

Analysis of Residual Strain Profiles in Distorted Aluminum Engine Blocks by Neutron Diffraction

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ABSTRACT

In recent years, light weight components have been an area of significant importance in automotive design. This has led to the replacement of steel and cast iron with aluminum alloys for many automotive components. For instance, Al-Si alloys have successfully replaced nodular and gray cast iron in the production of large automotive components such as engine blocks. However, excessive residual strain along the cylinder bores of these engine blocks may result in cylinder distortion during engine operation. Therefore, in this study, neutron diffraction was used to evaluate residual strain along the aluminum cylinder bridge and the gray cast iron liners of distorted and undistorted engine blocks. The strains were measured in the hoop, radial, and axial orientations. The results suggest that the residual strain along the aluminum cylinder bridge of the distorted engine block was tensile for all three measured components. Conversely, the undistorted engine block had compressive strains in the axial and radial orientations, while the hoop direction had tensile strain of lower magnitude. The gray iron liners, meanwhile, had compressive residual strain for both engine blocks. The variation in strain, specifically in the aluminum cylinder bridge, suggests that permanent dimensional distortion in the cylinders was triggered by tensile residual stress when exposed to service conditions.

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INTRODUCTION

The development of light weight aluminum alloy components is an important area in automotive materials research. 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 (319) 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 319 Al alloy system is a suitable replacement to cast iron for automotive powertrain components such as engine blocks.

The main issue with Al alloy engine blocks is that the hypoeutectic Al-Si 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. As such, 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 stress exerted due to rapid expansion of the air-fuel mixture during combustion may cause the engine blocks to be prone to permanent dimensional distortion. Distortion is very detrimental to engine operating efficiency since a loss of seal in the combustion chamber will reduce compression of the air-fuel mixture [2]. This may result in decreased vehicle fuel efficiency and cause costly warranty issues for the OEMs. For instance, engine blocks exhibiting distortion require that a whole engine must be replaced with a new "service engine"



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which typical runs between 6 to 10K USD per warranty replacement engine. It is therefore important to perform in-depth studies on residual strain along the cylinder bores for distorted and undistorted experimental engine blocks to determine the cause of this distortion and implement preventative measures during production.

Residual stress and strain measurements in aluminum engine blocks containing gray cast iron cylinder liners 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. In addition, previous studies by the current authors [3, 4, 5] applied neutron diffraction to study residual strain and stress along the cylinder bores of aluminum engine blocks. However, the focus of these studies was to determine the effect of processing stages on residual strain and stress. Additionally, Su et al. [6] performed finite element modeling of residual stresses along the cylinders, which showed high tensile residual stress in the cylinder bridge region. Although these previous studies reveal that aluminum engine blocks containing gray iron liners have large tensile residual stress and strain along the cylinder bores, they do not analyze the effect of in-service distortion on the residual strain profiles. This paper presents residual strain profiles for the aluminum cylinder bridge and gray iron liners in distorted and undistorted engine blocks following dyno testing.

EXPERIMENTAL PROCEDURE

The engine blocks examined in this study were cast using the Cosworth process at the Nemak Centre of Engineering in Windsor, Canada. The composition of the 319 type aluminum alloy, used for casting the examined engine blocks, is shown in Table 1. Cylinder liners, made of gray cast iron, were also preheated to approximately 400 °C and inserted into the precision sand mould prior to pouring molten aluminum. The engine blocks were then subjected to a thermal sand reclamation (TSR) treatment at 480 °C for 4.5 hours. Heat treatment to a T7 temper was carried out with a solution heat treatment at 480 °C for 7.5 hours followed by aging at 240 °C for 5.5 hours. The rate of quenching following solution treatment varied between 80 and 100 °C/minute. The cylinder bores were then machined to the appropriate operating dimensions and select engine blocks were service tested for 20 hours on an engine dynamometer. Engine dynamometer effectively tests an engine through extensive operating conditions that replicate field operation of an automobile. In other words after a customer has purchased his or her vehicle and begins driving.

A coordinate measuring machine (CMM) was used to measure the cylinder bores to determine the extent of distortion in each block. Cylinder bore measurements were carried out every 15° around the circumference of the cylinder at depths between 5 and 100 mm. The resulting CMM data was utilized to determine the location and magnitude of the maximum distortion. From this analysis,

engine blocks exhibiting significant and negligible distortion were selected for residual strain measurement.

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.

Residual strain mapping was carried out from top to bottom along the bridge between cylinders 4 and 6 of the engine blocks as indicated by the rectangles in Figures 1 (a) and (b). Residual strain 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, Ontario, Canada.

In this study, neutron diffraction was carried out on the Al (311) and (331) planes as well as the Fe (211) plane. The monochromated neutron beam wavelength was 1.55 Å. Residual strain (ϵ) was first determined along the aluminum cylinder bridge and gray iron liner using the “peak shift” method (Equation 1). The peak shift method, which is described in detail in [5], 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.

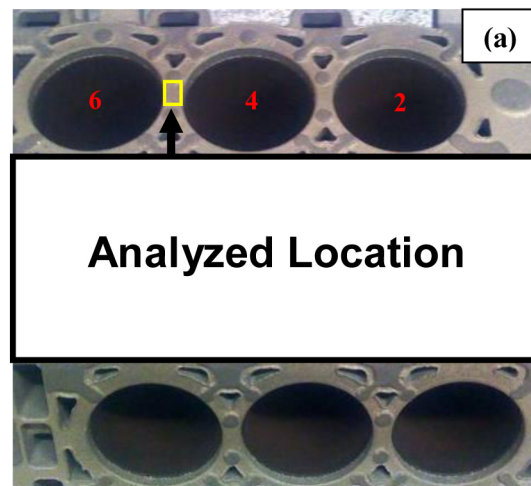


Figure 1. Images of: (a) top view of engine block, indicating analyzed sections, (b) cross-section of the cylinder bridge showing sections analysed along the cylinder depth.