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# Effect of solution heat treatment on residual stress in Al alloy engine blocks using neutron diffraction

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ABSTRACT

Tensile residual stress in the cylinder bore region is a significant problem associated with Al engine blocks containing cast-in gray iron cylinder liners as it can result in cylinder distortion or engine block fracture. These issues can lead to significant environmental (emissions) and economic (recalls) problems for automotive OEMs. In this study, in-situ and ex-situ neutron diffraction was used to measure the change in residual strain in the cylinder bridge as a function of time during solution heat treatment and map to the stress profiles following heat treatment. A heating system, consisting of coiled tubular heaters in the cylinder bores and strip heaters along the front and side faces of the engine block, was designed and built to heat the blocks to the solution temperatures The results indicated that solutionizing at 470 °C caused a gradual relief of tensile residual strain up to approximately 5 h, where strain was completely relieved. At 500 °C, the strain relieved more rapidly, which resulted in complete relief in under 0.5 h. Cooling to ambient temperature caused the partial re-development of tensile residual stress throughout the cylinder depth due to thermo-mechanical mismatch, however the magnitude was lower than for the as-cast condition.

## 1. Introduction

Automotive powertrain components such as engine blocks are increasingly produced using light weight Al alloys in an effort to improve vehicle fuel efficiency. The impetus to develop and implement light alloys in the automotive industry has been mainly due to government legislation requiring automotive OEMs to have a corporate average fuel economy (CAFE) of 4.2 L/100 km (54.5 US MPG) by 2025 [1]. Aluminum, having a density of approximately 2.7 g/cm$^3$, is approximately 65% lighter than ferrous alloys such as cast iron, which was used extensively in engine block production [2]. In addition, common automotive Al casting alloys (Al-Si-Cu-Mg) have excellent castability and good strength at ambient and elevated temperatures. For these reasons, Al alloys are suitable in fulfilling this lightweighting mandate.

Although Al alloys have many advantages with regards to use in engine blocks, there are significant challenges such as generation of tensile residual stress (type-I macro-stress) during processing. Tensile residual stresses are generated following heat treatment (during quenching) by two mechanisms. The first is due to thermal gradients caused by the rapid cooling rate during quenching, while the second pertains to thermo-mechanical mismatch in components containing dissimilar materials [3–5]. There have been several studies which investigated the development of residual stress following heat treatment of Al alloys for various processes and parameters [6–12] since residual stresses may severely impair component integrity and performance.

With regards to Al engine blocks, the relative softness of hypoeutectic Al-Si alloys (commonly used in automotive castings) requires the use of protective cylinder sleeves, made of gray cast iron, to mitigate the insufficient wear resistance of these alloys in critical locations such as the cylinder bores. However, the large difference in the thermal expansion coefficient ($\alpha_{Fe} = 1.5 \times 10^{-5}\,K^{-1}$, $\alpha_{Al} = 2.4 \times 10^{-5}\,K^{-1}$, [13]) between the gray iron liners and the surrounding Al alloy results in tensile residual stress along the cylinder bores during post-casting or post-heat treatment cooling. This tensile residual stress was quantified in previous studies on Al engine blocks containing cast iron liners at each production stage (as-cast, T4 treated, T7 treated, and following in-service testing) [13–17]. Furthermore, the current authors also found in a previous study [18] that excessive tensile residual stress may induce

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permanent dimensional distortion in the engine block, which may result in energy (reduced engine efficiency), environmental (increased carbon emissions) and economic (expensive automotive recalls) repercussions.

The magnitude of the tensile residual stresses can be reduced via heat treatment. Solution heat treatment (SHT), annealing and artificial aging have been shown to effectively relax tensile residual stress in Al alloy components [19–23], and more specifically Al alloy engine blocks containing gray iron cylinder liners [13–17,24]. Most of the previous research on residual stress relaxation during heat treatment was carried out with ex-situ methods, and as such did not quantify the relief of stress as a function of heat treatment time. However, two previous studies by Chen et al. [20] and Rolph et al. [21] used in-situ neutron diffraction to measure the relief of residual stress with soaking time in a welded steel pipe and RR1000 Ni-based superalloy plate, respectively. It was postulated in these studies that tensile residual stress was relaxed predominantly via creep with the initial rapid stress relief attributed to primary creep and the subsequent linear stress relief caused by steady state creep. In contrast to the relatively simple and monolithic components examined by Chen et al. [20] and Rolph et al. [21], the current authors [24] applied in-situ neutron diffraction, in a pioneering study, to measure the relief of strain as a function of solutionizing time in Al engine blocks containing gray iron cylinder liners. Although this study was successful in measuring strain relief, it was carried out at only one solutionizing temperature and for a single location along the cylinder bridge of the engine block. Therefore, this sequel study used in-situ neutron diffraction to measure the transient relief of strain during heat treatment at multiple temperatures and compared the resulting rates of strain relief for each parameter. Furthermore, ex-situ neutron diffraction was used to measure residual stress in the hoop, radial and axial directions from top to bottom of the cylinder bridge. This analysis enabled the influence of SHT on stress relief to be quantified at different cylinder depths, which had a transition from coarse-to-fine microstructure as was observed in the previous studies of the current authors [15,18,25]. This study will further assist in the development of optimal heat treatment schedules for multi-material components such as engine blocks to help prevent potential problems such as in-service cylinder distortion or engine fracture.

## 2. Experimental methodology

Aluminum alloy 319 (chemical composition shown in Table 1) was used in the production of the V6 engine blocks, which were precision sand cast using the Cosworth process, at the Nemak Engineering Centre in Windsor, Canada. Cylinder liners, made of gray cast iron (preheated to 400 °C) and a Cu bulkhead chill plate were inserted into the sand mould prior to the pouring of the molten 319 Al alloy. The thermal sand reclamation (TSR) treatment entailed homogeneous soaking at 480 °C for 1 h (time that the engine is at this temperature) following the casting process to remove the sand mould from the engine block. The TSR treatment was completed with a “shake out” and a forced air quench with the airstream flowing directly into the cylinder bores.

Regarding the in-situ neutron diffraction (ND) experiments, initially TSR treated engine blocks were solution heat treated at 470 and 500 °C for 8 h while at the neutron spectrometer. Higher temperatures were not considered as previous studies indicated that incipient melting of $Al_2Cu$ and $Al_5Mg_8Cu_2Si_6$ occurred above 500 °C [25,26]. The 8 h soaking time was selected to conform to the industrial practice of Al alloy engine block production.

**Table 1**
Chemical composition of the 319 Al alloy engine block (wt%).

| Si | Cu | Zn | Fe | Mg | Mn | Ti | Ni | Cr | Sr | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.0 | 2.9 | 0.59 | 0.69 | 0.37 | 0.41 | 0.14 | 0.07 | 0.04 | 0.015 | Bal. |

Engine block heating was accomplished using tubular coil heaters inserted into the cylinder bores as well as strip heaters strategically placed in the locations shown in Fig. 1(a). Superwool Plus® insulating blankets (~50 mm thick) were wrapped around the engine blocks to reduce heat loss to ambient air during the elevated temperature experiments. The heating system was completed by inserting thermocouples (TC) into the locations specified in Fig. 1(b) to continuously monitor the temperature at several areas of the engine block. In addition, select thermocouples, illustrated by the dashed boxes in Fig. 1(b), were used to provide feedback for PID temperature controllers which maintained the engine block temperature to within 1 °C of the set point throughout the neutron experiments.

Neutron diffraction analysis of the engine blocks was carried out at the Canadian Neutron Beam Centre in Chalk River, Canada. Due to the limited beam time for these experiments, all neutron diffraction analysis was restricted to the interbore region between cylinders 4 and 6 (indicated by the rectangle in Fig. 1(a)). The interbore region was chosen for these experiments as they are the critical locations in the engine blocks with respect to applied stresses and heating, resulting from the combustion process. The cylinder depth of approximately 50 mm (shown in Fig. 2) was selected for the in-situ neutron diffraction experiments since this region had high initial stress and was also in the vicinity of the area where maximum distortion was found in a previous study by the current authors [18]. However, ex-situ neutron diffraction was carried out at ambient temperature along the entire cylinder depth ($0 < Z < 120$ mm), as indicated in Fig. 2, to develop residual stress profiles for the entire cylinder bridge.

In-situ neutron diffraction analysis was confined to the axial orientation, as limitations in the apparatus prevented the simultaneous measurement of strain in the three principal directions. Preliminary experiments confirmed that the axial orientation had the lowest beam attenuation which resulted in better temporal resolution. At the completion of the in-situ neutron diffraction experiments, the engine block was allowed to cool while remaining wrapped in the Superwool® insulation (average cooling rate: 0.7 °C/min following SHT 470 °C; 0.45 °C/min following SHT 500 °C).

In contrast to the in-situ experiments, ex-situ neutron diffraction at ambient temperature was carried out in the hoop, radial and axial orientations. This analysis was performed on the engine blocks prior to and following solution heat treatment. In addition, engines treated with the production T4 schedule (SHT at 470 °C for 7.5 h, followed by forced air cooling) were also analyzed to observe the influence of thermal gradients induced by air quenching on the residual stress profiles. Therefore, while the in-situ experiments measured the change in axial residual strain as a function of time during soaking, the ex-situ experiments developed residual stress profiles along the cylinder bridge for all three principal directions to observe the influence of elevated temperature soaking and cooling on residual stress in other cylinder locations.

Neutron diffraction utilized a monochromatic neutron beam with a wavelength of 1.55 Å. The Al {331} planes (axial direction only due to equipment constraints) were used for the in-situ neutron diffraction experiments, while for the ex-situ experiments, the Al {311} (hoop direction) and {331} (axial and radial directions) planes were used. In addition, the neutron spectrometer table oscillated by ± 4° throughout the neutron diffraction experiments to improve the sampling statistics and reduce the impact of the coarse grain structure in the engine block (documented in previous studies [15,16,18]).

In both the in-situ and ex-situ portions of this neutron diffraction analysis, residual strain (ε) was measured using the “peak shift” method (Eq. (1)). The peak-shift method related the interplanar spacing (in Å) of the specimen ($d_{hkl}$) to that of stress-free samples of the same composition and processing history ($d_{0,hkl}$).

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