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Residual Stress, Stress Relief, and Inhomogeneity in Aluminum Plate

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Abstract

Through-thickness residual-stress profiles in rolled 7050-T74 aluminum plate were measured before and after stress relief by stretching (-Tx51). Measurement required adapting the crack compliance method to measure both in-plane stress components. Unexpected features in the profiles could be explained by through-thickness yield strength variations caused by crystallographic texture.

Keywords: cold working, mechanical properties, structural behavior, plastic anisotropy, aluminum alloy

Introduction

7000 series wrought aluminum alloys are used for aerospace applications because of their combination of high strength, stress-corrosion-cracking resistance, and toughness. The quenching process that results in high strength also leaves high residual stresses, which cannot be thermally relieved while maintaining the alloy's favorable mechanical properties. Therefore, the stresses are relieved by applying a uniform plastic strain, which for rolled plate involves uniaxially stretching in the rolling direction from 1.5% to 3% strain and carries the T*x*51 temper designation. The residual stresses left even after the stress relief are sufficient to cause distortion in aircraft components machined from this material. The resulting re-work and scrap of distorted parts is extremely expensive for manufacturers [1]. However, because of their low magnitude, these residual stresses are difficult to measure using common techniques such as layer removal.

Unique advantages of the crack compliance method [2,3] make it almost ideal for measuring the post-relief residual stresses. In the crack compliance method, strains are measured as a slot is incrementally cut through a part. Crack compliance is more sensitive and has better spatial resolution than layer removal and can measure a full through-thickness stress profile, unlike hole drilling. Also, as will be demonstrated here for the first time, one can automatically account for any partial stress relaxation when a small sample is removed from a large plate.

Experiments and Data

Experiments were performed on 7050-T74 plate, an alloy favored for its ability to retain strength properties, even in thick sections (over 50 mm). Plates nominally 76 mm thick were chosen for the study because machining distortion is most problematic for plates 60-90 mm thick [1]. 150 mm square specimens were removed by saw cut from the central region of 760 mm long × 760 mm wide plates. The effect of this parting out is discussed later.

A new application of the crack compliance method was necessary in order to measure both the rolling direction and transverse stresses. Normally, one cut is made incrementally, and the stress component normal to the cut plane is determined. Figure 1 shows a new procedure used to determine two stress components. The first cut determines σ_x, and then a second cut on one of the remaining pieces determines σ_y.

Figure 1 also shows the arrangement of eight strain gages used during each test. For each cut, one strain gage is placed very close to the cut on the surface where the cut begins (top), and another is placed centered on the cut plane on the opposite surface (bottom). Gages parallel to the cut (transverse gages) were also placed at each location to check if the deformations were approximately plane strain or plane stress. The gages used were Micromeasurements CEA-13-125UT-350 constantan gages with an active gage length of 3.18 mm.

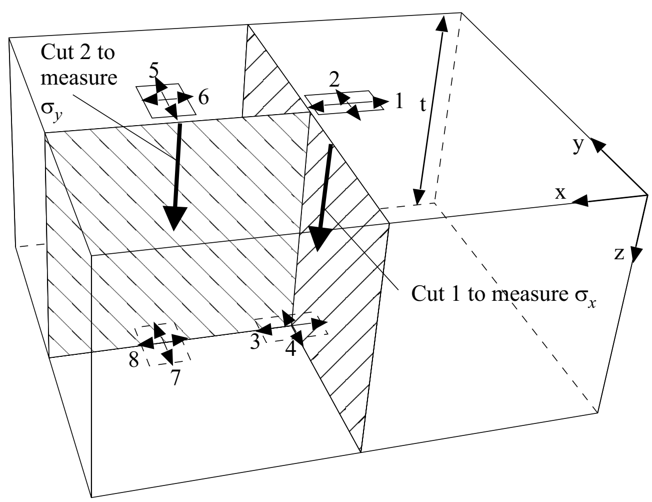

Figure 1. Test procedure and strain gage layout.

The first test was performed on 77.9 mm thick 7050-T74 (not stress relieved) plate. For this specimen, the x-direction in Fig. 1 corresponded with the rolling direction of the plate. The cuts were made using wire electric discharge machining with a 0.3 mm diameter brass wire. The machine was set to “skim cut” settings to minimize the stress induced during cutting [4]. The slot was cut in 0.5 mm increments to a depth of 12 mm and then in 1 mm increments for the remainder of the test. At a cut depth of 26 mm, the top surface of the cut pinched closed because of high compressive residual stress. Since such closure would affect the measured strains and violate the crack compliance assumptions, the slot was opened up by re-cutting in from the top surface. Gages 1 and 2 were removed in the process but were no longer needed because their readings were no longer changing with slot depth. Cutting then proceeded until the plate was cut in two. The second cut on one of the remaining pieces was performed in the same manner as the first cut. Unfortunately, gage 5 did not give meaningful readings during the second cut.

Figure 2 shows the strains measured during the cuts, where for clarity readings on the gages not relevant to a particular cut are not plotted. The near-zero readings from gages 5 and 7 during the first cut clearly indicate that the first cut had negligible effect on the stresses in the *y*-direction, to be measured by the second cut.

The test on the 75.8 mm thick stress-relieved (7050-T7451) specimen was performed under the same conditions as the previous test, except that this time the *y*-direction in Fig. 1 corresponded to the rolling direction of the plate. The top gage for the first cut did not function during the test. Figure 3 shows the strains measured during the cuts.

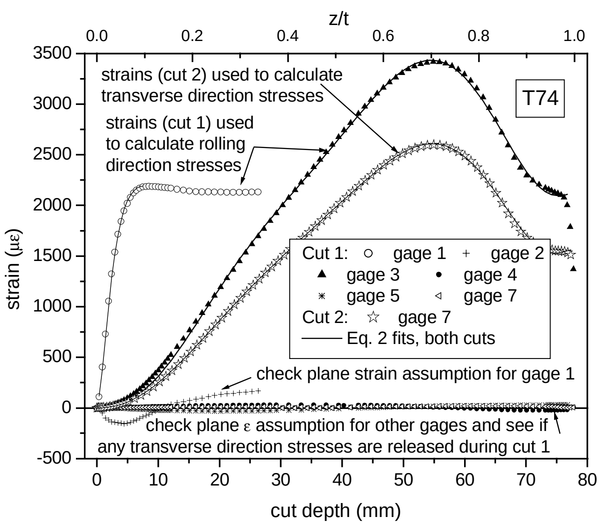

Figure 2. Measured strains, T74 specimen.

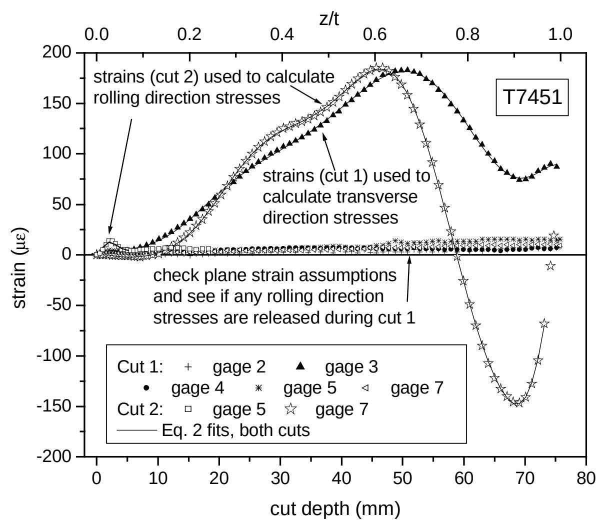

Figure 3. Measured strains, T7451 specimen.

The near-zero measured transverse strains indicated that the deformations for all of the cuts were very nearly plane strain.

Analysis

The original residual stresses were determined from the measured strains using the series expansion approach [3,5], which is very tolerant of noise and errors in the measured strains [6]. It is first assumed that the unknown stress variation as a function of the through-thickness coordinate can be expressed as a series expansion,

$$\sigma_{x,y}(z)=\sum_{i=1}^{n} A_i P_i(z)=[P]\{A\}, \qquad (1)$$

where the A_i represent unknown coefficients to be solved for. For this application, Legendre polynomials expanded over the thickness of the plates were chosen for the P_i because, by excluding the 0^{th} and 1^{st} order polynomials, the resulting stress distribution is guaranteed to satisfy force and moment equilibrium.

The strains that *would* be measured at the cut depths a_j are calculated for each term in the series. These are called the compliance functions C_{ij}. Using superposition, the strains given by the series expansion can be written as

$$\varepsilon_{x,y}(a_j)=\sum_{i=1}^{n} A_i C(a_j,P_i)=[C]\{A\}. \qquad (2)$$

A least squares fit to minimize the error between the strains given by Eq. 2 and the measured strains gives the A_i, and hence the stresses by Eq.1, and can be written as

$$\{A\} = \left([C]^T[C]\right)^{-1}[C]^T\{\varepsilon_{measured}\}. \qquad (3)$$

The effect of relaxing stresses when removing the test specimen from a larger plate was corrected for by using a new finite element (FE) method for calculating the compliance functions C_{ij}. The test specimen, not the whole plate, was first meshed. Each term in the series expansion for stresses, P_i in Eq. 1, was applied to the model as an initial stress condition. One analysis step in the FE code is performed to allow the initial stress distribution to equilibrate with the stress-free boundary conditions. This first analysis step correctly calculated the relaxation from the test specimen removal, assuming that the stresses are independent of the x and y-directions in the region of the large plate originally containing the specimen. Subsequent FE analysis steps calculated the further stress relaxations from incrementally cutting the slot, and the C_{ij} strains were taken relative to the state after relaxing the initial stresses. Using these compliance functions in Eq. 3 means that Eq. 1 gives the original stresses in large plate before removing the test specimen.

The aforementioned calculations were done using the commercial FE code ABAQUS [7]. A 2-D plane strain mesh was used with quadratic shape function elements (CPE8) sized at about 1 mm. The elastic modulus was taken as 71.7 Gpa and Poisson's ratio as 0.33. Only half of the specimen was meshed because of symmetry about the cut plane. Incremental cutting was simulated by incrementally removing symmetry displacement boundary conditions on the cut plane. The strains for the strain gages in Fig 1 were then calculated using nodal displacements. Note that this FE model approximated the actual, finite-width slot (~ 0.47 mm) as a crack. For the gage positions in these tests, the error caused by this approximation is quite small [8]. Hence, the extra effort to mesh the actual slot width is not justified.

Finally, the series expansion coefficients A_i were determined by least squares fit (Eq. 3) using the measured strains for the relevant gages and the FE-calculated compliance functions. The order of fit was chosen to minimize the uncertainty in the calculated stresses [9]. An eight term series (Legendre polynomial order 2 to 9) was sufficient for fitting that data from three of the cuts, with the data from the second cut on the 7050-T7451 specimen requiring 11 terms. The calculated strains (Eq. 2) generated by the fits are shown in Figs 2 and 3.

Results

Figures 4 and 5 show the through-thickness residual stresses measured before and after the stretch stress relief, respectively. Note that the vertical scales on the plots differ by a factor of 10. The pre-relief stresses show a typical quenching distribution of compression near the surfaces balanced by tension in the center. The stress magnitudes are approximately 40% greater in the rolling direction, and the peak magnitudes are about half of the manufacturer's yield stress specification of 414 MPa. The uniaxial stretch has relieved the stresses by a factor of approximately 10 in both directions, while maintaining the same basic shape of the profile.

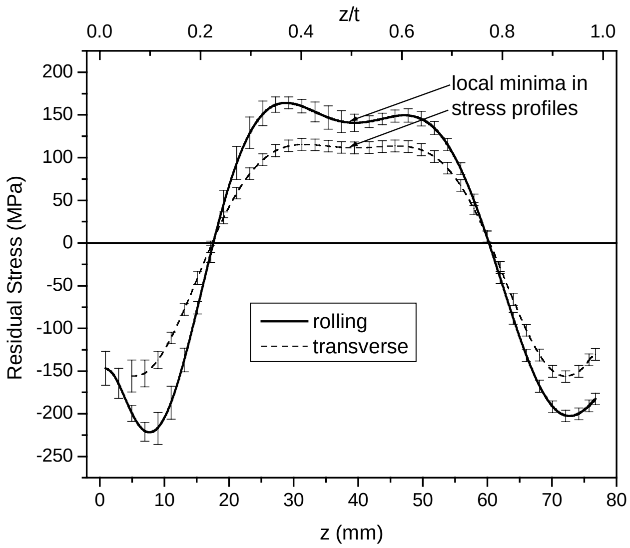

Figure 4. Residual stresses in 7050-T74 aluminum plate.

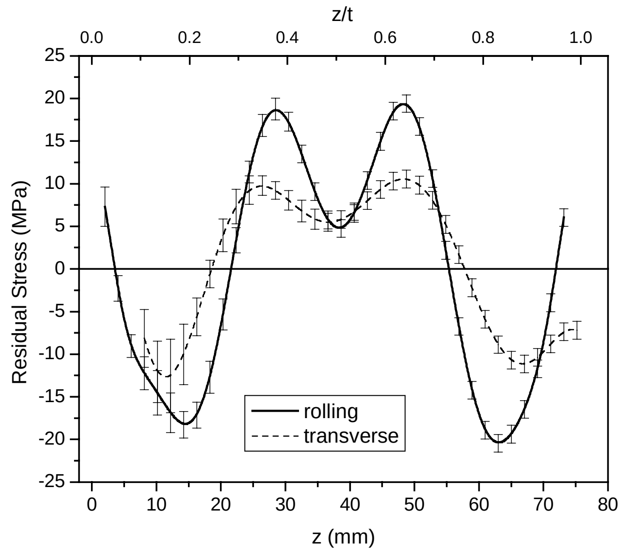

Figure 5. Residual stresses after stretch stress relief (7050-T7451).

Discussion

All four residual stress profiles show features that would not be expected for a homogeneous plate subjected to the same thermo-mechanical processing. A local stress minimum occurs at the midplane of the plate thickness, and the maximum compressive stress occurs subsurface rather than at the surface. Figure 6 shows results exhibiting the same features from similar measurements on a 25 mm 7050-T7451 plate, which indicates that the effect is not only due to slower quenching at the center of thicker plate. Previous studies have consistently shown through-thickness inhomogeneity in mechanical properties and toughness in 7000 series alloys [e.g., 10,11]. Figure 7 plots through-thickness variations in tensile yield strength for specimens of rolled 7050-T74 plate specially prepared to have no through-thickness composition gradient, and the strengths were analytically adjusted for the differing quench paths [12]. The W-shaped strength variations were then directly correlated with gradients in crystallographic texture. For conventionally prepared plate, like that tested in this study, further through-thickness strength variations can be expected because of the chemical composition gradient (i.e., the regions of solute depletion near the midplane and solute enrichment towards the surface) [13]. Even so, the difference in strengths observed through the plate thickness, Fig 7, is similar to the through-thickness difference in residual stresses after stretching, Figs 5 and 6. One could reasonably expect the amount of stress relief by stretching to be limited by the through-thickness variations in strength.

Differences between the rolling and transverse direction residual stress profiles, especially after stretching, can be attributed to the plastic anisotropy evident in Fig. 7. Studies have indicated that this anisotropy cannot be attributed to texture, composition gradients, and quench path alone but is also effected by precipitate habit plane [12].

In measuring the stresses, the compensation for the effect of removing the specimens from a larger plate proved to be significant. Calculations that did not account for the removal resulted in underestimating the peak stress magnitudes by about 5%. Further calculations revealed that if the size of the removed specimen were increased by 20% (to a length of about 2.4 times the thickness) the underestimation of peak stresses would be reduced to only 1%. Still, the correction is fairly simple, does not require the specimen to be instrumented during the removal, and allows the use of smaller specimens.

The two-cut, crack-compliance procedure for measuring two residual stress components proved to be relatively straightforward. Strain gage readings demonstrated that the first cut did not relax any of the stresses in the second direction. Thus, the two cuts can be considered independently. Measurements of transverse strains also indicated that the often used, but seldom confirmed, assumption of plane strain behavior is reasonable. The excellent spatial resolution and sensitivity to low stresses demonstrated by the results in Figs. 5, 6 and 7 would be difficult to achieve with other residual stress measurement techniques.

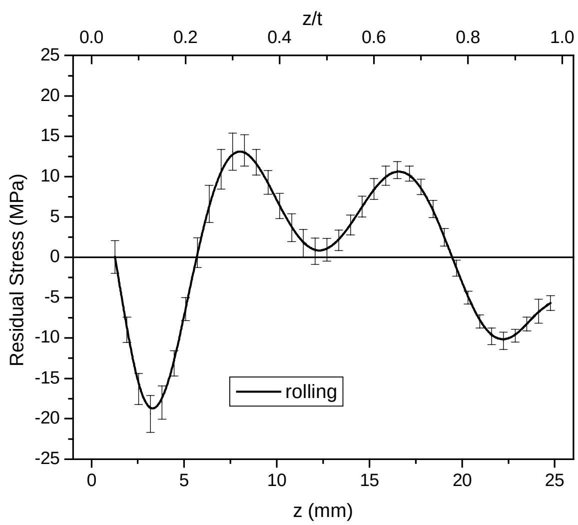

Figure 6. Residual stresses in 25 mm thick 7050-T7451 aluminum plate.

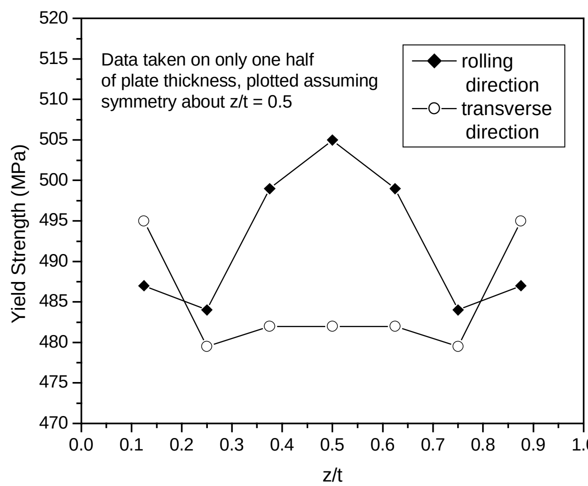

Figure 7. Through-thickness variations in tensile yield strength on a 50 mm thick 7050-T74 plate, from [12].

Acknowledgements

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