% reduction in residual stress occurs. For the benchmarking mentioned earlier where the part had much more thermal mass a 40% reduction in residual stress occurs. The additional mass allows for a more significant temperature gradient and a higher level of force to reduce the residual stress in the part. Figure 14 also shows that a noticeable level of tensile stress develops where the heat transfer coefficient is the highest. One of the challenges with uphill quenching is that it can create undesirable tensile stresses that can lead to early fatigue failure or distortion issues.

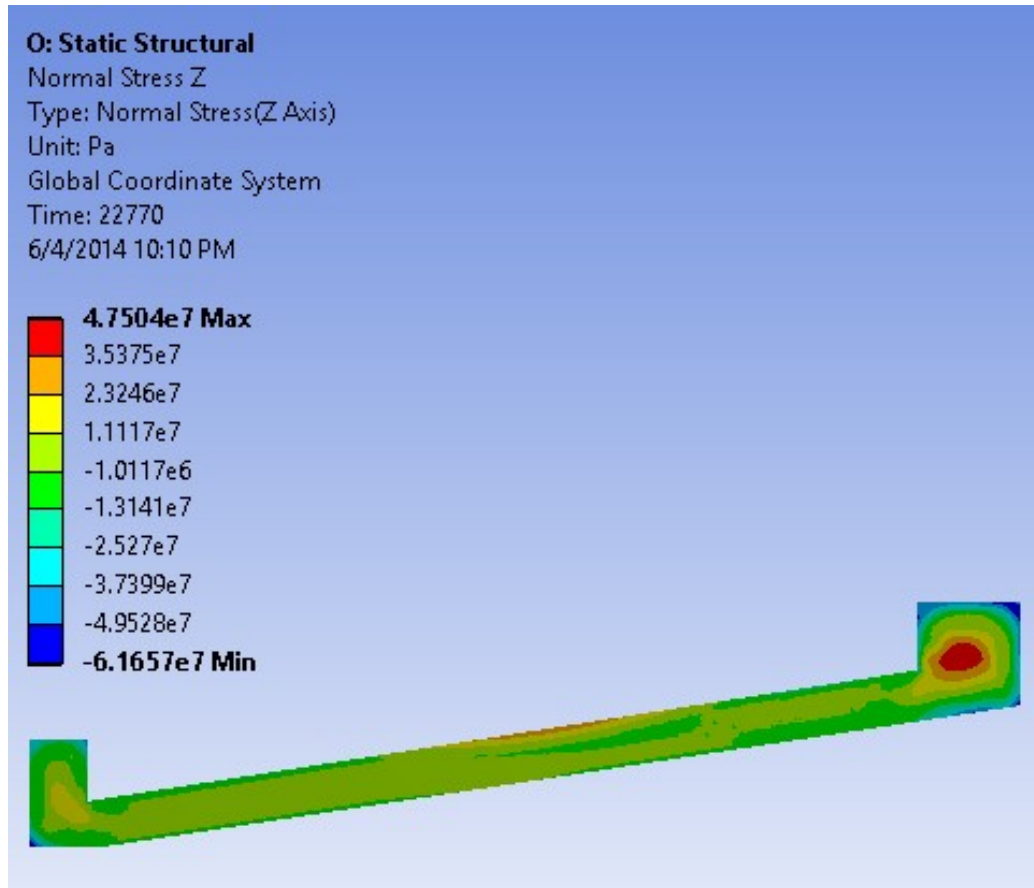


Figure 14 Circumferential residual stress after steam blast/uphill quench.

To verify the results of this analysis the predicted results were compared against measured circumferential stress; see Table 6. The uphill quench process performed on the part shown in Figure 3 was done by Newton Heat Treating Company Incorporated. Measurements were conducted by Proto Manufacturing using the X-ray diffraction method. Measurements were made at the surface, .0254 mm down, and .127 mm below the surface. Electro polishing was used to remove material without impacting the residual stress in the part. By measuring the residual stress .127 mm below the surface the surface effects can be eliminated. Typically the

effects of uphill quenching are much more pronounced right at the surface. The elements used in this analysis are not small enough near the surface to capture surface effects.

Table 6 Measured and predicted residual stress for the uphill quench model.

	Circumferential stress	
	Predicted (MPa)	Measured (MPa)
Larger Flange Outer Diameter	-43.3	-41.4 +/-6.9
Smaller Flange Outer Diameter	-20.1	-6.9 +/- 6.9

The analysis here assumes an axially symmetric part. In reality there is some asymmetric behavior from the way the quench nozzles are mounted to the steam fixture. The steam nozzle input to the side of the fixture was not continuous around the outside of the fixture but occurred in a few separate locations. In the analysis the model was suspended in the fluid where in the real situation the part sits on mounts that would block the steam flow. The measurements made on the part were after age to final temper. The analysis assumes the age is not a significant contributor to the final stress; however, Ko shows an additional 15-20% stress reduction during age [18,19]. Material variability and the previously mentioned factors all contribute to the errors in the results.

A major advantage of the uphill quench process is that despite the residual stress being fairly large the shape of the residual stress pattern follows the shape of the final part. Once the final material is removed the part remains in equilibrium because material is removed evenly on all surfaces. In the end the analyzed part only

moved .03 to .05 mm after final machining which was well within the desired dimensional stability for this part.

The residual stress analysis for the distortion model was handled the same way as the uphill quench model but with fewer steps. The temperature profile from the quench step was set as an input into a static non-linear analysis. Figure 15 shows the circumferential stress that resulted in the distortion model after quench.

Unfortunately no residual stress measurements were made on this part. However, extensive distortion measurements were made on the part. Figure 16 shows the total deformation, or deformation magnitude, that the part experienced after being final machined.

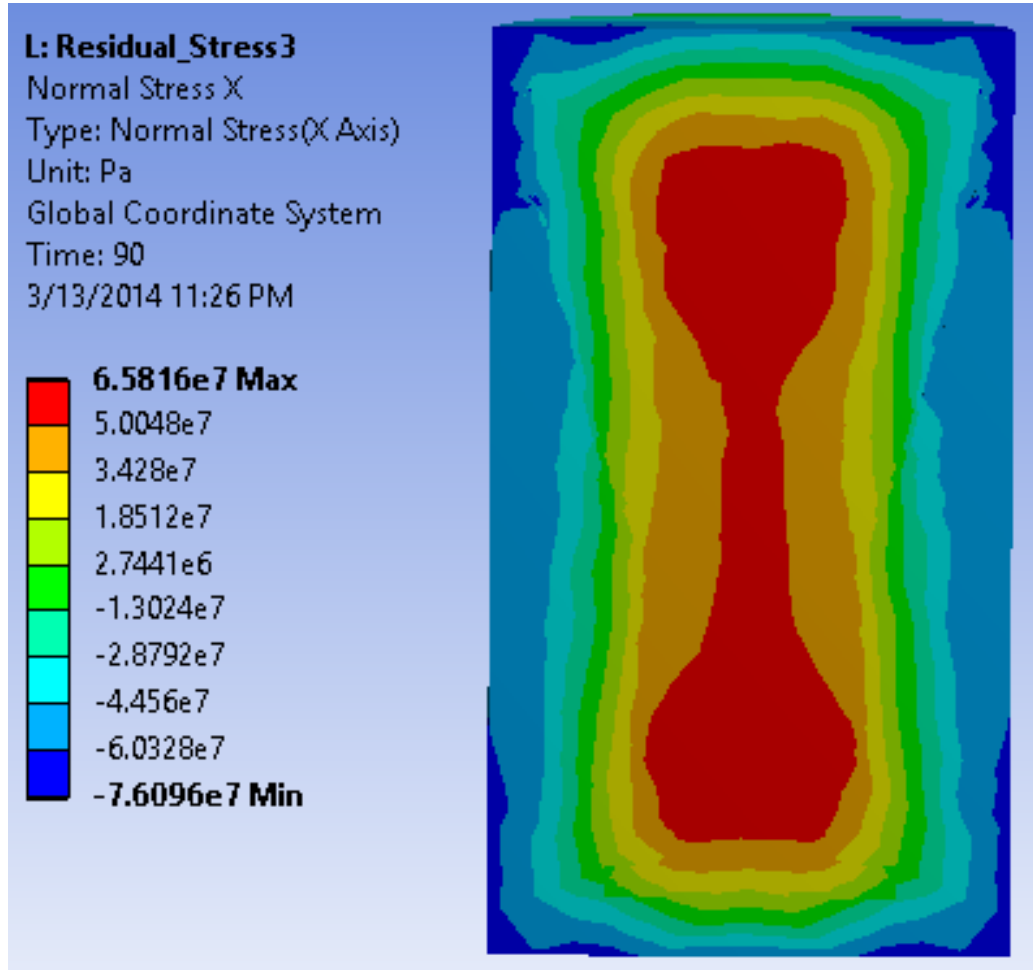


Figure 15 Circumferential stress for the distortion model after quench.

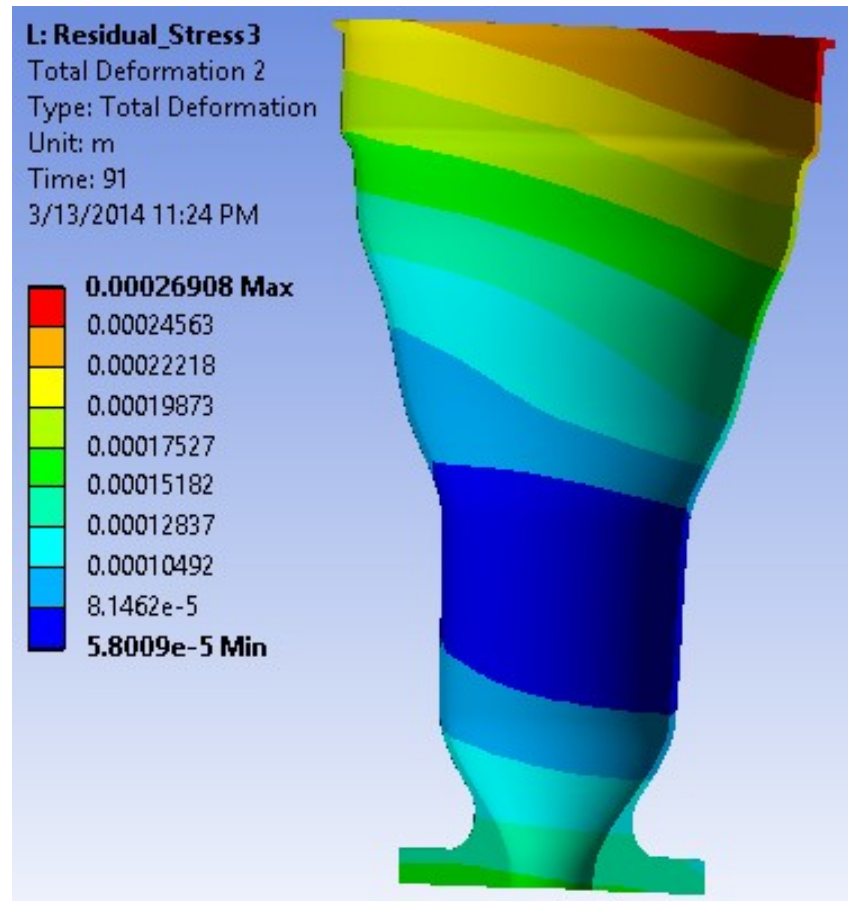


Figure 16 Total deformation of distortion analysis model after rough material removed.

It can be seen in Figure 16 that the deformation experienced by the part here is not axially symmetric. It is important to remember that right after quench the outside of the original billet is in compression. The areas of the finish machined distortion sub-model that have a larger diameter were experiencing this state of compression. Once the material is removed the larger diameter sections expand to relieve the

compression. The inner area of the original billet is in tension right after quench. The smaller diameter sections of the distortion model were experiencing this state of tension. Once the material is removed the smaller diameter sections contract to relieve the tension. Since there is an axis offset the compressive areas further away from the billet center axis expand more than the compressive areas closer to the billet center axis. The same is true for the areas in tension but the contracting is higher in magnitude the closer the section of the finish machined distortion sub-model is to the billet center axis.

The inspection results in Figure 17 are showing the elliptical effect that was mentioned earlier. It is important to note when comparing Figure 17 and Figure 16 that the magnitude differences in results appear because Figure 16 are deformations relative to the initial solution heat treated part (at temperatures well above room temperature). Figure 18 shows deformations for Figure 14 that have been normalized at the largest inner diameter section. The normalizing performed in Figure 18 was done by taking the average predicted deformation at the largest inner diameter section on the finish machined distortion sub-model and subtract it off the total deformation.

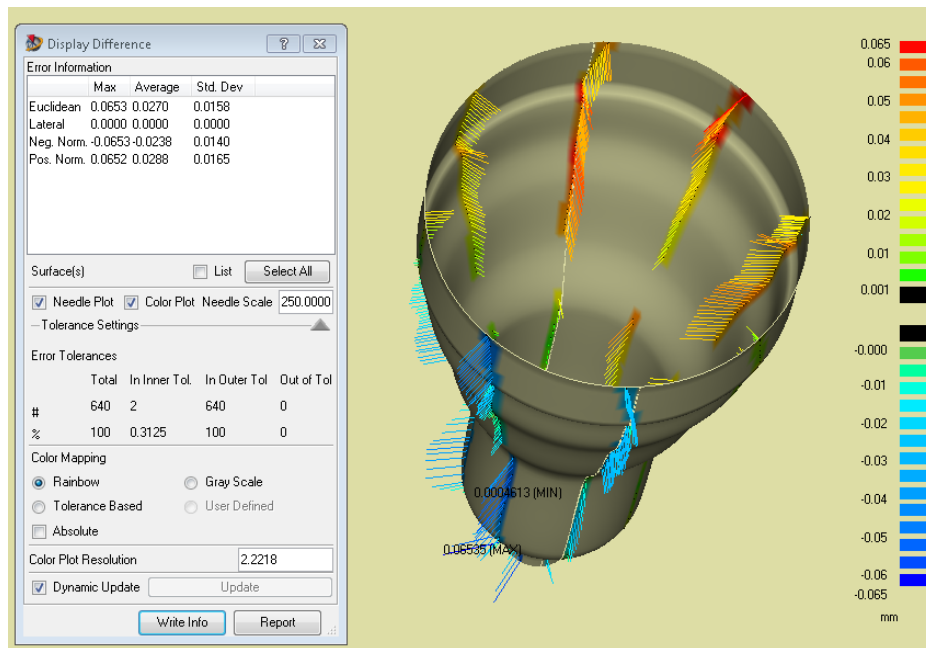


Figure 17 Internal measurement results using Imageware.

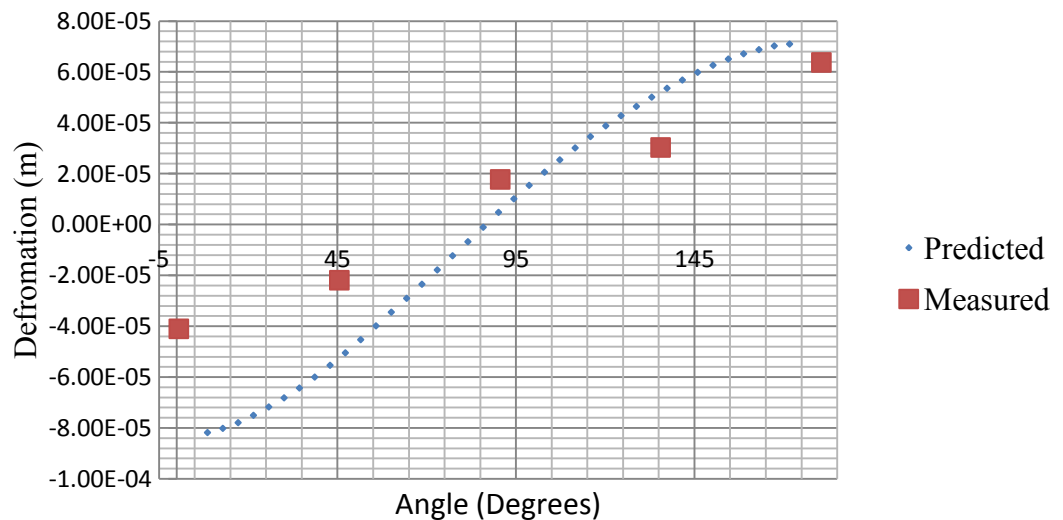


Figure 18 Predicted vs. measured distortion of the finish machined part for distortion modeling.

The distortion results in Figure 18 are good but could use some further development. The real part for the finish machined distortion sub-model was one of the main inspirations for this thesis and the behavior seen in the part was unexpected. To really ensure good correlations between the measured and predicted the part would have to be carefully measured before starting machining to see where the machining center axis would end up relative to the heat treat center axis. In addition residual stress measurements and temperature measurements should be taken to help verify the heat transfer coefficients used. Another problem is that to date the ANSYS license available has been limited to 32,000 nodes because it is an academic license and access to the unlimited version was not available to use during the given study time. The distortion results are good enough to demonstrate that the approach has great merit.

The machine shop can also have an impact in the final distortion measurements. It is common practice for machinists to rough the part, take the part out of the machine, and watch the part move. Once the part has moved the machinist shims the part into the mill/lathe (being careful to not constrain the deformations that occurred after removing material). The process is completed as the part gets closer and closer to final dimensions.

4.0 CONCLUSIONS

The residual stress in the tapered cylinder with flanges shown in Figure 3 was predicted for the uphill quench procedure. To predict the residual stress heat transfer coefficients were used from literature for initial quench and liquid nitrogen. The heat transfer coefficient for the steam blast was predicted using ANSYS fluent. In the end the temperature profile for the entire procedure was predicted and used in establishing the residual stress. The predicted vs. measured residual stress on the larger diameter section was accurate to within 4.6% whereas the smaller diameter section accuracy was much worse. Further development could be done in predicting the residual stress due to the uphill quenching procedure by measuring the temperature of the part in multiple locations as well as the steam pressure inside the fixture.

Despite the high levels of residual stress that existed in the part after the entire process the strength of the part is much higher than in the original billet and the residual stress pattern inside the part follows the part shape. The final part moved .03-.05 mm after final machining, which was within the desired dimensional stability. By modeling the steam flow for the uphill quenching process the areas of high steam velocity and low velocity can be identified. The fixture and nozzle design can be optimized by moving around the nozzles and configuring the holes in such a way to more evenly spread out the steam across the part. The steam temperature and pressure at the inlet can be optimized to get a high enough heat transfer to reduce the residual stress while not reversing the residual stress (going from high compression on/near the surface to high tension on/near the surface). The steam output is an

important parameter because it plays a major part in maintaining the pressure inside the fixture. Design work could be done to leave the lid of the fixture unclamped but apply weight so that only the desired pressure or higher would open up the container. These are just a few process parameters that could be optimized with this analysis approach.

The distortion results for are a good set of initial results. Further development could be done to refine the results. A more refined mesh and closer investigation into the contact pressure between the rough part and the final tapered cylinder would aid in the accuracy of the results. The most helpful way to further refine the analysis results would be to develop a test unit and make the needed dimensional measurements and temperature measurements through the process to more fully correlate the analysis model. In many cases the distortion results are what the designer cares about most. By having good distortion prediction results the designer could know if they needed to do uphill quenching or some of the other methods listed in Table 1.

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APPENDIX RESIDUAL STRESS AND MACHINING

During the first few parts at Space Systems Loral that were getting processed using uphill quenching a test coupon was processed, shown in Figure 19. After the uphill quenching was processed X-ray measurements were taken at Newton Heat Treating Company Incorporated. The results of the measurements were much higher than expected. The concern was whether or not the measurement results were surface effects or not. At the very top of Figure 19 a lighter colored section of the test coupon can be seen. The lighter colored section is where .05 in of material were removed all around. The material removal was done before the measurements were taken at Proto Manufacturing. The measurement at point W1 shows the high tensile stresses that were developed because of the material removal process. The measurements also show that the machining effects disappear at about .005 in below the surface.

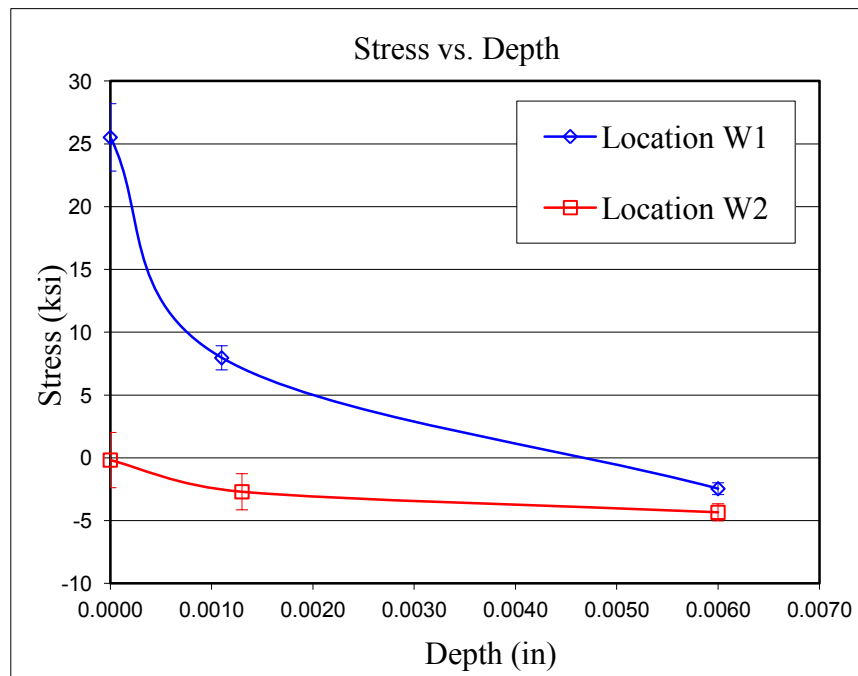


Figure 19 X-Ray diffraction results from Proto Manufacturing (below) with locations (above).