

Analysis of Residual Stress Profiles in the Cylinder Web Region of an As-Cast V6 Al Engine Block with Cast-In Fe Liners Using Neutron Diffraction

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ABSTRACT

Continuous efforts to develop a lightweight alloy suitable for the most demanding applications in automotive industry resulted in a number of advanced aluminum (Al) and magnesium alloys and manufacturing routes. One example of this is the application of 319 Al alloy for production of 3.6L V6 gasoline engine blocks. Aluminum is sand cast around Fe-liner cylinder inserts, prior to undergoing the T7 heat treatment process. One of the critical factors determining the quality of the final product is the type, level, and profile of residual stresses along the Fe liners (or extent of liner distortion) that are always present in a cast component.

In this study, neutron diffraction was used to characterize residual stresses along the Al and the Fe liners in the web region of the cast engine block. The strains were measured both in Al and Fe in hoop, radial, and axial orientations. The stresses were subsequently determined using generalized Hooke's law. Further, detailed microscopy and hardness measurements were performed from top to bottom along the interbore region of each cylinder. The microstructure was characterized using an optical and scanning electron microscope (SEM). Further, composition analyses were performed using energy dispersive X-ray spectroscopy

(EDX). The results suggest that a variation in cooling rate along the cylinder caused a refinement of Al₂Cu, Al₁₅(Mn,Fe)₃Si₂ and eutectic silicon at the bottom of the cylinder. Increased cooling rate at the bottom of the cylinder also led to a more globular and uniform distribution of second phase particles, thereby resulting in increased hardness.

This study gives invaluable insight on anticipated service properties of the engine block and demonstrates that neutron strain mapping is an efficient tool for optimization of manufacturing technologies.

INTRODUCTION

Aluminum (Al) alloys are increasingly popular in the automotive and aerospace industries. These alloys boast low density, excellent strength and good castability. One of the most widely used Al alloys is the aluminum-silicon-copper (Al-Si-Cu) system. These alloys benefit from Cu additions, which contribute to strengthening and machinability and Si additions, which improve castability. Aluminum alloy 319 is the most frequently used Al-Si-Cu alloy. Common applications of this alloy include transmission cases, cylinder heads and engine blocks.

Engine blocks manufactured by 319 require the use of gray iron (Fe) liners to resist wear from sealings mounted in pistons. These liners are often cast-into the block, which allows for high productivity [1]. However, these cast-in iron liners may pose a problem. During casting, molten Al solidifies around the gray iron liners at the interbore regions. As a result, a significant variation in cooling rate may occur in these regions, leading to a non-uniform microstructure and mechanical properties. This lack of uniformity in microstructure and mechanical properties may lead to further problems when the engine blocks are heat treated and subsequently exposed to in-service conditions. For instance, a non-uniform microstructure along the engine block may result in a more complete dissolution of equilibrium phases in certain sections of the engine block. This non-uniform dissolution of phases can further result in a variation of material strength and lead to dimensional distortion when the engine blocks are exposed to in-service conditions [2]. Therefore, there is a need to characterize the microstructure along the cylinder of the engine block, specifically at the interbore regions. Further, residual stress measurements at these regions will enable a quantification of the severity of distortion.

Investigation of the cause of the distortion in the V6 engine block was the focus of this study. Neutron diffraction was carried out to characterize residual stresses along the Al and the Fe liners in the web region of the cast engine block. The strains were measured both in Al and Fe in hoop, radial, and axial orientations, thereby enabling the stresses to be determined using generalized Hooke's law. Detailed microstructural characterization was correlated with the hardness measurements for the engine block from the top of the cylinder bridge to the bottom.

NEUTRON DIFFRACTION ANALYSIS BACKGROUND

Neutrons are electrically neutral and can interact directly with nuclei of the atoms that make up the material. As a result neutrons are highly penetrating. For example, neutrons can penetrate through approximately 1 inch of steel. Neutron diffraction therefore provides a technique for the non-destructive measurement of residual strains and stress at depth of the sample material [3, 4].

Neutrons provided by a nuclear reactor are directed towards the measurement location within the specimen where they are diffracted from the lattice planes of the crystallites that form the material. The angle, 2θ , at which the neutrons are diffracted depends on the wavelength of the incident neutron beam, λ , and the spacing between the lattice planes, d , through Bragg's law,

$$\lambda = 2d \sin(\theta). \quad (1)$$

The lattice strain, ε , is the fractional change in the lattice spacing with reference to the *stress-free* lattice spacing, d_o , viz.,

$$\varepsilon = \frac{d - d_o}{d_o}. \quad (2)$$

The volume defined by the intersection of incident and diffracted neutron beams is called the sampling volume (Figure 1). The specimen is moved by a computer-controlled translation and rotation system to position the sampling volume at locations of interest within the specimen.

The strain is measured in the specimen direction parallel to the bisector of the incident and diffracted neutron beams (Figure 2). This bisector is known as the *scattering vector*. By re-orienting the specimen, various components of strain can be determined. For a "classical" cylindrical specimen these strain components are likely to be radial (R), axial (A) and hoop (H).

The three residual stress components, σ_x , where for a cylinder $x = (R, A, \text{ or } H)$, are then calculated from the three strain components using the expression,

$$\sigma_x = \frac{E}{1 + \nu} \left[\varepsilon_x + \frac{\nu}{1 - 2\nu} (\varepsilon_R + \varepsilon_A + \varepsilon_H) \right], \quad (3)$$

where E is the Young's modulus and ν is the Poisson's ratio ratio.

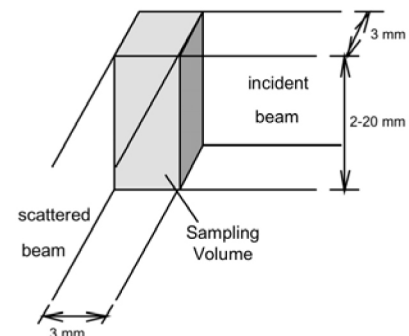


Figure 1. Sampling volume defined by the intersection of rectangular cross-section incident and diffracted neutron beams.

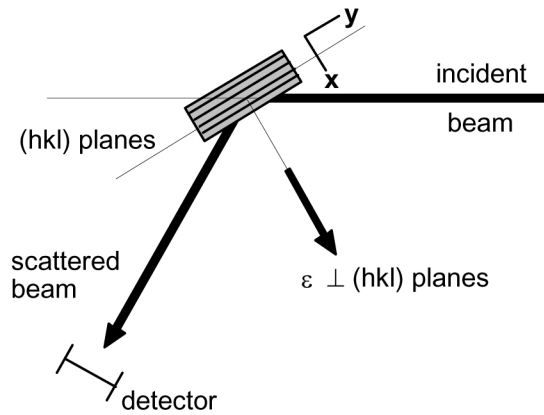


Figure 2. The component of strain parallel to the bisector of the incident and diffracted neutron beams (the scattering vector) is measured at the intersection of these beams.

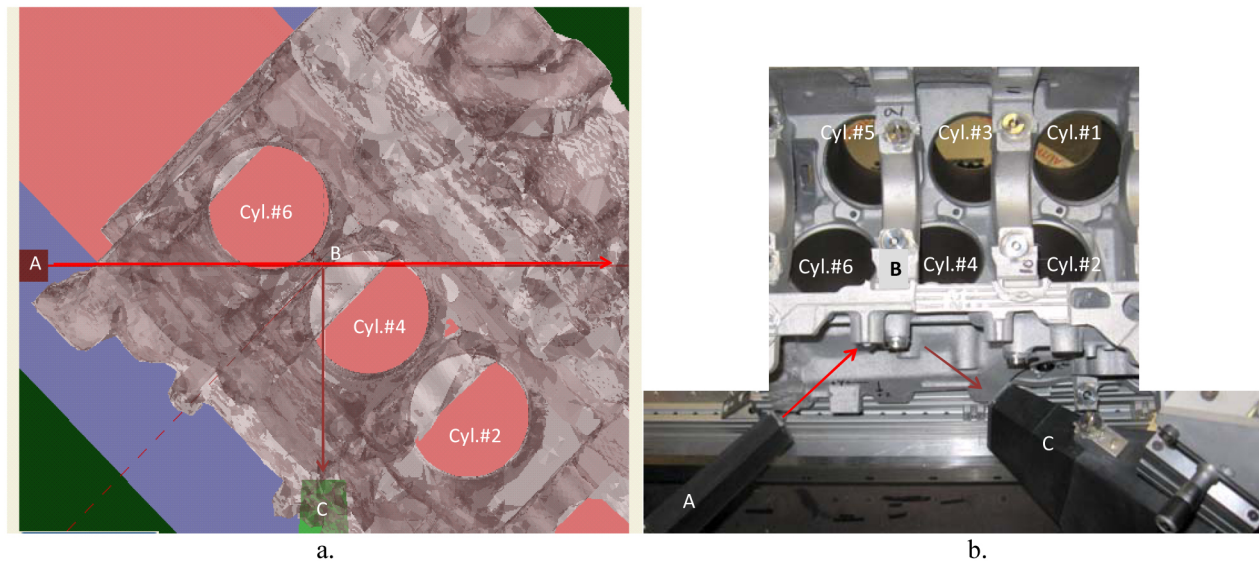


Figure 3. Orientation of incident and scattering beams and the engine block in measurement of hoop component of strain in the cylinder web region; a - control system map; b - actual positioning of the engine block on the spectrometer sample table.

HOOP STRAIN MAPPING

The as-cast engine block was positioned on the sampling table as shown in [Figure 3](#). [Figure 3a](#) shows the image generated by the spectrometer's control system for measurements of strains in Al and also in Fe liners in the cylinders' web area. The measurements were performed in the web between cylinders 6 and 4 on one side of the V-type engine block. The actual hoop-strain setup is shown in [Figure 3b](#). The sample was positioned on the table with the over-all precision of ± 0.5 mm.

The selected neutron wavelength for the experiment was 1.73 Å. According to the Bragg's law ([equation 1](#)) this corresponded to a diffraction angle 2θ of 90.1 degrees for Al (using the 311 planes for Al 319) and 95.4 degrees for Fe (211 reflection for gray iron). The monochromated incident

beam from the reactor-side slit system (A, [Figure 3](#)) penetrates through the bulk of the sample material (both Al and Fe). The sampling volume (B) is then formed by the intercept of the incident beam A and diffracted beam that reaches the neutron detector through the slit system C.

After collecting the neutron data at a specific location in the cylinder web the engine was translated in XYZ directions so that the next point-of-interest was positioned in the location of the sampling volume B. The neutron scan was then repeated for the new point. [Figure 4](#) depicts the progress in determining the hoop strain in the selected locations in Al in the web region along cylinders #4 and #6. [Equations \(1\) and \(2\)](#) were used to convert the measured position of the diffracted peak to the interatomic d -spacing and then to the values of strain. The reference value of the d -spacing for stress-free material, d_0 in [equation \(2\)](#) – was determined from

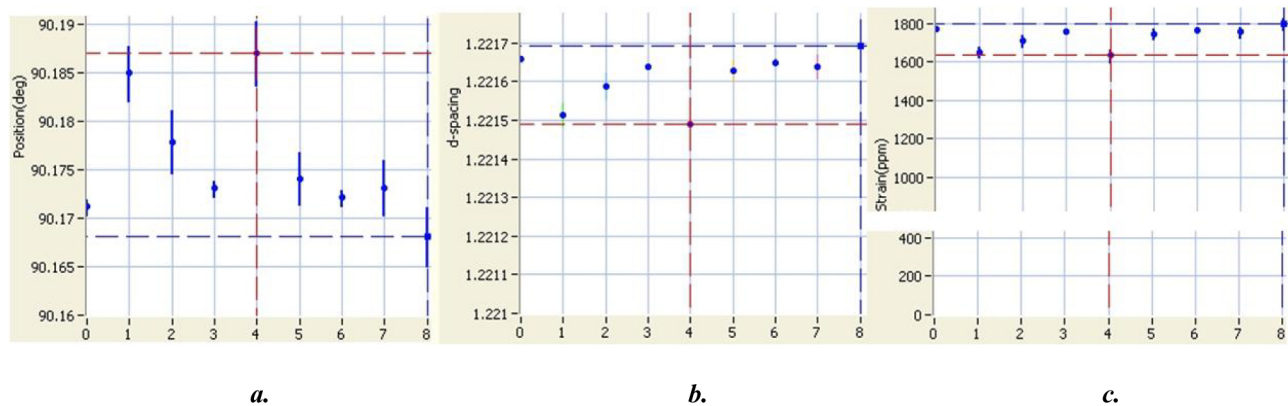


Figure 4. Results of neutron scan of the hoop component of strain in aluminum in the web region between the cylinders #4 and #6; a - angular position of the Bragg's peak for the nine measured locations; b - calculated d-spacing for the measured locations; c - hoop strain for the measured locations.

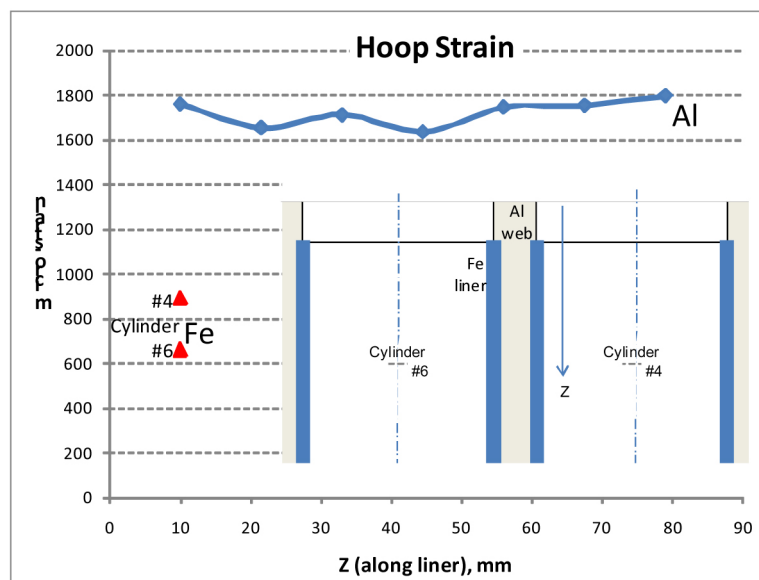


Figure 5. Hoop strains in Al casting and Fe liners along the web region.

neutron scans of “match stick” samples cut from a low-stress area of the casting. Special care was taken not to introduce any extra stress into the sample material during the machining operation. It was assumed that any residual stress in the material would be relieved during machining of the tiny (2×2×20 mm) stress-free samples. The d_0 value for Al was determined as 0.12 nm (1.22 Å) and 0.117 nm (1.17 Å) for Fe.

The values of hoop strain for the Al web between the cylinders, and the Fe liners were plotted against Z-coordinate - that is along the cylinder liners - to a depth of 79 mm (Figure 5). The top of the cast-in Fe liners corresponded to the position of 10 mm of Z coordinate. The hoop strain in Fe was measured at this position in both liners. As follows, all the strains were tensile, ranging from ~650 to 900

microstrain (or $\text{strain } 10^6$) in the top part of the Fe liners and from ~1600 to 1800 microstrain in Al along the web.

RADIAL STRAIN MAPPING

The radial-orientation strains were determined in the casting in a similar fashion as the hoop strains. Figure 6 depicts positioning of the engine block on the sample table.

The progress in determining the radial strain in the selected locations of Al is shown in Figure 7. The final results of strain for Al and Fe are presented in Figure 8. It follows that the Fe liners were experiencing tensile strain of $1200 \sim 1500 \times 10^{-6}$ (1200~1500 microstrain), while the strains in Al were compressive and very low in value, ranging from 0 to 400×10^{-6} (or 0 to 400 microstrain).

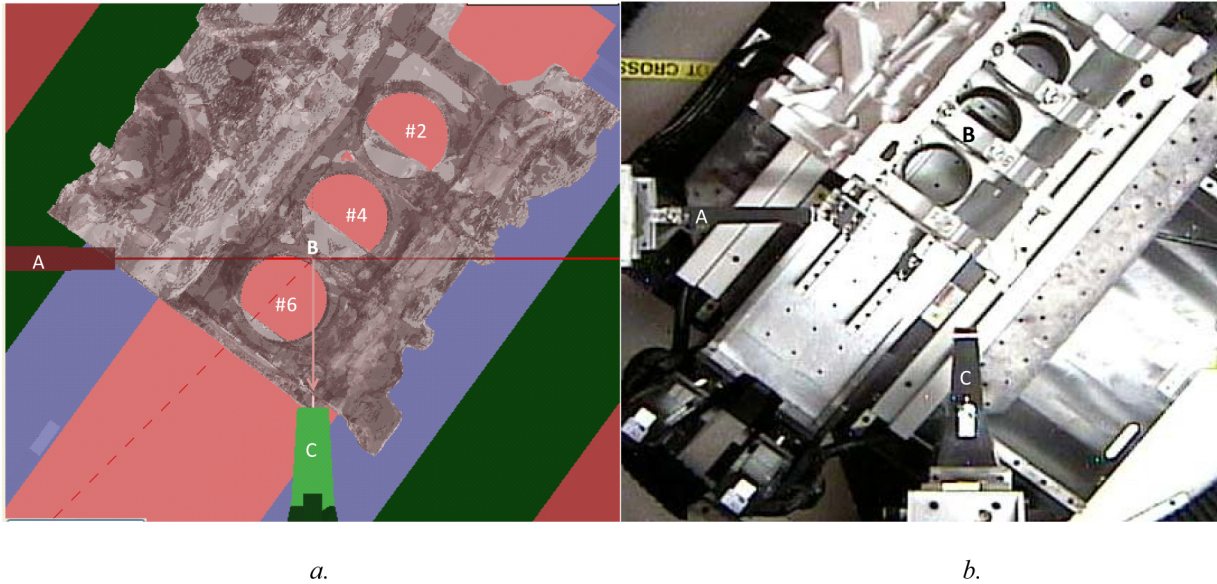


Figure 6. Orientation of incident and scattering beams and the engine block in measurement of radial component of strain in the cylinder web region; a - control system map; b - actual positioning of the engine block on the spectrometer sample table.

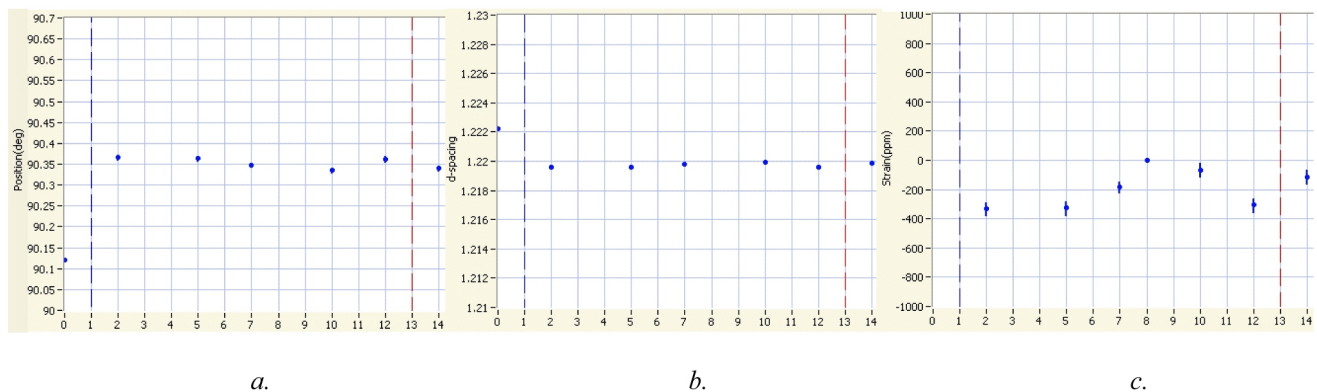


Figure 7. Results of neutron scan of the radial component of strain in aluminum in the web region between the cylinders #4 and #6; a - angular position of the Bragg's peak for the nine measured locations; b - calculated d-spacing for the measured locations; c - hoop strain for the measured locations.

AXIAL STRAIN MAPPING

Axial strain mapping completed the 3D characterization of strains in the web region. Figure 9 depicts positioning of the engine block on the sample table.

The progress and results of these measurements are presented in Figures 10. Two web regions were examined in this part of the study; namely, between cylinders #4 and #6 (1st Web) and also, between cylinders #2 and #4 (2nd Web). The purpose of the second web scan was to compare the results received for the two web regions and confirm (or deny) whether both were experiencing similar strain conditions.

It follows from Figure 10 that axial strain in Al was similar in both cases. The values were found to be tensile and typically ranging from 750 to 1500 microstrain. The very top of the web was found to have the lowest values ranging from 0 to 800 microstrain. Axial strains for the Fe liners, on the other hand, were lower. These values were under 500 microstrain and were both tensile (1st web) and compressive (2nd web). The very top of the Fe liners was under compressive strain reaching 2000 microstrain.

RESIDUAL STRESS ANALYSIS

The approach used in this study for determining the three components of strain (hoop, radial, and axial) allows for characterization of residual stress by applying the generalized