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Residual Stresses Measured in Quenched HSLA-100 Steel Plate

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ABSTRACT

Residual stresses over the cross section of a 60.75 mm thick plate of HSLA-100 steel were measured using the contour method. HSLA-100 is a low carbon, copper precipitation hardened, High-Strength Low-Alloy steel used for naval ship hulls, armor, and containment vessels. The material was prepared by hot cross-rolling, Austenitizing at 900 ºC for 75 minutes and water quenching, and then tempering at 660 ºC for 200 minutes followed by another water quench. A cross-sectional map of residual stresses was measured using the contour method: 1) the specimen was carefully cut in two using wire electric discharge machining; 2) the contour of the cut surfaces were measured by using a Coordinate Measuring Machine; and 3) the residual stresses were determined from the measured contours using a 3-D elastic finite element (FE) model. The results showed a typical quenching stress distribution with peak compressive stress of about 165 MPa a few mm below the surface and tensile stress of 200 MPa in the center of the plate thickness. The stress magnitudes, at less than 30% of yield, are somewhat low for water-quenched steels, which is discussed. An FE analysis showed that edge effects in the measured stress map were shown to be consistent with relaxation from removing the test specimen from a larger plate.

Introduction

Residual stresses play a critical role in failure mechanisms including fatigue, wear, stress-corrosion cracking, fracture, buckling, and distortion. Residual stresses, stresses present in a part free that is of external loads, are generated by virtually all manufacturing processes. Because of their major contribution to failures and almost universal presence, knowledge of residual stresses is crucial for any engineering structure. Ideally one would like to accurately model and predict residual stresses resulting from the various manufacturing operations. A great deal of research effort is focused on this task. However, the problem is very complex. Development of residual stress generally involves nonlinear material behavior and often involves phase transformations and coupled mechanical and thermal problems. For the majority of problems, the current predictive capabilities are insufficient to adequately predict residual stresses. So, the ability to measure residual stress is critical for two purposes: (1) to minimize residual-stress related failures and (2) to aid in developing predictive capabilities by validating models. This paper reports measurements of residual stress in a steel valued for its high yield strength and toughness.

Specimen

The plate material tested in this study was a low carbon, copper precipitation-hardened, High-Strength Low-Alloy steel: HSLA-100. This steel is used for naval ship hulls, armor, and containment vessels. The chemical composition is given in Table 1. The 60.75 mm thick plate material was prepared by hot cross-rolling. It was Austenitized at 900 ºC for 75 minutes and then water quenched. The plate was then tempered at 660 ºC for 200 minutes followed by another water quench. The specification for this material does not allow thermal stress relief [1] because of potential loss of strength. Therefore, the quenching stresses can be expected for all uses of this material. Mechanical testing gave yield strengths of 690 MPa in the final rolling direction and 685 MPa in the transverse direction, with corresponding ultimate strengths of 813 MPa and 829 MPa, respectively. A section of plate measuring 151.6 mm wide and 305 mm long was saw cut from a larger plate for this measurement of residual stress.

Table 1. Alloying elements of HSLA-100 steel plate in weight-%

C	Mn	P	S	Cu	Si	Ni	Cr	Mo	V	Ti	Al
0.06	0.85	0.005	0.002	1.56	0.26	3.45	0.56	0.58	0.003	0.001	0.025

Method

Contour Method Measurement of Stresses. A cross-sectional map of the longitudinal residual stresses (σ_z) in the test specimen was measured using the contour method [2]. In the contour method, 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.

The specimen was cut in half on the measurement plane indicated in Figure 1 using wire electric discharge machining (EDM) and 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 [3]. Because the part deforms during the cutting as stresses are relaxed, 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 steel plate, which was in turn clamped in the EDM machine. To prevent any thermal stresses, the specimen and the fixture were allowed to come to thermal equilibrium in the water tank before clamping.

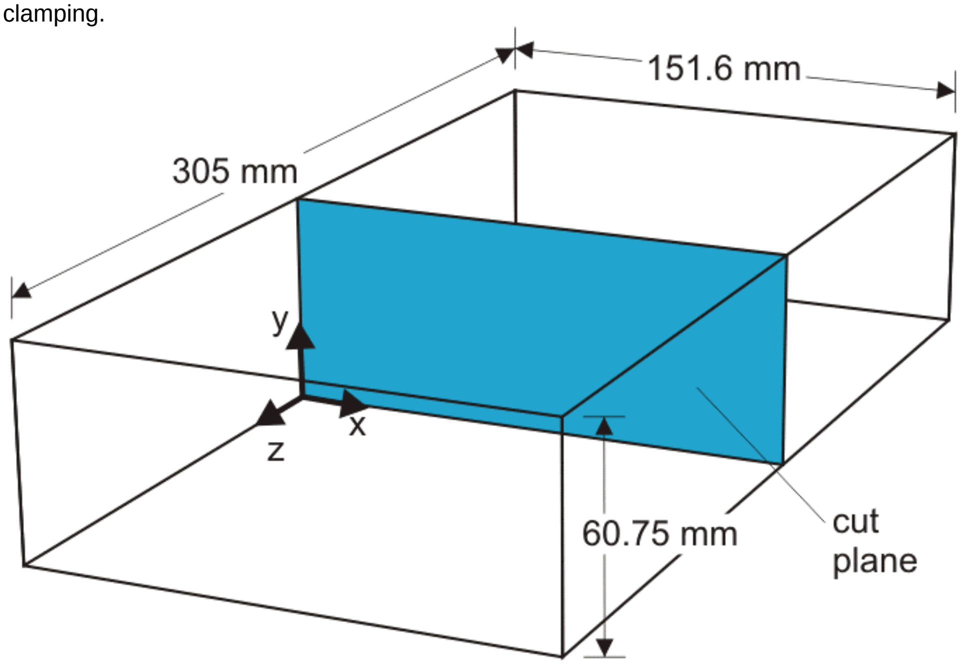

Figure 1. Dimensions of the HSLA-100 test specimen. The plane where the specimen was cut to measure residual stress is highlighted.

After cutting, the plate was removed from the clamping fixture. The contours of both cut surfaces were measured using a MS Impact II coordinate measuring machine (CMM), an inspection tool that uses a touch trigger probe. A 1 mm diameter spherical ruby tip was used on the probe. The cut surfaces were measured on a 0.5 mm spaced grid, giving about 36,500 points on each cut surface. Figure 2 shows the average of the contours measured on the two opposing surfaces created by the cut. The peak-to-valley amplitude of the contour is about 50 μm. The primary shape of the contour is low in the mid-thickness of the plate and higher toward the top and bottom.

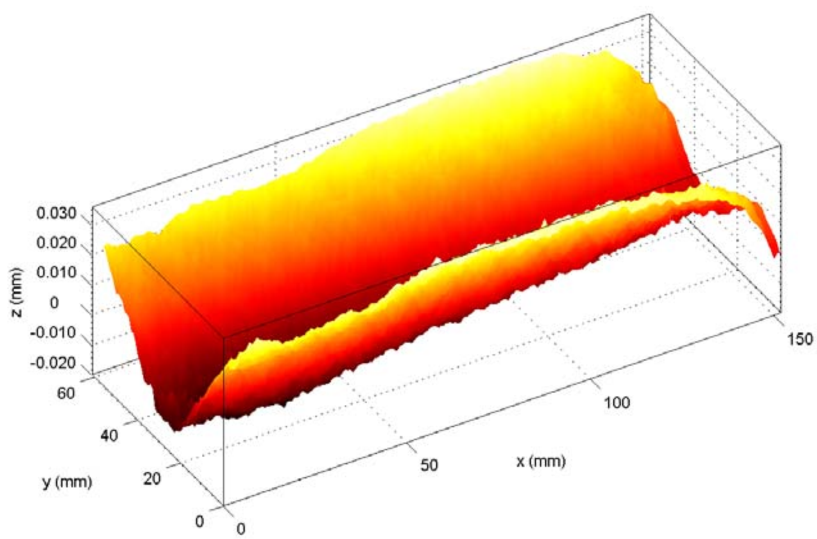

Figure 2. Contour measured on cut surface after cutting test specimen in two.

The σ_z 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 [2]. 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. The mesh used 210,00 linear hexahedral (8 node) elements. The material behavior was isotropic elastic with an elastic modulus of 197 GPa and Poisson's ratio of 0.29. In order to smooth out noise in the measured surface data and to enable evaluation at arbitrary locations, the data were fitted to bivariate Fourier series. The bivariate Fourier series fits to the measured contour data were evaluated at a grid corresponding to the FE nodes, averaged between the two sides, and then applied as *z*-direction displacement boundary conditions. Figure 3 shows the finite element model with the cut surface deformed into the opposite of the measured contour.

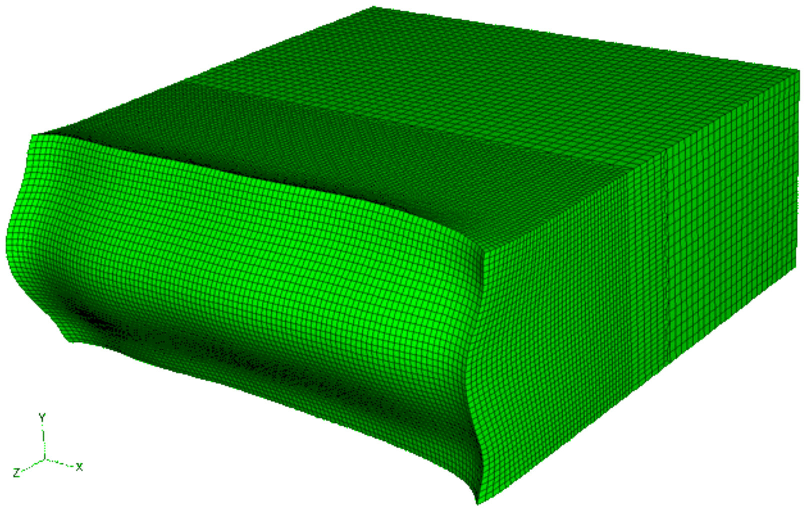

Figure 3. Finite element model of HSLA-100 steel block, deformed into opposite of measured shape in order to calculate original residual stresses. Deformations magnified by 400. This mesh corresponds to the back half of the specimen in Figure 1, and the deformed surface corresponds to the cut plane.

Results

Figure 4 shows the results of the contour-method measurement of residual stresses in the HSLA-100 plate. Typical quenching stresses, tension in the center balanced by compression at the top and bottom, are evident. Within about 20 mm of the lateral edges, the stresses are noticeably different from those in the central region. Later in this paper, it is demonstrated that those edge effects were consistent with stress relaxation when the test specimen was removed from a larger plate.

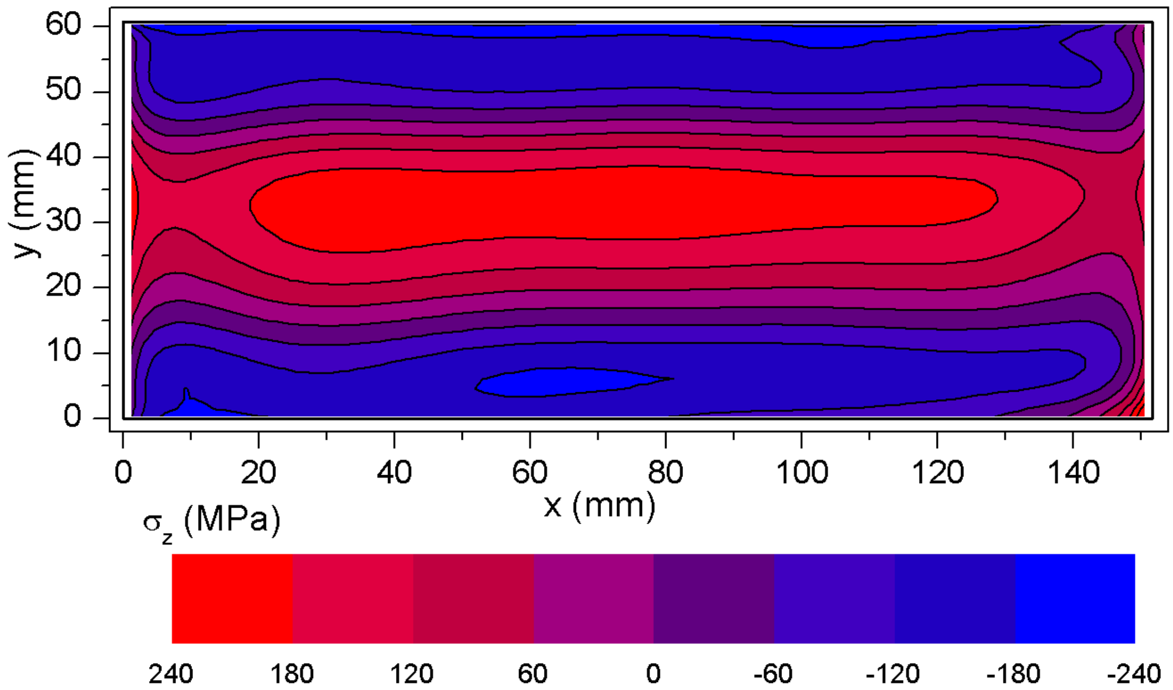

Figure 4. Longitudinal (σ_z) residual stresses in HSLA-100 specimen measured by the contour method. Location of this cross-section is shown as the cut plane in Figure 1.

Other researchers may find the distribution of residual stresses in the as-received plate to be useful for other applications of HSLA-100 steel. Away from the edges, the stress distribution in Figure 4 is primarily a 1-D through-thickness variation. Figure 5 plots the through-thickness stresses for the stress map in Figure 4, excluding data within 30 mm of the edges. A symmetric fit of the data gives a good estimation of the stresses to within an uncertainty of about ±20 MPa. The fit is given by the equation

$$\sigma/S_y = 0.29 - 0.96\tilde{y}^2 - 3.371\tilde{y}^4 + 11.568\tilde{y}^6 - 12.179\tilde{y}^8 + 4.455\tilde{y}^{10}, \quad (1)$$

where the through-thickness variable $\tilde{y}$ is normalized to go from –1 to +1 through the thickness of the plate and Sy is 690 MPa.

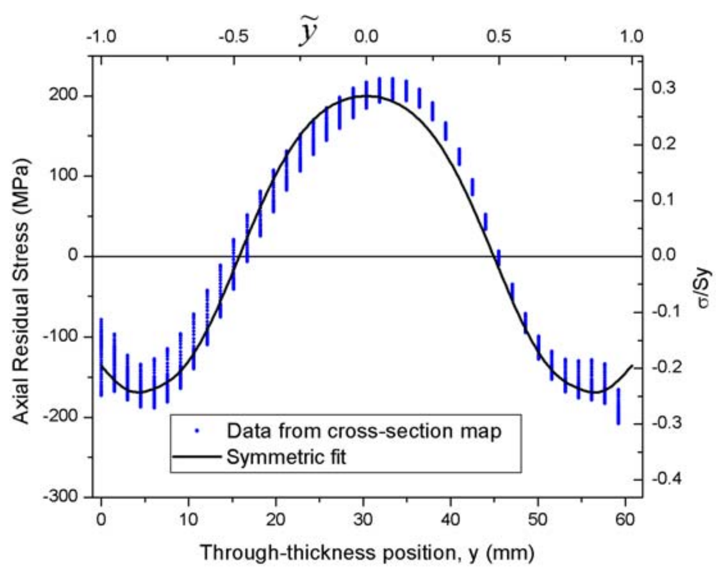

Figure 5. Through-thickness variation of residual stresses in quenched HSLA-100 plate.

Discussion

Stress Magnitudes. The residual stress magnitudes measured in the plate are somewhat lower than might be expected for a water-quenched phase-transforming steel. The alloying elements make this HSLA-100 quite hardenable, and martensitic structures have been observed in HSLA steels [4]. A published study including both finite element simulations and examining literature reports of stresses showed that residual stress magnitudes could be correlated with the Biot number *hl/k* where *h* is the convective heat transfer coefficient during cooling, *l* is a characteristic length, and *k* is the thermal conductivity of the material [5]. An order-of-magnitude estimate of *h* for water quenching is taken as 2000 W/m-K. Taking *l* as the half-thickness of the plate, 30.75 mm, and using 20 W/m-K as an average value of *k* for low-carbon steels over a range of temperatures [5] gives a Biot number of about 3. For Biot numbers greater than one, stress greater than half of yield would typically be expected [5], yet the stresses measured in the HSLA-100 are only about 30% of yield. There are several possible explanations. First, the tempering could have partially relaxed the stress, and since the subsequent water quench was from a lower temperature, 660 ºC compared to 900 ºC, a lower final residual stress might be expected. Also, the exact sequence and timing of transformations can affect the stress magnitude, even sometimes causing tension at the surface [5].

Nonetheless, the residual stress magnitudes are quite significant and could be expected to affect performance. With stress magnitudes over 0.1% of the elastic modulus, part distortion after machining to final shape is likely. Distortion problems have been reported for materials with lower values of residual stress relative to the elastic modulus [6,7]. At 30% of yield, the stresses could also be expected to affect fatigue and fracture performance. Residual stresses less than 10% of yield have been demonstrated to significantly affect fatigue and fracture [8].

Edge Effects from Removing Test Specimen. In Figure 4, within about 25 mm of the lateral edges, the stresses are noticeably different from those in the central region. The stresses that might be induced by plasticity during saw cutting would not be expected to extend more than a mm or two from the cut. Therefore, the edge effects were hypothesized to be caused by elastic relaxation when the tests specimen was removed from a larger plate. The cuts to make the test specimen 151.6 mm wide would have relaxed σ_x on the lateral edges which in turn would have changed σ_z near the edges.

A simple, elastic FE analysis was used to confirm that the edge effects were mostly consistent with stress relaxation upon removal of the test specimen from a larger plate. Because of the cross-rolling and symmetry in quenching, it was assumed that the stresses in the plate were equi-biaxial with $\sigma_x = \sigma_z$. Since the σ_z stresses in the test specimen were measured far from a free edge, they could be assumed to be representative of the stresses in the central region of the large plate.

The stress relaxation was simulated using the FE mesh from Figure 3. Because of the symmetry in the simulation of relaxation, the mesh could have been halved in the *x*-direction and symmetry enforced. It was simpler just to use the existing mesh.

The first step was to simulate the stress state in the large plate. The model was given an initial residual stress of $\sigma_x = \sigma_z$ throughout the model using the Equation 1 approximation to the measured σ_z. The cut surface was constrained in the *z*-direction to enforce symmetry. The lateral edges (at the + and – extremes of *x*) were constrained in the *x*-direction to simulate the constraint of the large plate. The back edge of the model (-*z*) was not constrained because it would have no effect on the stresses of interest at the cut plane. A static equilibrium step was then taken in the FE analysis to achieve equilibrium. In effect, because the back edge was not constrained, the simulation would at this point represent when two cuts had been made to cut the test specimen to length, but it was still infinitely wide. Figure 6 shows the results. Relaxation has occurred at the back edge, but at the symmetry plane, σ_z has not changed. At this point it was confirmed that the constraints did not induce any non-physical stresses.

The second step was to simulate cutting the test specimen to its final width. The constraints at the lateral edges were removed, and an another static equilibrium step was taken. Figure 7 shows the results. The relaxation of σ_x at the lateral edges has also changed σ_z near the edges.

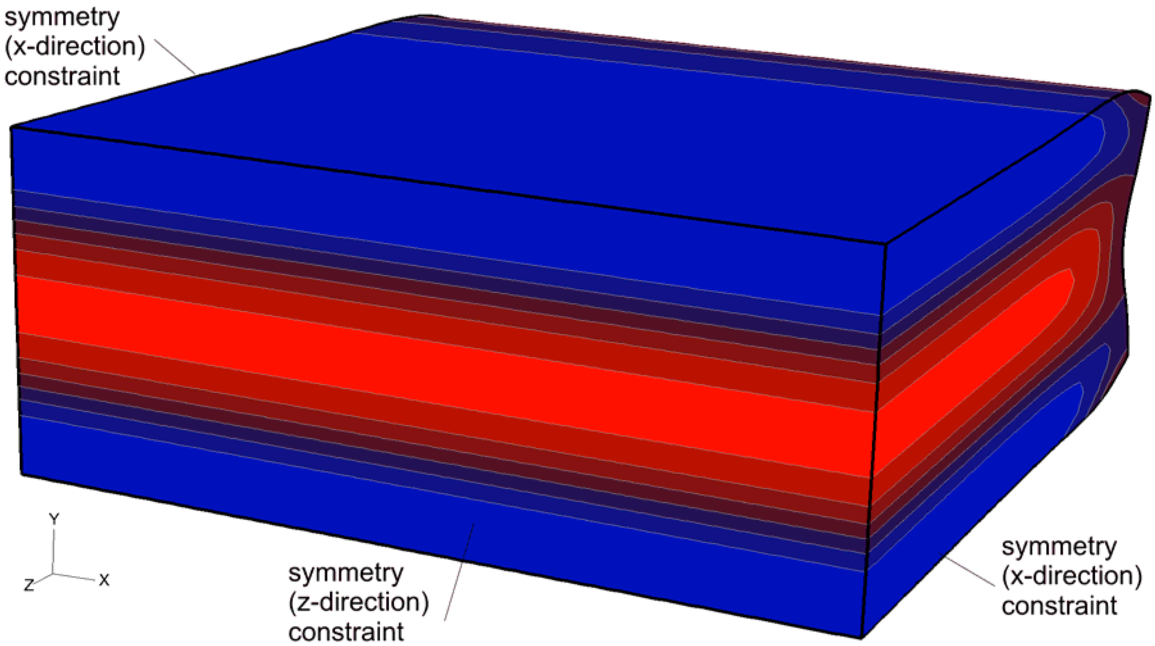

Figure 6. FE simulation (step 1) of residual stresses after cutting test specimen to length (z-direction) but still infinitely wide. This mesh corresponds to the back half of the specimen in Figure 1. The scale is the same as Figure 4, and the displacements are exaggerated by a factor of 300.

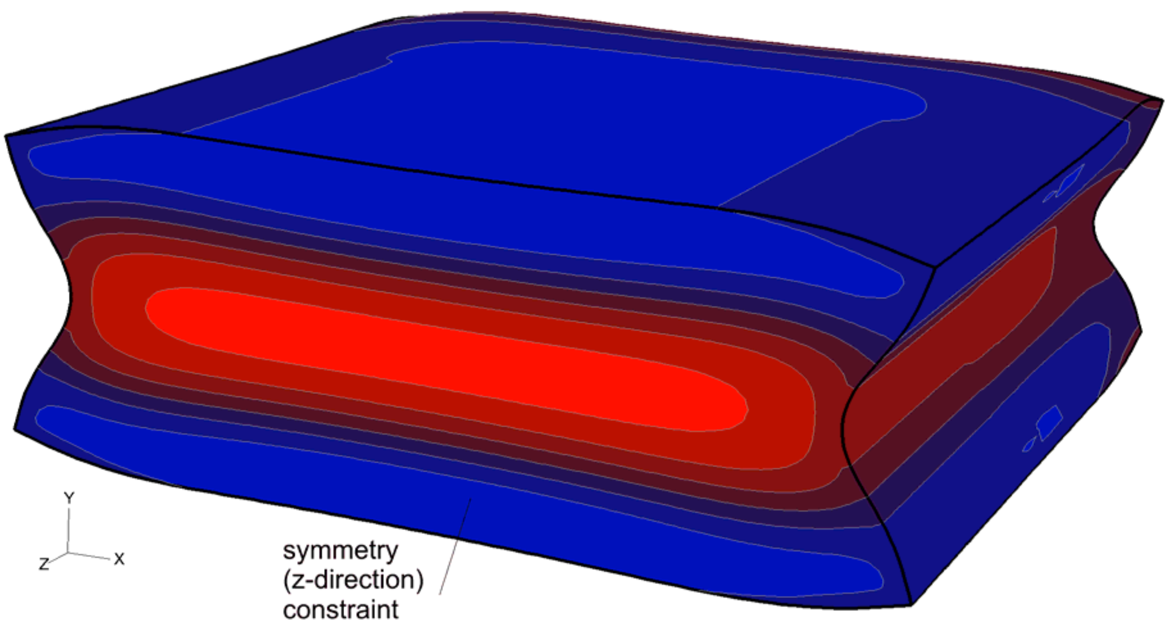

Figure 7. FE simulation (step 2) of residual stresses in test specimen. Cutting the specimen to final width has relaxed the stresses near the lateral edges.

Figure 8 shows the results of the simulation from Figure 7. The agreement with the measured stress map in Figure 4 is striking. The agreement of the extent, about 25 mm, and magnitude of the edge regions where the stresses have relaxed is excellent considering the assumptions and the uncertainty in the measurements. Compared to Figure 8, the measured stress map in Figure 4 shows more tensile stresses very near the edges, within a few mm. These higher tensile stresses would be consistent with plasticity-induced stresses from sawing.

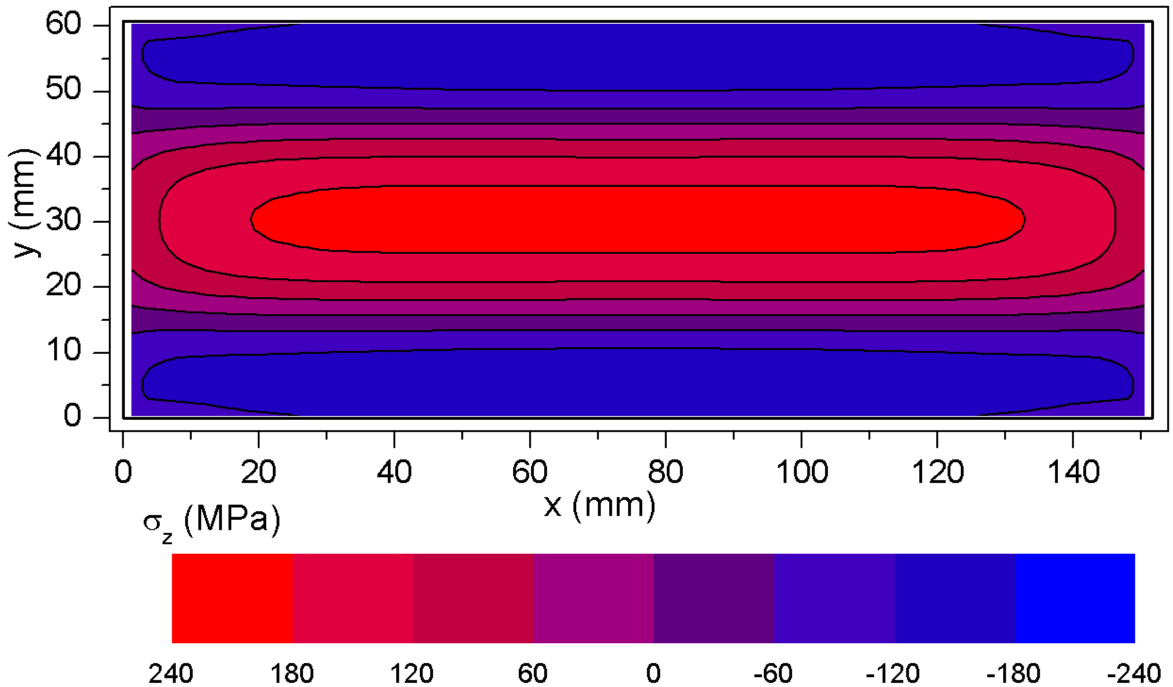

Figure 8. Finite Element prediction of residual stress in test specimen after relaxation from removing from larger plate. Agrees well with measured stress map in Figure 4.

Conclusions

The contour method successfully measured a residual stress map in a 60.75-mm thick plate of HSLA-100 steel. A typical quenching stress distribution was found with peak compressive stress of about 165 MPa a few mm below the surface and tensile stress of 200 MPa in the center of the plate thickness. Because the contour method measures a full cross-sectional map, features in the stress map such as edge effects caused by removal of the test specimen from a larger plate were evident. Simpler measurement methods that only measure a depth profile of residual stresses, such as layer removal or crack compliance, would not have been able to resolve those features. Furthermore, such methods tend to average the stresses at a given depth over the whole part width, which would include the edge-affected regions and, therefore, underreport the peak stresses.

Acknowledgements

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References

1. MIL-S-24645A(SH), United States Navy (1990) .
2. Prime, M.B., "Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut," *J. Engineering Materials and Technology*, **123**, 162-168, 2001.
3. Cheng, W., I. Finnie, M. Gremaud, and M.B. Prime, "Measurement of Near Surface Residual Stresses Using Electric Discharge Wire Machining," *J. Engineering Materials and Technology*, **116** (1), 1–7,1994.
4. Dhua, S.K, D. Mukerjee, and D. S. Sarma, "Effect of Cooling Rate on the As-Quenched Microstructure and Mechanical Properties of HSLA-100 Steel Plates," *Metallurgical And Materials Transactions A*, **34A**(11), 2493-2504, 2003.
5. Lacarac, V., D.J. Smith, C. McMahon, and M.J. Tierney, "Non-dimensional approach for estimation of residual stresses during cooling in steel - Part I - Without phase transformation," Surface Engineering: Coating And Heat Treatments, Proceedings, 7-10 October, 2002, Columbus, Ohio, pp. 570-577, 2003.
6. Lequeu P, P. Lassince, T. Warner G.M. Raynaud, "Engineering for the Future: Weight Saving and Cost Reduction Initiatives," *Aircraft Engg Aerospace Tech*. **73**, 147-159, 2001.
7. Schultz, R.W., M.E. Karabin, "Characterization of Machining Distortion By Strain Energy Density And Stress Range," Materials Science Forum, **404-407**, p.61-67, 2002.
8. John, R, K. V. Jata, and K. Sadananda, "Residual Stress Effects on Near-Threshold Fatigue Crack Growth in Friction Stir Welds in Aerospace Alloys," *Int. J. of Fatigue*, **25**(9-11), 939-948, 2003.