

Neutron Diffraction Study on Residual Stress in Aluminum Engine Blocks Following Machining and Service Testing

Anthony Lombardy
Ryerson University

Dimitry Sediako
National Research Council Canada

Francesco D'Elia and C. (Ravi) Ravindran
Ryerson University

Robert I. Mackay
Nemak of Canada

ABSTRACT

Development of lightweight alloys suitable for automobile applications has been of great importance to the automotive industry in recent years. The use of 319 type aluminum alloy in the production of gasoline engine blocks is an example of this shift towards light alloys for large automobile components. However, excessive residual stress along the cylinder bores of these engine blocks may cause problems during engine operation. Therefore, in this study, neutron diffraction was used to evaluate residual stresses along the aluminum cylinder bridge and the gray cast iron liners. The strains were measured in the hoop, radial, and axial orientations, while stresses were subsequently calculated using generalized Hooke's law. The results suggest that the residual stress magnitude for the aluminum cylinder bridge was tensile for all three measured components and gradually increased with cylinder depth towards the bottom of the cylinder. The residual stress in the gray cast iron liner was highly compressive with a relatively constant stress magnitude.

CITATION: Lombardy, A., Sediako, D., D'Elia, F., Ravindran, C. et al., "Neutron Diffraction Study on Residual Stress in Aluminum Engine Blocks Following Machining and Service Testing," *SAE Int. J. Mater. Manf.* 5(1):2012, doi: 10.4271/2012-01-0188.

INTRODUCTION

The large increase in use of aluminum alloys for automotive powertrain applications, such as engine blocks and cylinder heads, is a prime example of the shift towards lighter materials for the production of automobiles. Aluminum alloys are approximately 65% lighter than ferrous materials such as steels and cast irons. In addition, heat treatable aluminum alloys, such as the Al-Si-Cu alloy system, exhibit good strength at ambient and elevated temperatures ($\sim 200^{\circ}\text{C}$). For this reason, and due to stricter government legislation on fuel consumption and carbon emissions, the use of aluminum alloys has significantly increased in the automotive industry.

The typical aluminum alloys that are currently used in the production of engine blocks are hypoeutectic Al-Si alloys,

which have insufficient wear resistance to withstand the reciprocating motion of the piston within the combustion chamber during engine operation. The cylinder liners, commonly made of gray cast iron, are inserted into the cylinder bore region to improve wear resistance. The presence of gray cast iron, however, causes the generation of residual stress during casting and heat treatment due to the significant difference in thermal expansion coefficient between aluminum ($\sim 2.4 \times 10^{-5} \text{ K}^{-1}$) and gray cast iron ($\sim 1.5 \times 10^{-5} \text{ K}^{-1}$) [1]. These large residual stresses along the cylinder bores, in addition to stresses exerted due to combustion, may cause the engine blocks to be prone to permanent dimensional distortion or premature fracture. It is thus important to perform in-depth studies on residual stresses along the cylinder bores in aluminum engine blocks containing gray cast iron liners at different stages in the

Table 1. Composition of the modified 319 engine block (wt %).

Si	Cu	Zn	Fe	Mg	Mn	Ti	Ni	Cr	Sr	Sb	B	Bi	Al
8.5	2.8	0.5	0.4	0.35	0.35	0.15	0.04	0.03	0.005	0.002	0.001	0.001	Balance

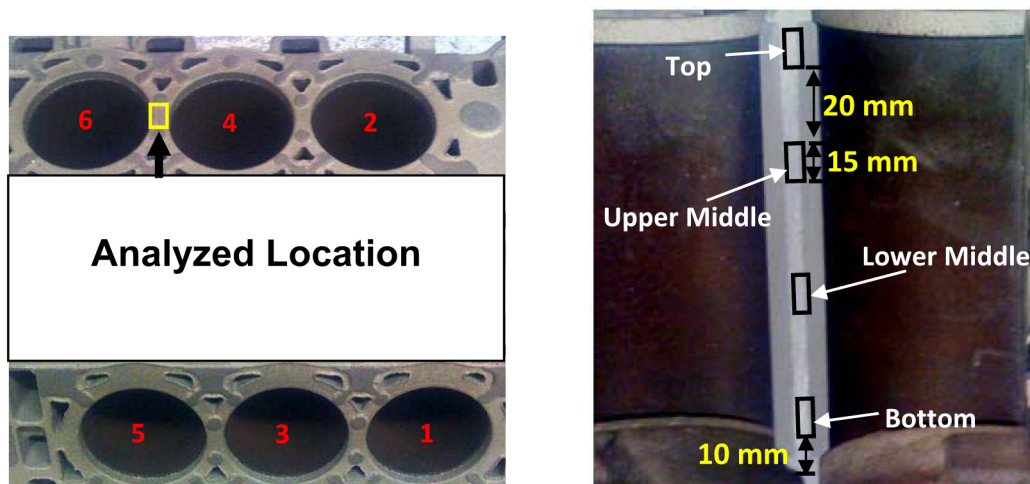


Figure 1. Images of: (a) top view of engine block, indicating analyzed sections, (b) cross-section of the cylinder bridge showing sections analysed along the cylinder depth.

production process in order to determine processing procedures to reduce residual stress.

Residual stress measurements in aluminum engine blocks have been carried out by Carrera et al. [1]. However, in this study, strain gauges were used and thus only the deck face portion of the engine was examined. The work of Weisner et al. [2] used neutron diffraction to measure residual stress but this work focused on the bulkhead portion of the engine block. Additionally, Su et al. [3] performed finite element modeling of residual stresses along the cylinders. However, experimental measurements along the entire depth of the cylinder are required to verify the stresses predicted by this model. For this reason, there is a need to generate residual stress profiles along the length of the cylinder bores in aluminum engine blocks. This paper presents residual strain and stress profiles, obtained using neutron diffraction, measured along the aluminum cylinder bridge and gray cast iron liners for a service tested engine block. This paper also presents variations in interplanar spacing along the cylinder for the stress free samples, which are required for neutron diffraction stress mapping.

EXPERIMENTAL PROCEDURE

The engine blocks examined in this study were cast at the Nemak Centre of Engineering in Windsor, Canada. The composition of the 319 type aluminum alloy used in engine block production is shown in Table 1. Prior to pouring of molten aluminum into the precision sand moulds, gray cast iron cylinder liners were preheated to approximately 400 °C

and inserted into the mould. Following the casting process, the engine blocks were subjected to a thermal sand reclamation (TSR) treatment at 495 °C for 1 hour. Heat treatment to a T7 temper was carried out by first subjecting the engine blocks to a solution heat treatment at 480 °C for 7.5 hours followed by aging at 240 °C for 5.5 hours. Thereafter, the cylinder bores were machined to the appropriate operating dimensions and select engine blocks were service tested for 20 hours on an engine dynamometer.

Residual stress mapping was carried out from top to bottom of the cylinder bridge between cylinders 4 and 6 of the engine blocks as indicated by the rectangles in Figures 1 (a) and (b). Residual stress was measured along the aluminum cylinder bridge and the gray cast iron cylinder liners in the hoop, radial and axial directions using neutron diffraction. Neutron diffraction was carried out at the Canadian Neutron Beam Centre in Chalk River, Canada.

In this study, neutron diffraction was carried out on the Al (311) and (331) planes as well as the Fe (211) plane. The initial neutron beam wavelength was 1.55 Å. To quantify the residual stress along the aluminum cylinder bridge and the adjacent gray cast iron liner, residual strain (ϵ) was first determined using the “peak shift” method. The peak shift method relates the interplanar (d_{hkl}) spacing obtained from the region of interest to the interplanar spacing of a stress free sample ($d_{0,hkl}$) of the same composition. The residual strain was then calculated (Equation 1).

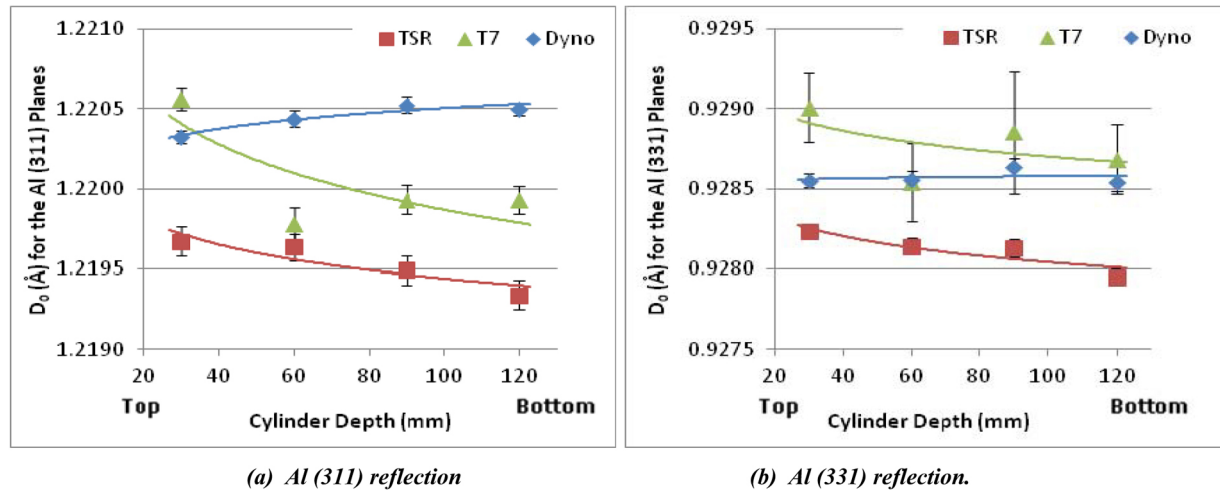


Figure 2. Variation in d_0 along the cylinder for engine blocks in each treatment condition

$$\varepsilon = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} \quad (1)$$

The stress free samples were extracted from the top, upper middle, lower middle and bottom regions of the cylinder (Figure 1 (b)) to account for the changes in microstructure. Although these samples were taken from a high stress region, it was assumed that sectioning the samples into the $2 \times 3 \times 20$ mm geometry effectively relieved the residual stresses. In addition, to average and negate the influence of any remaining hoop and radial strains on the d_0 value, the match stick samples were installed on a low-rpm rotation stage during the neutron diffraction experiments. Once the strain was determined, residual stress was calculated for the hoop (σ_H), radial (σ_R) and axial (σ_A) components using generalized Hooke's Law, shown in Equation 2.

$$\sigma_{H,R,A} = \frac{E}{2\nu} \left[\varepsilon_{H,R,A} + \frac{\nu}{1-2\nu} (\varepsilon_H + \varepsilon_R + \varepsilon_A) \right] \quad (2)$$

Where, E is the modulus of elasticity, ν is Poisson's ratio.

RESULTS AND DISCUSSION

VARIATION IN d_0 ALONG CYLINDER

The use of neutron diffraction to measure residual strain and stress is dependent on the interplanar spacing measured from the stress free sample. In this project, stress free samples were taken from sections along the cylinder bridge to account for microstructural changes. The resulting d_0 values for the Al (311) and (331) planes along the cylinder for each treatment condition are shown in Figure 2. The results for the engine block in the TSR condition indicate that the d_0 spacing decreases slightly with increased cylinder depth. A similar trend was found for the T7 heat treated engine block,

although the variation in d_0 was slightly larger than that observed in the TSR engine block. Finally, for the dyno tested engine block, the d_0 spacing slightly increased with increasing depth, although this variation in d_0 was significantly smaller than that observed in the TSR and T7 conditions.

The variation in d_0 spacing with cylinder depth was likely caused by the change in microstructure observed along the cylinder bridge. In-depth microstructural characterization was performed from top to bottom along the cylinder bridge in previous studies [4, 5]. The results from microstructural analysis confirmed a significant refinement in microstructure (dendrite size and morphology of secondary phases) at the bottom of the cylinder relative to the top. The average secondary dendrite arm spacing decreased from approximately $35 \mu\text{m}$ at the top of the cylinder to $20 \mu\text{m}$ at the bottom. These results suggest that there was a significant variation in cooling rate along the cylinder during solidification, which was likely caused by the presence of risers near the top of the cylinder and chills near the bottom.

The lattice parameter and thus the interplanar (d) spacing in the FCC aluminum lattice are largely dependent on the quantity of alloying elements, such as copper and magnesium, in solid solution with the aluminum matrix. The work of Hunsicker [6] demonstrated that the lattice parameter in aluminum alloys is reduced significantly with increased copper content in solid solution. In addition, Li et al. [7] observed that the amount of Al_2Cu in the 319 alloy microstructure decreases with increased cooling rate suggesting that rapidly solidified 319 alloys retain more copper in solid solution. Therefore, the slight reduction in d_0 spacing may be the result of increased cooling rate at the bottom of the cylinder which caused more copper to remain in solid solution following solidification. With regards to the service (dyno) tested engine block, additional production processes such as machining of the cylinder bores and dynamometer testing at elevated temperature, (cylinders