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RESIDUAL STRESS ANALYSIS IN SEMI-PERMANENT MOLD ENGINE HEAD CASTINGS

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Abstract

In heat treatable cast aluminum alloys used for engine head manufacturing, typical heat treatment includes solutionizing followed by rapid cooling (quenching) of the material. Depending on the quenching technique the cooling rates can be quite different; these also vary greatly at different locations throughout the cylinder head. This results in residual stresses of different magnitude and complicated stress profiles. Engineering and optimization of the manufacturing process, therefore, has to incorporate consideration of the resulted stress profiles because of the fact that areas of the castings that are in tension, require less loading before possible failure.

Neutron diffraction was employed in this study to characterize residual stresses along the valve webs to the depth of 10~14 millimetres. The focus of this paper is to demonstrate the ability to measure and analyze residual stresses at various locations of heat treated cylinder heads, therefore enabling improvements in part design and heat treatment methods.

Introduction

Cylinder head castings for internal combustion engines require high tensile and fatigue strength to be able to handle the loads imposed on them during the engine combustion cycle. The demands for lighter, more efficient, vehicles will only increase the material demands in these castings. In the 300 series heat treatable cast aluminum alloys, precipitation hardening is accomplished by first bringing the casting up near 500 C in a furnace and holding it for an extended period of time (known as solutionizing) and rapid cooling (known as quenching), followed by again heating the specimen to a lower temperature (known as aging). In the automotive industry, the quenching process is based on either water or forced air. The quenching process, in particular with water, introduces significant residual stresses in the component, therefore reducing the service load that the material can sustain.
A neutron diffraction analysis was performed on two semi-permanent mold castings of a cylinder head. One casting was quenched using water and the other was air quenched. The neutron diffraction experiment compared the strains/stress profiles along the web area between the intake and exhaust valve ports indicating the main differences in strain/stress distribution for the two alternative quenching practices.

Neutron Diffraction Analysis

Cylinder head castings for internal combustion engines require high tensile and fatigue strengths to be able to handle the loads imposed on them during the engines combustion cycle. The demands for lighter, more efficient, vehicles will only increase the material demands in these castings. In the heat treatable cast aluminum alloys, precipitation hardening is accomplished by first bringing the casting up near 500 C in a furnace and holding it for an extended period of time (solutionizing) and rapid cooling (quenching). After this procedure, the part is “artificially aged” by again bring the casting up to 150-180 C. The quenching media may be water, forced air, or polymer based. However in the automotive industry, the quench media is typically either water or forced air. The quenching process, in particular with water, introduces significant residual stresses in the component, therefore reducing the service load that the material can sustain.

It is presumed that forced air quenching with its slower cooling rate will typically produce parts with lower residual stresses than water quenching. With a slower cooling rate, the potential precipitate density achieved during aging is also reduced. Thus the maximum potential strength obtainable is also reduced. Thus there is a balance between residual stress management and maximum material strength obtainable by the chosen quench procedure.

Two partially machined cylinder head castings of similar design were provided for residual stress evaluation via the neutron emission technique. One head had been solutionized, water quenched, and aged (sample A), while the other had been solutionized, air quenched, and aged (sample B). The water quenched head was made of secondary 356 aluminum while the air quenched head was made of A356 alloy with an additional 0.5wt.% Cu. Although there are slight alloy differences, the effect of the quench should supersede any effects due to the alloy differences.

The purpose of this test run is to determine how effectively the neutron measurement technique can spatially resolve the residual stress pattern in the combustion face side of the head. The focus of the experiment is the bridge (web) area between the intake-exhaust valves, as it is critical that this region have low residual stresses (Figure 1). The technique of this experiment was earlier reported for a similar study performed for a cylinder bridge of a V6 engine block [1].

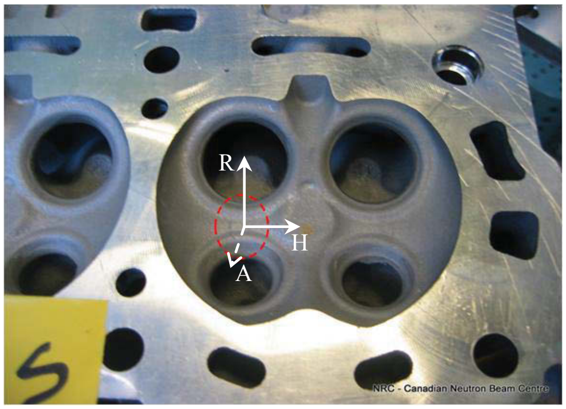


Figure 1. Top deck of a cylinder head indicating the measuring location, the bridge (web) between intake and exhaust (I-E) valve seats. The radial (R), axial (A), and hoop (H) orientations of the valve bridge are marked.

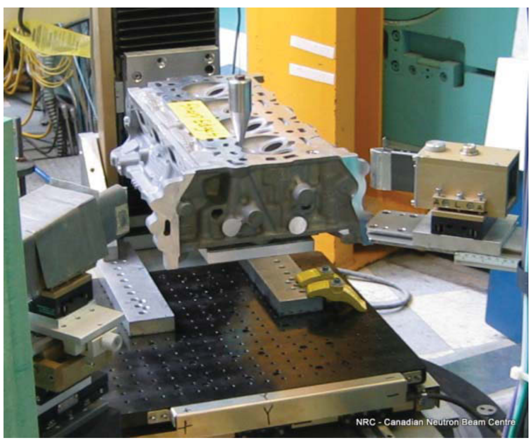
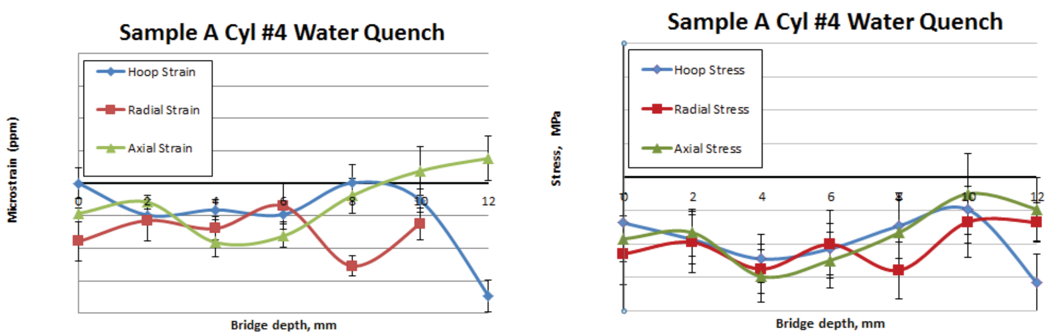


Figure 2. Cylinder head setup at L3. Longitudinal orientation of the engine head corresponds to the "hoop" orientation of the I-E valve bridge.

For strain measurements in the "hoop" orientation of the Intake-Exhaust valve bridges the cylinder heads were positioned at the L3 spectrometer as shown in Figure 2. The measurements were made in three orthogonal orientations (hoop, radial, and axial) from the top surface of the bridge to a depth of 12 mm. This scan line orientation corresponds to the starting point on the surface of the combustion chamber (0-mm position) and ending at 12-mm below the combustion chamber surface.

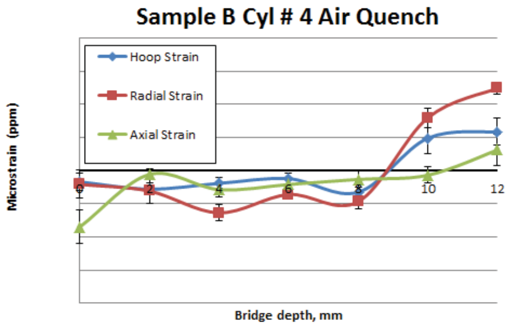
The measurements were performed with a neutron wavelength of 1.55 A using the <311> crystallographic orientation in aluminum castings. The results obtained for the Sample A (water quenched) are shown in Figure 3, while results for Sample B (air quenched) are presented in Figure 4. Although actual data values are not provided, the scales are identical in figures 3 and 4 and thus comparisons can be made between the two processes. It follows from the figures that along most of the scanned length the strains and stresses are compressive for both samples and all orientations. Except for a small tensile strain in the hoop direction at 10-12 mm below the surface, the strains in the water-quench head (Sample A) remain compressive. The stresses remain compressive through the entire sample volume. For the air-quenched head (Sample B), however, strains become tensile at approximately 9-mm below the combustion chamber surface and climb. The highest tensile strain was record for the radial orientation of the bridge corresponding to the transverse orientation of the engine head with relation to the scattering vector. The stresses in sample B behave in a similar manner to the strains; beginning compressive but all going tensile 9-mm below the surface.

At least in the areas tested, it can be concluded that the water quench head has higher compressive stresses near the surface than the air quenched head. To the depth measured, the stresses also remain negative to a greater depth, while the air quenched sample stresses become tensile. Because the parts are in equilibrium, the water quenched heads must show tensile stresses that balance the compressive stresses. These could be greater than the tensile stresses in the air quenched head but because of the complex geometry of a head, finding the location requires residual stress modeling. The value of this current research is that it can provide validation input into these models.

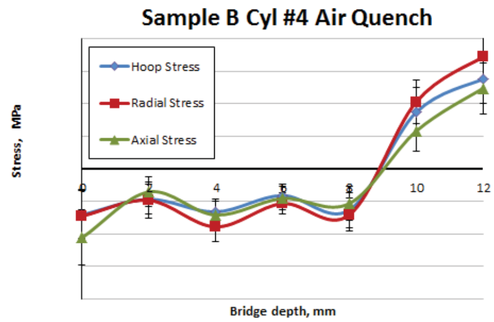


a. *b.*

Figure 3. General profiles of strains (a.) and stresses (b.) recorded along the I-E valve bridge in Sample A



a.



b.

Figure 4. General profiles of strains (*a.*) and stresses (*b.*) recorded along the I-E valve bridge in Sample B

References:

1. D. Sediako, F. D'Elia, A. Lombardi, A. Machin, C. Ravindran, C. Hubbard, and R. Mackay, "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", SAE International Journal of Materials and Manufacturing, June, 2011, pp. 138 - 151