

Residual Stresses in As-Quenched Aluminum Castings

Keyu Li and Bowang Xiao
Oakland University

Qigui Wang
General Motor Company

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ABSTRACT

A significant amount of residual stresses can be developed in aluminum castings during heat treatment. This paper reports an experimental study of the residual stress distributions in aluminum castings after solution treatment and water quench. The residual stresses in aluminum castings are measured using both optical and resistance strain rosettes. The optical strain rosette technique was recently developed in conjunction with ring-core cutting method for residual stress measurement. The measured residual stresses from optical and resistance strain rosettes are compared with the results of X-ray and neutron diffraction measurements. The advantages and disadvantages of various measurement methods are discussed.

INTRODUCTION

Residual stresses are those remaining in a component after manufacture processing. The residual stresses may be present in engineered components, thin films, surface coatings, composites, and multiphase materials. Residual stresses originate from a variety of sources. Macroscopic residual stresses can arise from heat treatment, machining, secondary processing and assembly. Microstructural stresses often result from the CTE (coefficient of thermal expansion) mismatch between phases and constituents or from phase transformations. It is unlikely that a manufacture component is entirely free from residual stresses.

In order to increase mechanical properties, cast aluminum alloys are usually subject to a T6 heat treatment which includes a solution treatment at a relatively high temperature, quench in a cold medium such as water, then age hardening at an intermediate temperature. A significant amount of residual stresses can be developed in aluminum castings during the heat treatment process. The existence of residual stresses in a structural component can have a significant influence

on its performance. With the increasing demand of reducing weight and improving fuel efficiency, cast aluminum components have been widely used in critical automotive components such as engine blocks, cylinder heads, and suspension parts. Many of them experience cyclic loading. Fatigue performance of cast aluminum components can be dramatically affected by the presence of residual stresses, in particular, the tension residual stresses in the surface layer.

There are many ways to measure residual stresses in the manufactured parts. Mechanical approaches such as hole drilling, curvature measurements, and crack compliance measure residual stress by changes in component distortion. Diffraction techniques such as Electron, X-ray and neutron diffraction measure elastic strains in the components due to residual stresses. Others including magnetic, ultrasonic, piezospectroscopy photoelasticity, and thermoelastic techniques are also being developed.

In this paper, the residual stresses in aluminum castings are measured using both RSR (Resistance Strain Rosette) and ISSR (Interferometric Strain/Slope Rosette) techniques in conjunction with hole-drilling and ring-core cutting methods. The RSR (hole-drilling) method has long been used since developed in 1856 [1] and has been included in the ASTM standard E837 [2]. The detailed procedures are documented in Measurement Group's Bulletin 304 [3]. The ISSR is a laser based technique that measures the strain changes based on diffraction and interference of laser light [4 - 6].

THEORETICAL BACKGROUND OF RSR AND ISSR METHODS

In RSR, the residual stresses are calculated using equation (1) when a hole is drilled in the center of a strain rosette [1 - 3]

$$\begin{bmatrix} \sigma_1 \\ \tau_{13} \\ \sigma_3 \end{bmatrix} = \begin{bmatrix} A+B, 0, A-B \\ A, -2B, A \\ A-B, 0, A+B \end{bmatrix}^{-1} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} \quad (1)$$

where the relieved strains in directions of 0, 45 and 90 degrees are measured by 3 strain gages (#1, #2 and #3), and the Coefficients Matrix (CM) is constructed from the coefficients A and B. The coefficients are calculated using elasticity theory and finite element method which has been reported in the literature [7-10].

ISSR (Interferometric Strain/Slope Rosette) consists of three micro-indentations and has the configuration of delta or rectangular rosette [4]. A delta rosette, also called 60-deg ISSR, contains three six-faced indentations and the three indentations form an equilateral triangle. Under illumination by an incident laser beam, the six facets of each indentation in a delta rosette reflect and diffract the light in six directions which are at 60° apart from each another and the diffraction patterns from three indentations superpose in six directions. The motion of the fringes is related to the displacements between the indentations and hence to the strains and slopes. The strains and slopes are determined through tracing the shifts of fringe patterns.

The ISSR/Ring-core method is a combination of the ISSR method and ring-core cutting method [5, 6]. The ring-core cutting method is a stress-relief method. The ring-core cutting is to remove a ring of the material around the ISSR, which is depressed on the surface of the material before cutting. The gage length of the ISSR on the core area is normally in the range of 50μm and 250μm while the resistance strain rosette (RSR used for the hole drilling method) has a 5mm gage length. The

core size with the ISSR is less than 1 mm which is much smaller than that used in the RSR. More localized residual stresses, especially in the small areas with the high stress gradients, can be measured by the ISSR/ring-core method. The relative positions of the ring-core center and the ISSR are shown in Figure 1.

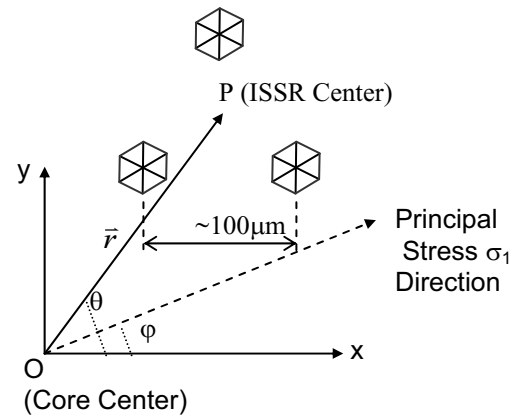


Figure 1 Rectangular and polar coordinates in the ISSR/ring-core method

The three ISSR micro-indentations are produced by micro-hardness tester on the surface of the test object. A small ring-core hole is introduced around the ISSR, using a precision drilling apparatus, Measurement Group's RS-200 Milling Guide. Three strain gages in the rosette measure three strain components simultaneously during the drilling.

In ISSR, the residual stresses are calculated from the relieved strains by equation (2):

$$\begin{bmatrix} \varepsilon_r \\ \varepsilon_\theta \\ \gamma_{r\theta} \\ \frac{\partial}{\partial r} \\ \frac{1}{r} \frac{\partial}{\partial \theta} \end{bmatrix} = \begin{bmatrix} \frac{\partial A(r)}{\partial r} & \frac{\partial B(r)}{\partial r} \cos 2\theta & -\frac{\partial B(r)}{\partial r} \sin 2\theta \\ \frac{A(r)}{r} & \frac{B(r)}{r} \cos 2\theta - \frac{2C(r)}{r} \cos 2\theta & -\frac{B(r)}{r} \sin 2\theta + \frac{2C(r)}{r} \sin 2\theta \\ 0 & \frac{2B(r)}{r} \sin 2\theta - \frac{\partial C(r)}{\partial r} \sin 2\theta + \frac{C(r)}{r} \sin 2\theta & -\frac{2B(r)}{r} \cos 2\theta - \frac{\partial C(r)}{\partial r} \cos 2\theta + \frac{C(r)}{r} \cos 2\theta \\ \frac{\partial D(r)}{\partial r} & \frac{\partial F(r)}{\partial r} \cos 2\theta & -\frac{\partial F(r)}{\partial r} \sin 2\theta \\ 0 & \frac{2F(r)}{r} \sin 2\theta & -\frac{2F(r)}{r} \cos 2\theta \end{bmatrix} \begin{bmatrix} \frac{\sigma_1 + \sigma_2}{2} \\ \frac{\sigma_1 - \sigma_2}{2} \cos 2\varphi \\ \frac{\sigma_1 - \sigma_2}{2} \sin 2\varphi \end{bmatrix}$$

Or

$$L = U \cdot I \quad (2)$$

where I is the 3-by-1 vector of unknown stresses, U is the 5-by-3 matrix of relaxation coefficients, and L is the 5-by-1 vector of displacement derivatives including strains and slopes. The components of strains and slopes are measured by the ISSR during the ring-core cutting. There are five equations to be solved for the three unknown stress components in Eq. (2). The least-squares method can be applied to solve this over-determined problem and the solution can be obtained

through the pseudo-inversion. The last two elements of the vector L represent the out-of-plane slopes. If ψ is taken as a 3-by-1 vector with the first three elements of the vector L and the upper 3-by-3 submatrix of the matrix U is designated as the matrix K , the residual stresses can be calculated by direct inversion as

$$I = K^{-1} \cdot \psi$$

The stress vector I can be solved if the coefficients in matrix U or K are provided. The Coefficients Matrix (CM) is constructed from the coefficients A through F . The coefficients are calculated using elasticity theory and finite element method and recorded in numerous published resources, e.g., ref [5, 6]. The residual stresses are computed from equation (3) based on the measured strains and the determined coefficients.

EXPERIMENTAL

ALUMINUM TEST CASTINGS - A mixed-leg test casting was employed in this work to investigate the residual stress development during water quench after solution treatment. The geometry of the test casting is shown in Figure 2. The nominal dimensions of the test casting are $120 \times 120 \times 25 \text{ mm}^3$. Two test castings were made in each mold from A356 alloy using precision sand casting process.

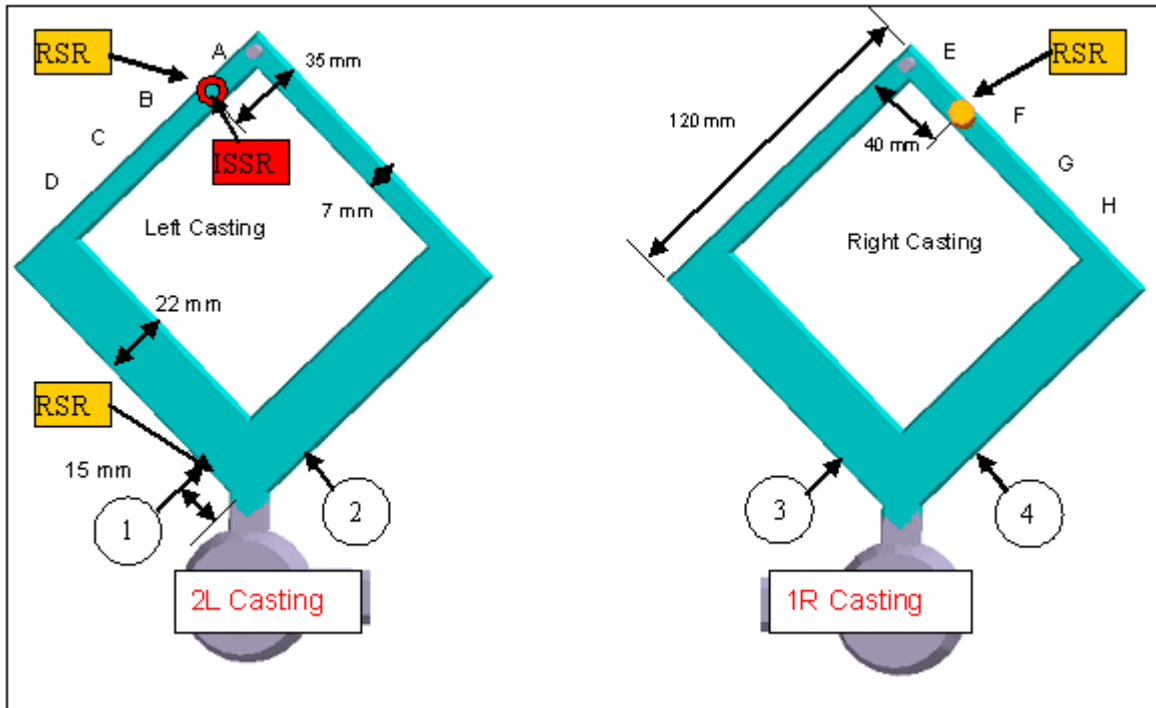


Figure 2 Schematic illustration of test castings and the locations for residual stress measurements by neutron at locations (1) through (4), X-ray diffraction methods at locations A through H and (1) through (4), ISSR and RSR methods.

HEAT TREATMENT - The aluminum test castings were subject to solution treatment at 540°C for 7 hrs and then quenched in water at 70°C .

RESIDUAL STRESS MEASUREMENT - The locations for ISSR, RSR, neutron and X-ray diffraction measurements are shown in Figure 2. ISSR measurements were made at 35 mm from the corner of two thin legs and on the centerline of the top surface. One of the RSR measurements was made at the similar location as ISSR. Other two RSR residual stress measurements were made at mid-height on the centerline of side surfaces as shown in Figure 2. Neutron diffraction residual stress measurements were made by NIST at mid-height of the side surfaces of thick legs at locations (1) through (4). X-ray diffraction measurements were made by Lambda also at locations (1) through (4). Additional surface only measurements were made by X-ray at mid-height (on the centerline) of side surfaces of thin legs at locations A through H as shown in Figure 2.

Residual stress distributions through the subsurface of the test castings are measured using incremental ring-core cutting technique when ISSR is used and hole-drilling method when RSR is used. A drill guide was used to hold the drill bit vertically. The hole depth was precisely controlled with a micrometer. Figure 3 shows the setup of the drilling system. When a thin layer of the material is removed, the relieved strains at that layer are measured. With multiple layers of material removed incrementally from the surface, the relieved strains in the multiple layers are measured. In this work, the residual stress distributions in the multiple layers are calculated using "integral method". [7,8]. A program was developed in Matlab to load measured strain data, to calculate the stress-strain coefficients and then to back-calculate the residual stresses.