

Residual Stress Analysis of Air–Quenched Engine Aluminum Cylinder Heads

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ABSTRACT

Residual stress of an air quenched engine cylinder head is studied in the present paper. The numerical simulation is accomplished by sequential thermal and stress analyses. Thermal history of the cylinder head is simulated by using the commercial Computation Fluid Mechanics (CFD) code FLUENT. The only parameter adjustable in the analysis is the incoming air speed. Predicted temperatures at two locations are comparable with available thermocouple data. Stress analysis is performed using ABAQUS with a Ford proprietary material constitutive relation, which is based on coupon tests on the as-solution treated material. Both temperature and strain rate impacts on material behavior of the as-solution treated material are considered in the stress and strain model. Predicted residual strain is shown to be consistent with measured data, which is obtained by using strain gauging and sectioning method.

INTRODUCTION

Cast aluminum is widely used in automobile industry for engine components, such as engine cylinder head and block. These engine components are often heat treated to improve mechanical properties of the material. Heat treatment includes solution treatment, quench and ageing. Residual stress can occur in both casting and

quenching stages of the manufacturing processes. Residual stress in the casting stage is caused by material shrinkage during solidification and the transient temperature gradient when it cools down. Residual stress introduced in this stage could be very high, manifested by occasional casting cracks seen at foundries. However, for aluminum alloys processed to a T7 heat treatment, 4 hours of solution treatment can release most, if not all, residual stresses from the casting stage. Residual stress of a heat treated engine cylinder head occurs from quenching. During quench, a cylinder head being solution treated at around 500 °C is cooled down to a low temperature with high cooling rate. High cooling rate is a necessity for the material to have improved mechanical properties, but it brings with it large temperature gradients inside the component being quenched. The large temperature gradients may lead to large mechanical strains and plastic deformation will occur. Non-uniform plastic deformation is the root cause of residual stresses remaining inside a component after quench.

Water is a very popular quench medium. However, water quench causes also large residual stresses inside quenched component. To strike a balance between better mechanical properties with lower residual stresses, air quench has been getting more popular recently. Air quench has been chosen for a number of engine heads at Ford Motor Company, notably for

the Australian Dingo I6 and Ford Europe's Lion V6 cylinder heads.

Residual stress analysis starts with a thermal analysis followed by a stress analysis. Since forced air quench involves only convective heat transfer, Computation Fluid Mechanics (CFD) is a natural choice for the thermal analysis. For stress analysis, FEA code ABAQUS provides options for user to consider the complicated material behavior. At the start of quench, when the temperature is close to the melting point, inelastic deformation of the material occurs mainly by creep. As the temperature gets lower, plastic deformation becomes dominant. The material stress-strain relation during quench process is thus highly temperature and strain rate dependent and a visco-plastic constitutive relation should be used in the stress analysis.

The present paper describes the residual stress analysis carried out for an engine cylinder head quenched by forced air.

THERMAL ANALYSIS

The air quench process simulated in the present paper is shown at Figure 1; hundreds of engine heads are positioned on the top deck of a rack and a number of fans positioned below blow air upwards. The whole facility is in an open environment. To simplify the CFD analysis, the quenching of an isolated engine head is idealized as shown in Figure 2.



Figure 1 Air quench facility

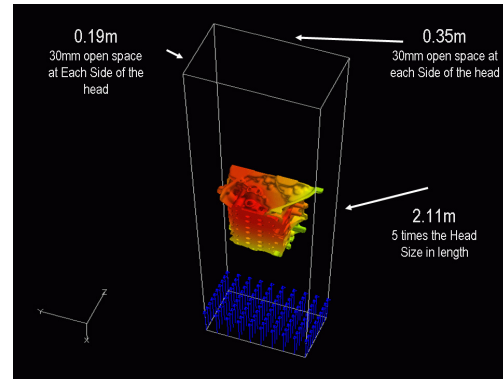


Figure 2 CFD model of an isolated engine head for air quench.

In Figure 2, the head is positioned in the center of a chamber. The incoming air flowing to the chamber has uniform velocity across a horizontal section; the dimension of this idealized chamber is decided by the distance between neighboring heads in the real quench facility. The commercial CFD code FLUENT is used in the analysis. Radiation effects are not included in the analysis, even though it might be important at higher temperatures. Since a head in the bracket is surrounded by other heads, and the final CFD analysis will be calibrated by thermocouple data, the impact of neglecting radiation on temperature profile is expected to be limited. The inlet air is assumed to be at ambient temperature, atmospheric pressure and with a uniform speed of 6.5 m/s. This inlet velocity is the result of a calibration of the prediction with thermocouple data. To interface with FEA stress analysis, a finite element model is used within FLUENT, which contains 283,450 tetrahedrons.

Figure 3 shows the CFD predicted temperature at two locations where thermocouple measurements are available. Considering that only the inlet air temperature is used for calibration, the predictions are reasonably close to the measurements.