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RESIDUAL STRESS MEASUREMENTS FOR STUDYING INGOT CRACKING

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High strength aluminum alloy ingots are subject to cracking due to residual stresses developed during casting. Previously, casting variables have been correlated to ingot cracking frequency. In addition to this go, no-go type of information, techniques were sought to provide data concerning the magnitude of residual stresses present in uncracked ingots. Such numerical data are more amenable for use in multiple regression correlations to the numerous process variables. Initial work involved strain gaging and sawing of laboratory sized ingots. Magnitudes and signs of the various stresses were determined both by deflection calculations and strain gage readings. A third technique involved a non-destructive strain gaging and precision hole drilling procedure. The latter technique has been used to monitor full sized production ingots. The various experimental measurement techniques and the current state of knowledge concerning the origin and distribution of stresses will be discussed in detail.

Introduction

Aluminum alloy ingots are subject to various types of cracking defects. The current paper describes techniques for determining the magnitude, sign (tensile or compressive) and direction of residual stresses resulting from the nonuniform cooling of ingots. While the majority of the work concerns the cold cracking of rectangular ingots, the techniques should be applicable to other ingot configurations and defect types. The purpose of the paper is to describe the procedures and type of information which can be obtained. The recommendations for preventing such defects enter the area of proprietary commercial casting practices, and therefore will not be discussed.

The impetus for the work was to develop quantitative data concerning how close an uncracked ingot was to cracking. Previous work at Reynolds attempted to relate ingot recovery (% uncracked ingots) to various casting parameters. A numerical value for residual stress level would allow multiple regression statistics to be employed, highlighting the most important variables and whether a variable tends to raise or lower residual stress.

Destructive Techniques

The first technique employed involved strain gaging a series of 6" x 21" x 72" laboratory ingots of 2024. Several days after casting, 45° rectangular rosette strain gages (MM type EC-13-RA-120) were mounted in selected locations, after locally grinding the surface of the ingot to a satisfactory finish. Figure 1 illustrates the gage locations. The ingots were then slit through the thickness (6 inch dimension), starting at the ingot head. The saw cut was made midway between the edges (21 inch dimension) with a vertical band saw with a motorized feed.

After various length cuts, sawing was halted, the strain gages read, and the opening or deflection between the ingot halves measured. The latter measurements were made with either feeler gages or inside calipers. Figure 2 depicts the experimental arrangement. For reasons of safety, guard rails and restraining chains were used, for many of the ingots separated violently after partial sawing. For the most highly stressed ingots this separation occurred after a small fraction of an inch of cut, while others could be sawed full length. For the ingots which split after a short distance of sawing, the resulting halves were clamped together at the ingot butt, and the deflection at the ingot head was measured.

Next a half section was sawed and the top 36 inches of the section discarded. A second series of measurements were made on the remaining portion of the half section, by cutting perpendicular to the original saw cut. In other words, the final cut resulted in two pieces, 3" x 10.5" x 36". After cutting, the pieces were clamped together and the through-the-thickness bow determined.

The magnitude and direction of the principal released strains in both the longitudinal or casting direction (e_L) and the transverse direction (e_T), at the ingot surface, were determined from the strain gage readings using the Baumberger graphical method. (1) From the strains, the principal stresses were computed from the Hooke's law relationships:

$$\sigma_L = \frac{E}{1-\mu^2}\left\{e_L + \mu e_T\right\} \qquad (1a)$$

$$\sigma_T = \frac{E}{1-\mu^2}\left\{e_T + \mu e_L\right\} \qquad (1b)$$

Where σ is the stress, psi; E is the modulus of elasticity = $10 \times 10^{+6}$ psi; μ is Poisson's ratio = 0.33; and e is the strain, in/in.

Released outside fiber stresses were calculated from the deflection measurements according to the beam formula of Dieter: (2)

$$\sigma = \left\{\frac{E}{1-\mu^2}\right\}\frac{\alpha W}{2L^2} \qquad (2)$$

The symbols and units are as defined above, with the additions: α = 1/2 the measured diflection (adjusted for the kerf of the saw cut); L is the length of saw cut, and W is the ingot width.

Stresses producing the through the thickness bow, were determined assuming a uniformly loaded (w/unit length) beam simply supported at its ends. (3)

Maximum beam deflection = $\Delta_{max.} = \frac{5}{384} \times \frac{wL^4}{EI}$ (3)

The moment of inertia,

$$I = \frac{bh^3}{12} = \frac{(10.37)(3.062)^3}{12} = 24.81 \text{ in.}^4 \qquad (4)$$

The bending moment at mid length, $M = \frac{wL^2}{8}$ (5)

$$E = \frac{10^{+7}}{1-\mu^2} = 11.2 \times 10^{+6} \qquad (6)$$

$$\sigma_{max.} = \frac{Mc}{I} = \frac{3wL^2}{4bh^2} \qquad (7)$$

combining the above equations:

$$\sigma_{max.} = \frac{164.5\,(\Delta_{max.}) \times 10^{+6} \text{ psi}}{L^2} \qquad (8)$$

Discussion of Destructive Technique

Figure three illustrates the directions and relative magnitudes of the principal stresses measured for 6" x 21" ingots of 2024. In the ensuing discussion the flats or sides refer to the 21" x 72" faces and edges refer to the 6" x 72" areas. Longitudinal is parallel to the casting direction and transverse is perpendicular to the casting direction. To a large extent our results differ from the theory proposed by Baldwin, whose explanation of stress generation is repeated with the aid of Figure 4. (4)

"The thermal contraction of the cooler edges produces a strain mismatch between the edges and center of the ingot which results in the distribution of longitudinal stress shown in Figure 4-b. Since the hot center has a lower yield stress, it cannot support the compressive stress imposed on that region and because of plastic deformation the center of the ingot shrinks to relieve some of the stress (Figure 4-c). When the center of the slab finally cools, the total contraction will be greater for the center than the edges because the center contracts owing to both cooling and plastic deformation (Figure 4-d). The center will then be stressed in residual tension, and the edges will be in compression."

The two observations in conflict with Baldwin's theory are: (1) longitudinal tensile stresses are consistently observed on the edges as opposed to compressive stresses suggested by Baldwin (Figure 4-d). (2) Even with a flat bottom starter block the ingot bottom tends to be convex (as in Figure 4-b) rather than concave as depicted in Figure 4-d. The convex bottom, and the marked tendency of rectangular ingot to "pants leg" crack are consistent with longitudinal tensile stresses on the edges. A possible explanation for the observed distribution of stresses is the reheating of the surface, resulting from contraction of the ingot away from the mold. This phenomenon, referred to as "air gap formation" also explains the inverse chemical segregation observed at ingot surfaces. (5) At this stage of our understanding, the actual stress distribution appears to be as depicted in Fig. 5.

Non-Destructive Method

While the techniques described previously are useful in a laboratory situation, for safety and productivity reasons, a non-destructive technique would be highly desireable for full sized commercial ingots. Rendler(6) developed a portable precision hole drilling apparatus which appeared to be applicable to the type of studies we wished to conduct with plant sized ingots. After preparing a small area (~8" in diameter) of an ingot surface with a portable disk grinder, a strain gage rosette and the drilling apparatus are attached to the ingot. An 1/8" diameter hole is drilled in the ingot, to a depth of 1/8". Scalping of the ingot later removes more than 1/8" of material, so the technique must be considered to be totally non-destructive.

The surface is first prepared by rough grinding with a disk grinder and finished with emery paper. After degreasing the surface, a preassembled strain gage rosette (type EA-13-125R E-120) is attached to the ingot, Figure 6. The three gages are connected to a switch box and then to a strain gage indicator. The apparatus is attached to the ingot with a quick setting dental cement. A microscope, Figure 7, is inserted into the bore and adjustments to level the instrument and center the bore on the center of the strain gage are made. The microscope is removed and replaced by a boring bar, Figure 8. A series of measurements are made whereby the depth of hole is increased in increments of 0.020 to 0.025 inches. At the completion of each drilling increment, the boring bar is replaced by a depth gage, the depth of the hole determined, and the three gages of the rosette are read, Figure 9. This sequence is continued until a hole depth slightly exceeding the hole diameter is achieved. The gage readings are plotted versus hole depth, and generally remain constant beyond the point at which the ratio of hole depth to diameter (R) is equal to 1.0. The values used for calculation of stress are taken at R = 1, for uniformity.

Calculation, of maximum and minimum stresses were performed using the equations of Rendler and Vigness (7). At residual stress levels approaching the yield strength of the material erroneously high stresses are observed. Calibration curves developed by Rendler (8) have been employed for correction of the raw data, Figure 10. Using a series of 9" rounds of 2024, the correlation between the hole drilling method and the slitting method was studied.

LONGITUDINAL STRESS (KSI)			HOOP STRESS (KSI)		
SLIT	HOLE		SLIT	HOLE	
	AS MEASURED	CORRECTED		AS MEASURED	CORRECTED
-2.3	-7.7	-7.7	-15.5	-25.4	-22.3
-15.6	-19.5	-18.5	-18.4	-25.4	-22.3
-18.9	-25.4	-22.2	-19.0	-31.7	-23.7

The agreement between the two techniques is seen to be better for the longitudinal stress than for the hoop stress. Also the changes in stress for this three ingot series agreed with ingot cracking experience, for the process variable which was tested for the series.

The hole drilling technique has been employed with over fifty full sized plant ingots. The measurements have proven to be reproducible, safe to make, and informative. In conjunction with detailed measurement of process and compositional variables, considerable insight has been gained in ways to minimize ingot cracking. One disadvantage is the difficulty of performing hole drilling on the edges of large ingots, without the construction of special ingot support and work structures, to permit drilling to be performed in a vertical position.

Acknowledgments

Mr. Grant Spangler is responsible for many of the ideas, leading to the work described above. John Miller and Robert Baughan also contributed extensively to the work.

References

1. Murray, W. M. and Stein, P. K., "Strain Gage Technique - Part 2," MIT Text on Lectures and Laboratory Exercises, 1956, pp. 566-574.
2. Dieter, G. E., Mechanical Metallurgy, McGraw Hill Book Company, 1961, pp. 405.
3. Nash, W. A., Strength of Materials, Schaum Publishing Company, 1957.
4. Baldwin, W. M., Jr., "Residual Stresses in Metals," Proceedings of the American Society for Testing Materials, Vol. 49, 1949, pp. 539-583.
5. Flemings, M. C., "Application of Solidification Theory to Large Castings and Ingots," Conference of Solidification, Brighton, England, 1967.
6. Rendler, N. J., "Portable-Precision Hole Locating and Milling Guide," U. S. Patent 3,471,935, Oct. 14, 1969.
7. Rendler, N. J and Vigness, I., "Hole-drilling Strain-gage Method of Measuring Residual Stresses," Experimental Mechanics, Vol. 23, 1966, pp. 577-586.
8. Private communication with N. J. Rendler.

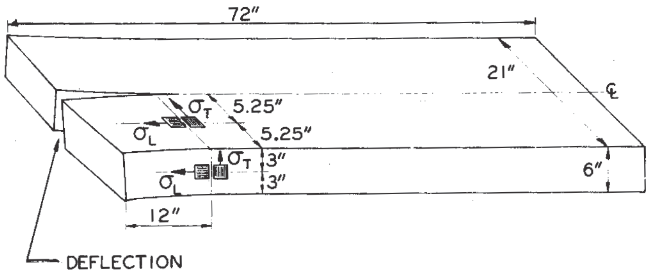

Figure 1. Schematic of Strain Gage Locations.

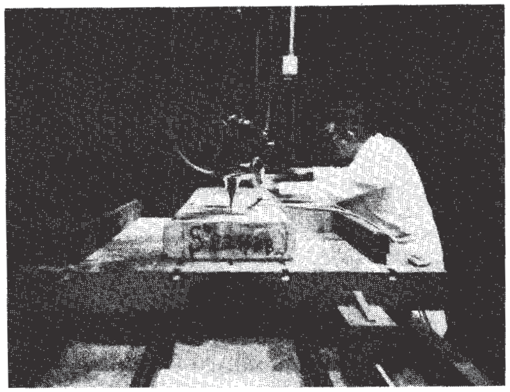

Figure 2. Experimental Arrangement for Measuring Residual Stresses by the Destructive Methods.

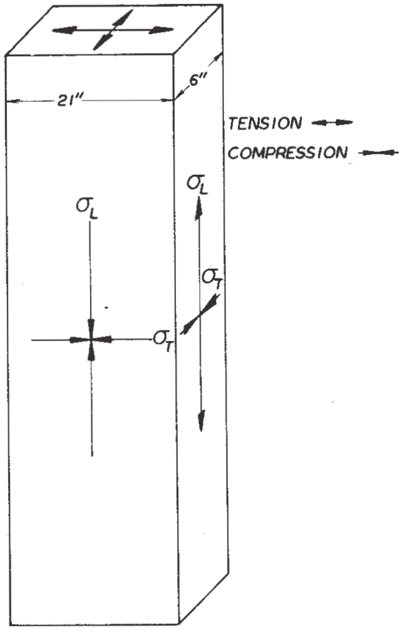

Figure 3. Principal Biaxial Stress Distribution indicated by Slitting 6" x 21" -2024 Ingots. Length of Arrows give relative magnitude of stress.

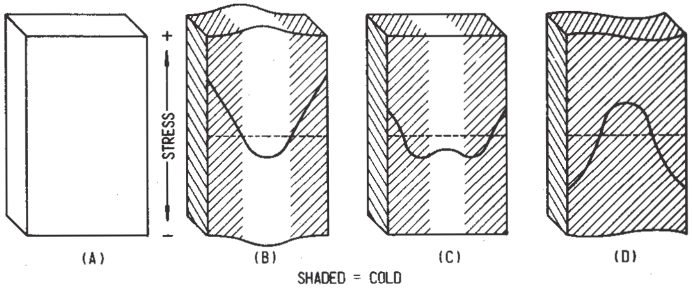

Figure 4. Theory of Development of Residual Stresses after Baldwin (4)

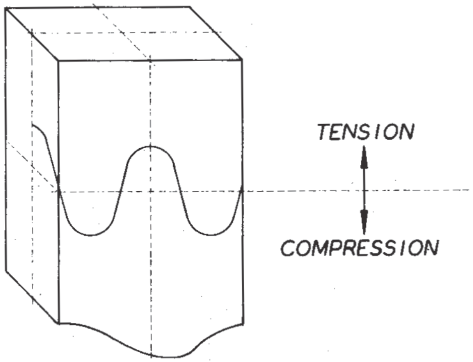

Figure 5. Proposed Distribution of Longitudinal Residual Stresses at Mid Thickness.

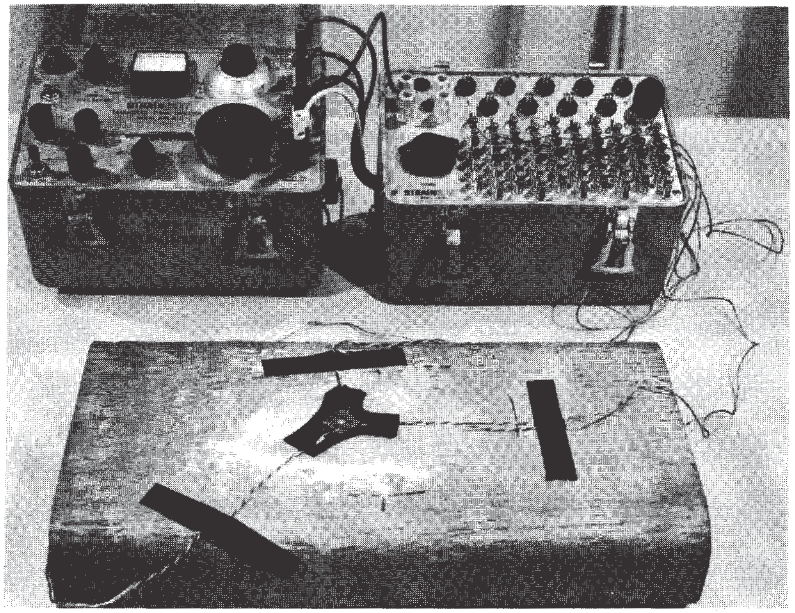

Figure 6. Strain Gage Rosette mounted to 3 x 8 inch Ingot and connected to Switch Box and Strain Indicator.

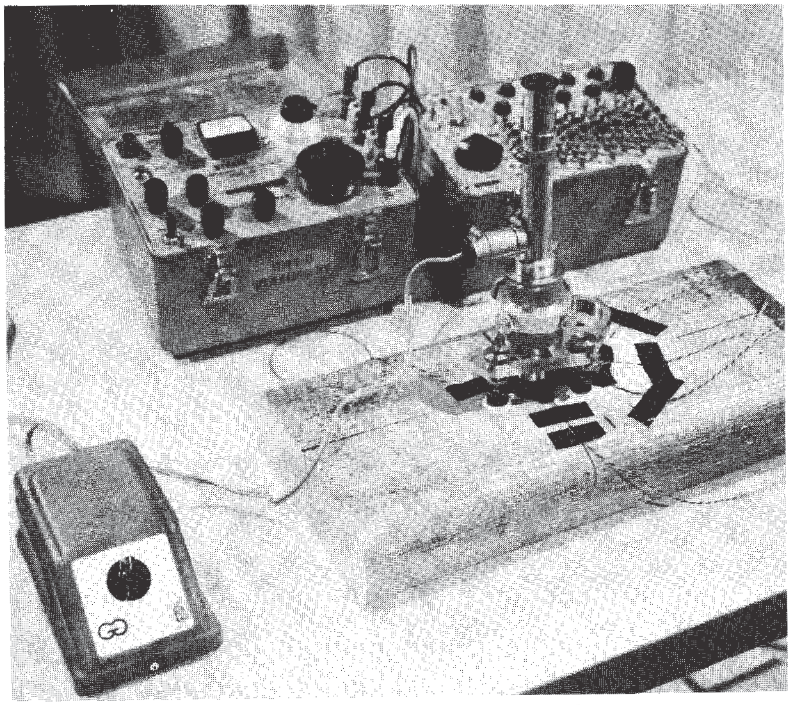

Figure 7. Precision Hole Locating and Milling Guide with Alignment Microscope.

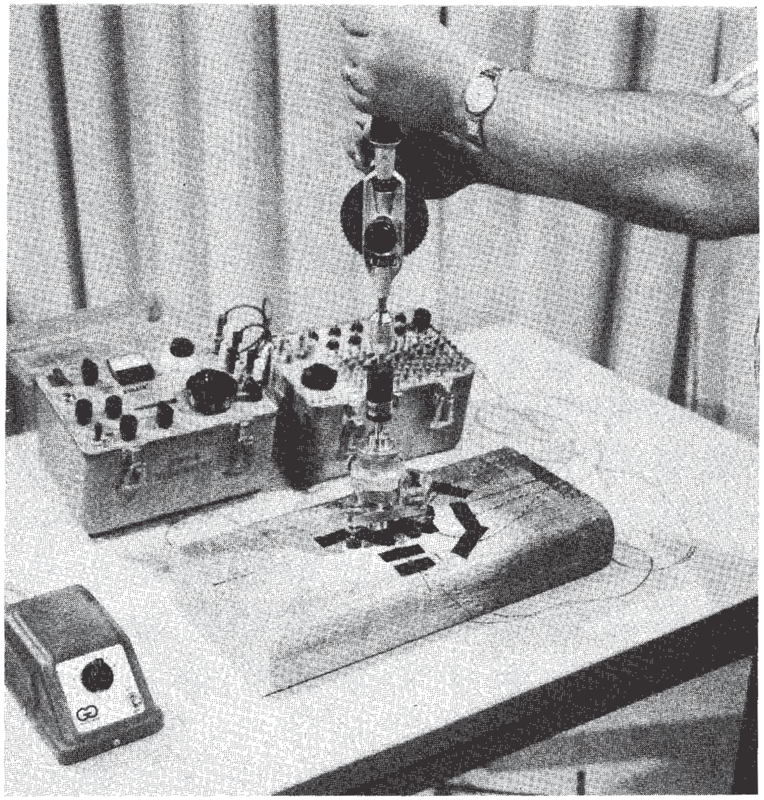

Figure 8. Microscope removed and Milling Tool inserted in Guide.

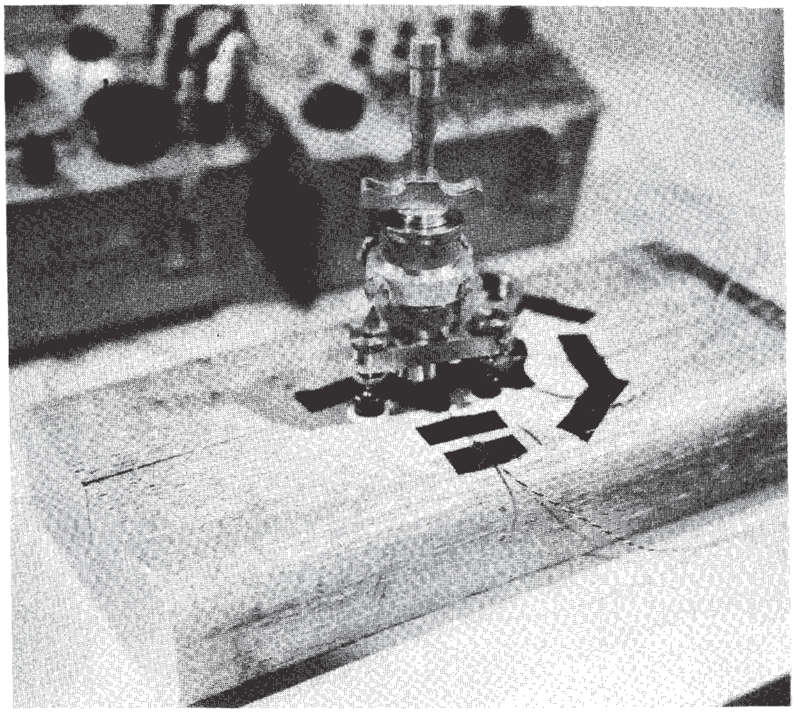

Figure 9. Hole Depth Measurement being made with Micrometer inserted in Guide Tube.

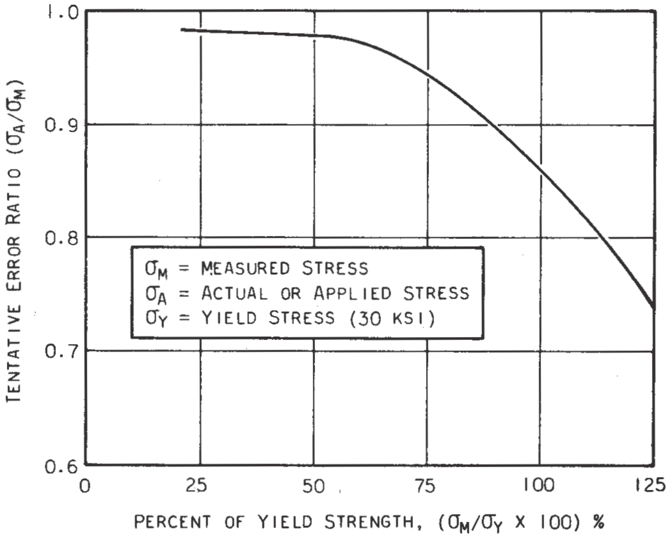

Figure 10. Calibration Curve after Rendler.