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Quenching and Cold-Work Residual Stresses in Aluminum Hand Forgings: Contour Method Measurement and FEM Prediction

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Abstract. The cold-compression stress relief process used to reduce the quench-induced stresses in high-strength aerospace aluminum alloy forgings does not fully relieve the stresses. This study measured and predicted the residual stress in 7050-T74 (solution heat treated, quenched, and artificially overaged) and 7050-T7452 (cold compressed prior to aging) hand forgings. The manufacturing process was simulated by finite element analysis. First, a thermal analysis simulated the quench using appropriate thermal boundary conditions and temperature dependent material properties. Second, a structural analysis used the thermal history and a temperature and strain-rate dependent constitutive model to predict the stresses after quenching. Third, the structural analysis was continued to simulate the multiple cold compressions of the stress relief process. Experimentally, the residual stresses in the forgings were mapped using the contour method, which involved cutting the forgings using wire EDM and then measuring the contour of the cut surface using a CMM. Multiple cuts were used to map different stress components. The results show a spatially periodic variation of stresses that results from the periodic nature of the cold work stress relief process. The results compare favorably with the finite element prediction of the stresses.

Introduction

High strength aerospace aluminum product forms are quenched to obtain desirable mechanical properties such as strength and fracture toughness. Quenching generates a stress state due to non-uniform plastic flow during cooling. In plates, stress relief by stretching is quite effective in reducing the residual stresses by a factor of about 10 [1]. Because of their size and shape, forgings require a cold-work compressive stress relief process to reduce the quench-induced stresses. Stress relief by compression does not fully eliminate the quench-induced stresses and thus, the product form contains residual stress. The product form is subsequently machined to final dimensions, and the residual stress can cause the final part to distort, a costly problem for aerospace manufacturers [2]. Understanding the generation and relief of residual stress through predictive techniques and measurements is critical to eliminating machining distortion problems during manufacturing. This study measured and predicted the residual stress in 7050-T74 and 7050-T7452 hand forgings.

Large cold-compressed forgings provide a challenge for residual stress measurement. The residual stress distributions are too complex to be measured by techniques such as layer removal [3] and crack compliance [4,5] that can only measure 1-D through-thickness stress variations. The forgings are too large for practical measurement using neutron diffraction [6,7]. The scarcity of the literature to date on residual stresses in similar forgings is evidence of the difficulty in measuring the stresses (and predicting them as well). For example, residual stresses in similar 7050-T7452 forgings were predicted with FEM and compared with neutron diffraction measurements [8]. However, the large size of the forgings constrained the measurements because of time limitations; therefore, the results were not very informative. Quenching stresses were also predicted in similar size 7010 forgings and then measured (near the surface only) using hole drilling and x-ray diffraction [9]. Stresses after cold compression were modeled subsequently, but were only compared against coarse measurements by layer removal [10].

Specimens

Two 7050 aerospace aluminum hand forgings were used for residual stress measurement. The dimensions of the first forging were 107 x 158 x 718 mm. This specimen was solution heat treated and quenched in a 70°C quenchant [11] followed by an appropriate compressive cold-work stress relief process using flat cold-work dies with rounded edges. This specimen also received an artificial age practice for a –T74 condition and thus, it has the designation of 7050-T7452 where the 52 declares a compressive stress relief process.

The dimensions of the second hand forging were 107 x 158 x 359 mm. This specimen was solution heat treated and quenched into a 60°C water quench, which typically generates large stresses. No stress relief processing was conducted on this specimen before receiving the appropriate artificial age practice. The designation of this specimen is 7050-T74. For this study, the objective for this material process path was to create a part with significantly high residual stress.

Residual Stress Measurement

In the contour method [12], a part is carefully cut in two causing the residual stresses normal to the cut plane to relax. The contour of each of the opposing surfaces created by the cut is then measured. The deviation of the surface contours from planarity is assumed to be caused by elastic relaxation of the residual stresses and is used to calculate the original residual stresses. One of the unique strengths of the contour method is that it provides a full cross-sectional map, as compared to just a 1-D depth profile, of the residual stress component normal to the cross section.

Part Cutting. Figure 1 illustrates the three cuts that were used to map residual stresses in the 7050-T7452 (cold compressed) forging. The first cut sectioned the part in two lengthwise and was used to measure the axial stresses. After the first cut, the contour of the surface created by the cut was measured on both of the two pieces. Then the second and third cuts were made on the remaining pieces of the forging in order to measure the transverse residual stresses. Cut 1 affected the stresses measured near cut 1 by cuts 2 and 3. Rather than try to correct for this affect, cut 1 was simulated in the predictive model to allow a direct comparison with the measured stresses. On the shorter 7050-T74 forging, a cut like cut 1 in Fig. 1 was used to map the axial stresses from quenching.

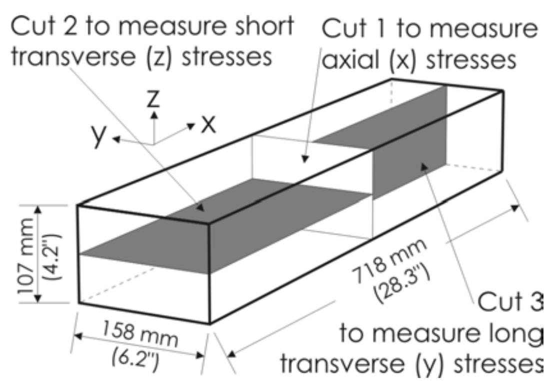

Figure 1. The 7050-T7452 forging and three cuts used to map residual stresses in the forging.

The cuts were made by wire electric discharge machining (EDM) using a 150 μm diameter brass wire. The part was submerged in temperature-controlled deionized water throughout the cutting process. "Skim cut" settings, which are normally used for better precision and a finer surface finish, were used because they also minimize any recast layer and cutting-induced stresses [13]. Because the part deforms as stresses are relaxed during the cutting, the cut could deviate from the original cut plane, which would cause errors in the measured stresses. Therefore, the part was constrained by clamping the part on both sides of the cut to a backing plate. To prevent any thermal stresses, the specimen, backing plate, and all the clamps were allowed to come to thermal equilibrium in the water tank before clamping.

Surface contouring. After each cut, the forging was unclamped, and the contours of both cut surfaces were measured using a coordinate measuring machine (CMM). A CMM registers mechanical contact with a touch trigger probe, and an opto-electric system using glass scales gives the probe location, which is combined with machine coordinates to locate the surface. For the measurements on these forgings, a 1 mm diameter spherical ruby tip was used on the probe. The cut surfaces were measured on a grid spaced 1 mm for the smaller surfaces up to 2 mm for the largest surfaces, giving between 13,000 and 17,000 points on each cut surface.

Figure 2 shows the contour measured for cut 3 from Fig. 1. The peak-to-valley amplitude of the contour was about 60 μm and was easily resolved by the CMM. The high spots in the contour correspond to regions of the forging that were under compressive residual stress, and the low spots to tensile regions. The periodic nature of the contour is indicative of the multiple cold compressions applied to the forging.

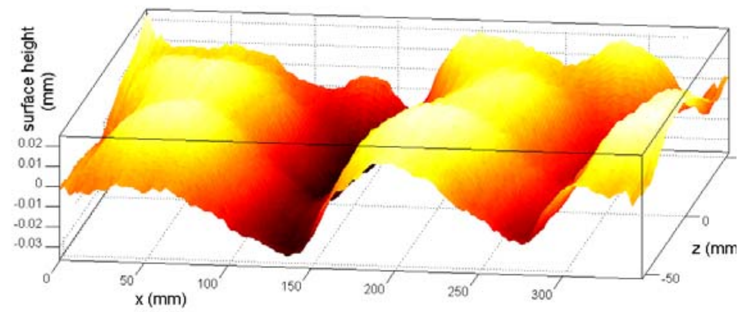

Figure 2. The contour measured for cut 3 in Fig. 1, averaged between the two opposing surfaces created by the cut.

Data Reduction. The stresses that were originally present on the plane of the cut were calculated numerically by elastically deforming the cut surface into the opposite shape of the contour that was measured on the same surface [12]. This was accomplished using a 3-D elastic finite element (FE) model. A model was constructed of one half of the part—the condition after it had been cut in two—but with the cut surface modeled as flat instead of the slightly deformed shape measured by the surface contours. The material behavior for 7050 aluminum was modeled as isotropic linearly elastic with Young's modulus of 72 GPa and Poisson's ratio of 0.33. For the stress calculation, the opposite of the measured surface contour was applied as displacement boundary conditions on the surface corresponding to the cut.

The steps outlined here to process discrete surface contour data, i.e., the point clouds, into a form suitable for calculating the stresses with the FE model are described in more detail elsewhere [14]. The point clouds from the two opposing surfaces created by a cut were aligned to each other, then interpolated onto a common, regular grid, and then averaged point by point. (Averaging the two contours is crucial to minimize several error sources [12]). Next, the data were fit to a smooth surface using smoothing splines. Finally, heights of the smoothed surface were evaluated at the coordinates of the nodes in the finite element model, the signs were reversed, and the results were written into the FE input deck as displacement boundary conditions.

Modeling

ABAQUS [15] was used to model the material and processing in 3-D for both specimens. Since the two hand forgings were to be cut in half lengthwise, quarter symmetry rather than eighth symmetry was used to model the parts. The longer piece was represented by 10 x 15 x 140 elements and the shorter part was modeled with 10 x 15 x 70 elements. The processing of the material was simulated using four types of models: thermal, mechanical, cold-work stress relief and cutting.

The thermal model used thermal boundary conditions for the given quenchant, i.e., heat transfer coefficients as a function of surface temperature, applied to all external surfaces of the modeled part. Symmetry planes were insulated. The results of this analysis were the nodal temperatures as a function of time. The longer part was subjected to thermal boundary conditions representing the 70°C immersion quenchant and the shorter piece was subjected to thermal boundary conditions for a 60°C water immersion quench. These models used an initial temperature of 477°C, the solution heat treatment temperature, and used variable thermal-mechanical values for the specific heat, thermal conductivity and density.

The mechanical model calculated the quench-induced stress state. This model used the nodal temperature histories along with the material's constitutive behavior model, which is both temperature and strain rate dependent, and the material's temperature sensitive expansion coefficients to predict the room temperature stress state after the quenching operation. Similar to the thermal modeling, two analyses were conducted here for the two forgings.

The cold-work stress relief model was a restart of the mechanical model as it used the quench-induced stress state as its starting point. The cold work die was modeled as a rigid surface with a 300 mm flat face and rounded edges. The stress relief process was modeled by 3% compression and a coefficient of friction of 0.25 as the die marched from the middle of the hand forging to one end with 150 mm of bite and 150 mm of overlap of the previous compression. Once the die completed the compressions in this direction, it marched from the center to the other end until the entire block had been compressed. The compressive cold work stress relief processing modeled here is typical of actual processing and should capture the general nature of the repetitive residual stress patterns. This analysis was only conducted on the longer forging because it was the only forging that had received stress relief processing.

The cutting model simulated cutting the long and short pieces in half, lengthwise. This model was a restart of the mechanical model for the shorter piece and a restart of the compressive cold work stress relief model for the longer piece. This model simply removed one half of the elements.

Results and Discussion

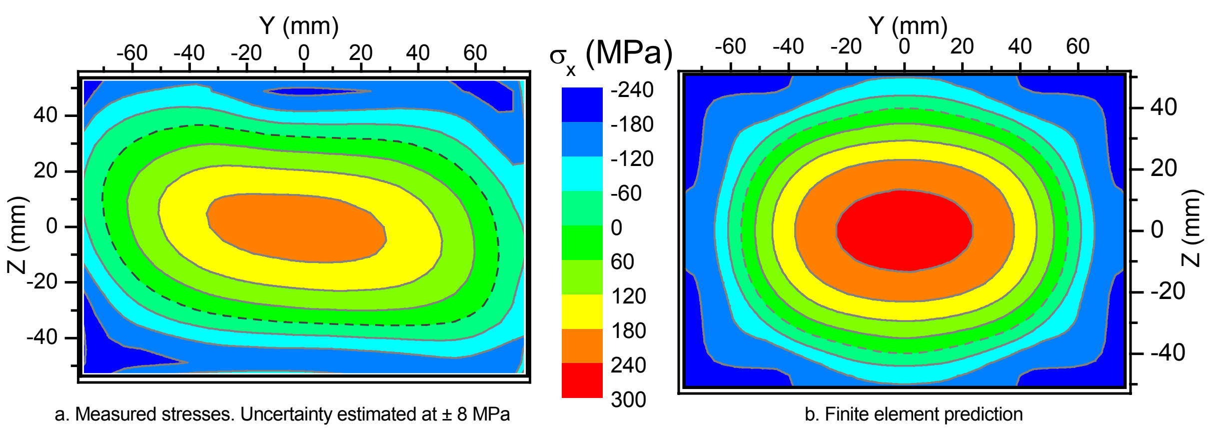

Figure 3. Axial (x) quenching stresses on plane of cut 1 (see Figure 1). a) measured by contour method. b) FEM prediction. The zero-stress contour line is dashed to distinguish tensile and compressive regions.

Figure 3a shows the measured axial residual stresses in the 7050-T74 forging, and Fig. 3b shows the corresponding FEM prediction. The results show similar stress distributions with similar peak compressive stresses but peak tensile stresses lower in the measurements by about 20% (both stress maps still satisfy equilibrium over the cross section). The predicted stress state is more symmetric than the measurements because the thermal boundary conditions are assumed to be identical around the perimeter. In the actual process, the proximity of other forgings in the quench bath and orientation of the forging all create asymmetries in the heat transfer. Considering the accuracy of the measurements and the difficulty in accurately simulating the material's constitutive response over the large range of temperature and strain rate, the agreement is quite good. The contour results also agree quite well with neutron diffraction measurements on a similar forging, and in that study an FEM model predicted lower stress magnitudes [8].

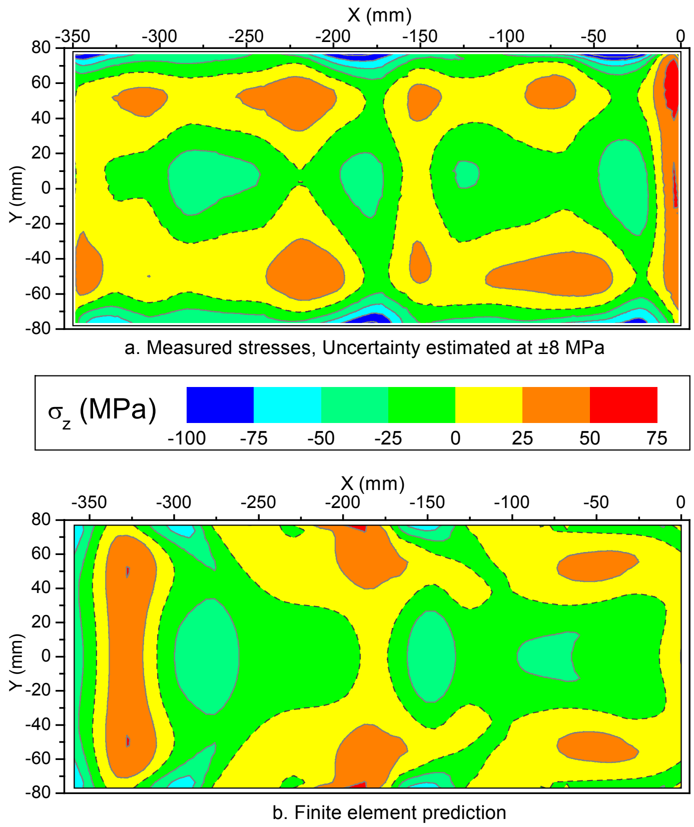

Figure 4. Short transverse (z) stresses on plane of cut 2 (see Fig. 1). Cut 1 was at x=0. a) Measured by contour method. b) FEM prediction for typical compressive treatment. The zero-stress contour line is dashed.

Figures 4 and 5 show the measured and predicted stress maps for cuts 2 and 3 (see Fig. 1). A comparison of these figures shows some similarities and some differences in the stress magnitudes and spatial patterns. Recall that the measured forging had received an appropriate cold compression treatment and that the modeled treatment was only meant to represent a typical compressive stress relief process. The comparisons are quite informative and are in good agreement. These figures show similar stress periodicity. The modeled stresses are repeatable every 150 mm, which corresponds to the 150 mm bite. The measured forging also has a repeatable stress pattern of approximately 150 mm. Given that a -Txx52 process permits anywhere from 1 to 5 percent compression, compared to the 3 percent in the modeled results, the agreement is quite good. The tendency of the model to predict higher surface tensile stresses than the measurements might be caused by using 0.25, rather than a smaller value, for the coefficient of friction in the model [10].

The axial stresses at cut 1 in the cold compressed forging are not reported in this paper. These stresses vary with position along the length. Since the exact details on the location and amount of each compression of the stress relief process were unavailable, it is not possible to select the correct location from which to take model predictions. Therefore, a comparison with the FEM is not very informative and is omitted.

Conclusions

- For the first time in the literature, cross-sectional measurements were made of the residual stresses in a quenched aluminum alloy hand forging subjected to a multiple compression stress relief process, and the measurements compared favorably with a thermomechanical FEM model.
- The FEM predictions of peak stresses were generally within 20% of the measurements. Given that no attempt was made to determine the exact thermal boundary conditions during the quench and the modeled stress relief process was typical, the resemblance in the results is excellent.
- In a residual stress measurement application that would be challenging for other methods, the contour was able to map the stresses quite precisely. The contour-method measurements were relatively simple both experimentally and analytically, even compared to other methods that would not have been able to measure the same stresses.
- Based on this validation, FEM models can be used to determine variations in the stress state as a function of processing. These stresses can be used as input to machining models that predict part distortion based on the residual stress, part geometry and part location within a forging.

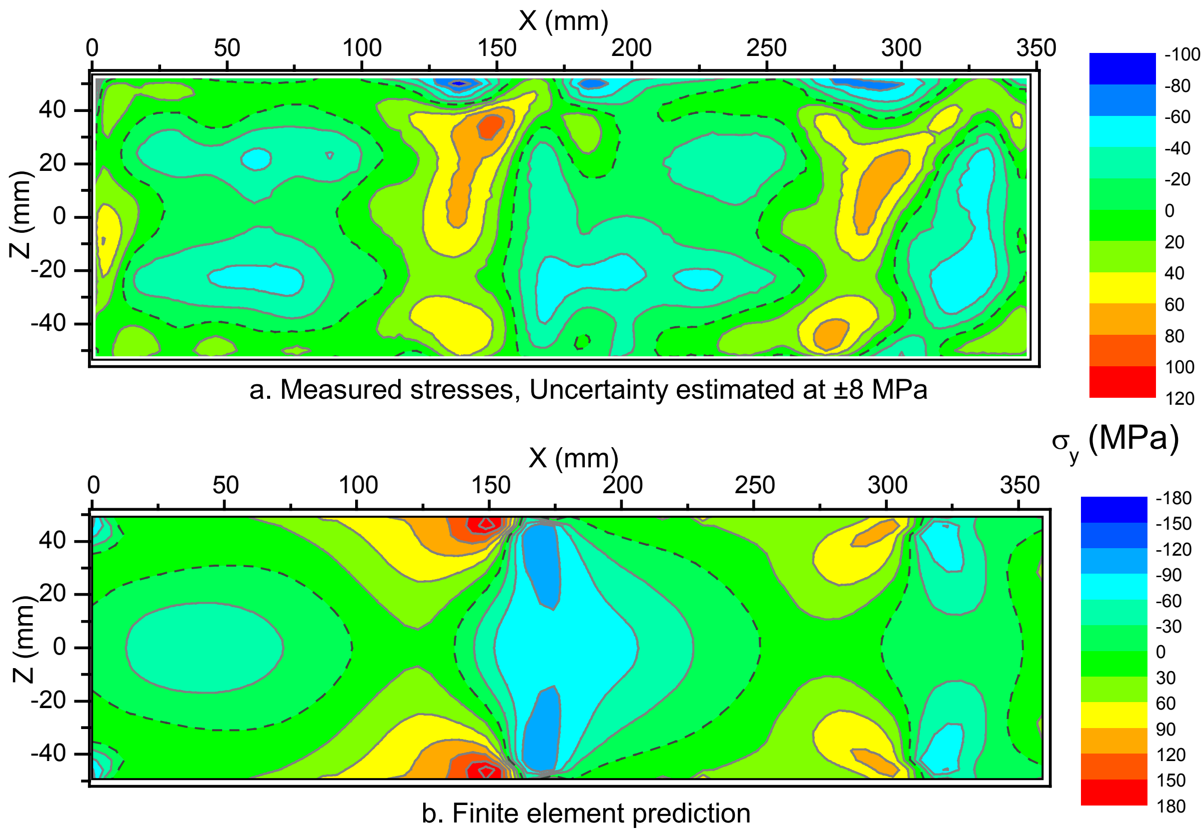

Figure 5. Long transverse (y) stresses on plane of cut 3 (see Figure 1). Cut 1 was at *x*=0. a) measured by contour method (from the contour of Fig. 2). b) FEM prediction of in forging that had a typical compressive treatment. To best show the similarities, different scales are used for the figures. The zero-stress contour line is dashed.

Acknowledgements

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