

Residual Stress Mapping along the Cylinder Bores of Al Alloy Engine Blocks Subjected to Production Solution Heat Treatment Schedule

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ABSTRACT

The development of an optimized heat treatment schedule, with the aim of maximizing strength and relieving tensile residual stress, is important to prevent in-service cylinder distortion in Al alloy engine blocks containing cast-in gray iron liners. However, to effectively optimize the engine block heat treatment schedule, the current solutionizing parameters must be analyzed and compared to the as-cast condition to establish a baseline for residual stress relief. In this study, neutron diffraction was carried out to measure the residual stress along the aluminum cylinder bridge following solution heat treatment. The stresses were measured in the hoop, radial and axial orientations and compared to a previous measured as-cast (TSR) engine block. The results suggest that solution heat treatment using the current production parameters partially relieved tensile residual stress in the Al cylinder bridge, with stress relief being more effective near the bottom of the cylinder.

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INTRODUCTION

Lightweighting has become an important aspect in the design and production of automobiles due to strict government legislation on fuel economy. This requires the development of low density alloys to replace ferrous alloys in automotive components. Aluminum alloys, being approximately 65% lighter than ferrous materials, are attractive to automotive OEMs to reduce vehicle weight and improve fuel efficiency.

Although Al alloys allow for a significant reduction in weight when used in large powertrain components, there are challenges with use of these alloys. For instance, the hypoeutectic Al-Si-Cu alloy system, which is typically used in engine block production, has insufficient wear resistance to withstand the reciprocating motion of the piston within the cylinder during engine operation. This limitation requires the use of protective gray cast iron cylinder liners to improve wear resistance.

The presence of gray cast iron results in the development of tensile residual stress during casting and heat treatment due to a combination of thermal gradients induced during quenching and the significant difference in thermal expansion coefficient between aluminum ($\sim 2.4 \times 10^{-5} \text{ K}^{-1}$) and gray cast iron ($\sim 1.5 \times 10^{-5} \text{ K}^{-1}$) as confirmed by several previous studies [1, 2, 3, 4, 5]. These tensile residual stresses along the cylinder bores, in addition to stress exerted due to rapid expansion of the air-fuel mixture during combustion may cause the engine blocks to fail pre-maturely or be prone to permanent dimensional distortion, which is detrimental to engine operating efficiency. Optimization of the engine block production process, specifically post-casting heat treatment, may minimize residual stress, reducing the likelihood of in-service engine failure. It is therefore important to study the residual stress along the cylinder bores of engine blocks subjected to a production solution heat treatment schedule, allowing a baseline to be determined for future process optimization.

Previous studies have examined the influence of heat treatment on residual stress but were limited in methodology or had a different scope. For instance, Su et al. [3] and Carrera et al. [4] applied strain gauges to measure the residual stress of as-cast and T7 (solutionized and overaged) heat treated Al engine blocks containing gray iron liners. However, these studies were restricted to the deck face portion of the engine due to limitations with strain gauges. In addition, Weisner et al. [5] used X-ray and neutron diffraction to measure residual stresses in as-cast and T7 heat treated Al alloy engine blocks, but this study focused on the bulkhead region of the block. Furthermore, the current authors [1,2] used neutron diffraction to examine residual stresses at increasing depths along the cylinder bores, but these studies focused on as-cast, T7 heat treated and dyno tested engine blocks, not the intermediate solution heat treatment (T4) production stage.

Although, the effect of solution heat treatment and quenching on residual stress in Al alloys was successfully investigated by other researchers [6, 7, 8] their work did not analyze forced air quenched engineering components with complex geometries and dissimilar materials as is the case with these Al alloy engine blocks. Therefore, this paper addresses the need to study production T4 treated engine blocks to isolate the influence of each production stage (when compared with as-cast and T7 treated blocks) on residual stress relief and provide valuable information for future process optimization.

EXPERIMENTAL METHODOLOGY

The composition of the engine blocks examined in this study is shown in Table 1.

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	0.01	0.002	0.001	0.001	Bal.

The V6 Al engine blocks were cast using the Nemak-Cosworth process with precision sand moulds. Prior to pouring molten 319 Al alloy (pouring temperature of 720 °C), gray cast iron cylinder liners were preheated to approximately 400 °C (using induction coils) and inserted into the sand mould.

Following casting, the engine blocks were subjected to a thermal sand reclamation (TSR) treatment at 495 °C for 1 hour. Solution heat treatment was then carried out on select engine blocks using the current production schedule (470 °C for 7.5 hours). Forced air cooling followed solution treatment at a rate of between 70 and 100 °C/minute in the cylinder bore region.

Microstructural analysis was carried out from top to bottom along the Al cylinder bridge of the T4 treated engine blocks (analyzed locations shown in Figure 1) using optical microscopy.

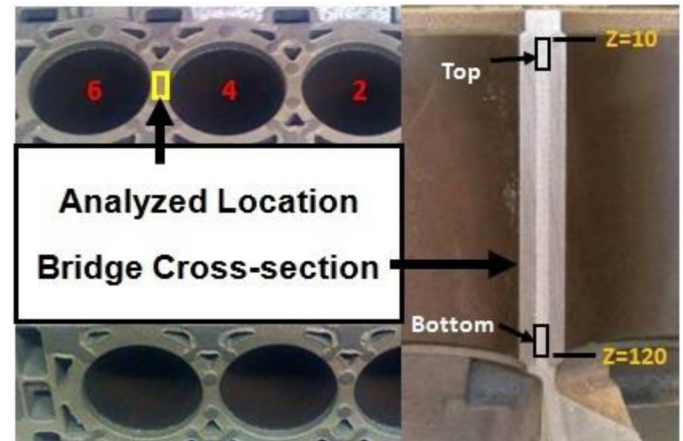


Figure 1. Images of: (left) top view of engine block, indicating analyzed sections, (right) cross-section of the cylinder bridge showing analyzed locations (dimensions in mm).

Residual stress mapping was carried on T4 treated engine blocks using neutron diffraction at the Canadian Neutron Beam Centre in Chalk River, Canada. The analysis was performed from top (z=10 mm) to bottom (z=120 mm) along the Al bridge between cylinders 4 and 6 (rectangle in Figure 1) and the adjacent gray cast iron cylinder liners. In addition, strain measurements were done in the hoop, radial and axial directions, relative to the cylinder bore axis.

The neutron diffraction analysis used a monochromated incident beam with a wavelength of 1.55 Å. The diffraction data was obtained using the (311) and (331) reflections for Al and the (211) reflection for gray iron.

In order to calculate residual stress, residual strain (ϵ) was first determined along the aluminum cylinder bridge and gray iron liner using the “peak shift” method (Equation 1), which 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 alloy composition and processing history.

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

The stress free samples were extracted from the top, upper middle, lower middle and bottom regions of the cylinder (Figure 1) to account for the changes in microstructure. In this analysis, it was assumed that sectioning the samples into the 3×3×20 mm geometry effectively relieved the residual stresses. However, to increase the accuracy of the d_0 measurements, the match stick samples were installed on a low-rpm rotation stage during the neutron diffraction experiments to negate the influence of any remaining stresses.