

Modeling of Residual Stresses in Quenched Cast Aluminum Components

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ABSTRACT

Cast aluminum alloys are normally quenched after solution treatment or solidification process to improve aging responses. Rapid quenching can lead to high residual stress and severe distortion which significantly affects dimension stability, functionality and particularly performance of the product. To simulate residual stress and distortion induced during quenching, a finite element based approach was developed by coupling an iterative zone-based transient heat transfer algorithm with material thermo-viscoplastic constitutive model. With the integrated models, the numeric predictions of residual stresses and distortion in the quenched aluminum castings are in a good agreement with experimental measurements.

INTRODUCTION

Cast aluminum alloys are widely used in critical automotive components such as engine blocks, cylinder heads, and suspension parts because of the increased demand in reducing weight and improving fuel efficiency. To improve mechanical properties, the aluminum castings are usually subject to a full T6/T7 heat treatment which includes a solution treatment at a relatively high temperature, quenching in a cold medium such as water or forced air, and age hardening at an intermediate temperature. A significant amount of residual stresses and distortion can be developed in aluminum castings during quenching because of the high non-uniformity of temperature distribution particularly in the complex components [1,2,3,4,5]. The existence of residual stresses, in particular tensile residual stresses, in a structural component can have a significant detrimental influence on its performance. In many cases, the high tensile residual stresses can result in a severe distortion of the component and even

cause cracking during quenching and subsequent manufacturing processes [3].

There are many ways to measure residual stresses in manufactured components, including those configured of aluminum alloys [4]. Mechanical techniques such as hole drilling, curvature measurements, and crack compliance methods measure residual stresses in components based on respective component distortion. Diffraction techniques, such as electron, X-ray, and neutron, measure elastic strains in components due to residual stresses. Other techniques, including magnetic, ultrasonic, piezospectroscopy, photoelasticity, and thermoelastic, also are being developed. Mechanical techniques, however, generally are destructive of the component, while the accuracy of diffraction and other non-destructive techniques in measuring residual stresses generally depends on the extent of microstructure variation and geometric complexity of the component structure. In addition, it is generally impracticable to measure residual stresses in every location of a component not only because of the geometric constraints, but also because of the required time and cost to do so. As such, there exists a need to accurately and computationally predict residual stresses and/or distortion of quenched aluminum castings.

The amount of residual stress produced in quenched aluminum components strongly depends upon the extent of non-uniformity of temperature distribution in the casting during quenching and temperature-dependent material properties. The temperature non-uniformity is directly related to quench rate and heat transfer coefficients (HTC) between the hot aluminum casting and quenching media. To model residual stress and distortion, it is very important to accurately simulate the non-uniform temperature distribution and the materials behavior. In this paper, a finite element method (FEM) is developed to predict residual stress and

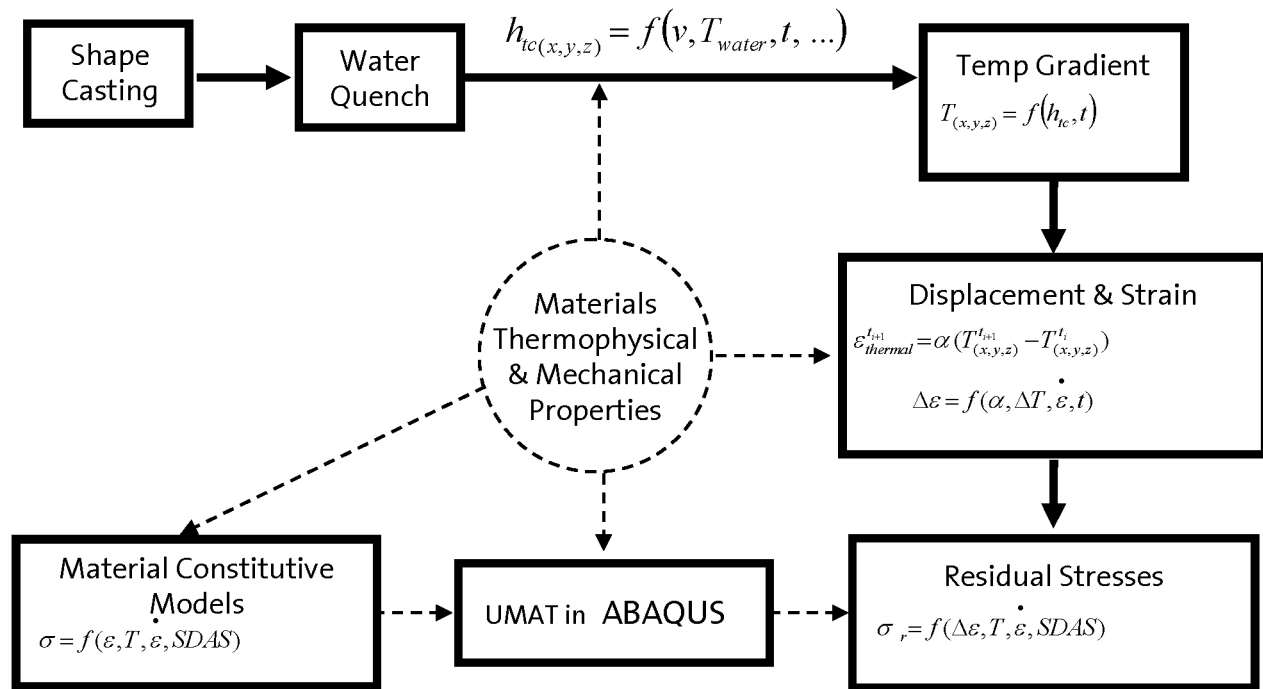


Figure 1. Finite element method for modeling of residual stress and distortion [6].

distortion, as illustrated in Fig. 1 [6]. The residual stress and distortion is modeled through incorporating thermal strains induced in the casting, due to non-uniform temperature distribution, with nonlinear constitutive behavior of aluminum casting during quenching. The transient temperature distribution of the aluminum casting during quenching is calculated based on heat transfer coefficients specific to one or more zones on the surfaces of the aluminum casting. The nonlinear constitutive behavior of the quenched aluminum casting is modeled as functions of temperatures, strain rates, and microstructure variations. A material constitutive model accounts for not only strain hardening and creep, but also precipitation hardening.

MODELING OF TRANSIENT HEAT TRANSFER

For given material physical and mechanical properties, the residual stresses are directly proportional to temperature non-uniformity in a component which is dependent upon the interfacial heat transfer coefficients between aluminum castings and quench media during quenching. The interfacial heat transfer coefficients (HTC) are functions of various variables including casting geometry, casting surface quality, quench media, and quench orientation, etc. There are many classical empirical equations reported in the literature for calculating convection HTC data by using dimensionless numbers (i.e. Reynolds number, Prandtl number and Nusselt number) [7]. However, their applications are limited since almost all of these dimensionless numbers are calibrated for specific experimental conditions which can be significantly

different from the actual production process. An experimental approach with a small probe can be utilized to determine HTC. With the so-called lumped heat capacity method [8-9], the cooling curves of the probe are acquired and used to inversely calculate HTC in terms of probe surface temperature [7, 10,11,12,13]. This method assumes that the temperature distribution in the small probe is uniform during cooling in order to calculate HTC inversely, which is also uniform over the probe surface [8]. Another method, known as the direct conduction method, assumes the temperature near a surface is a linear variation from the surface to the internal area measured so that the HTC can be obtained based on the equilibrium of heat flux at the surface by conduction and convection [8,14]. It is, however, difficult to obtain HTC distribution data with this experimental method. With the recent advances in computational fluid dynamics (CFD), the code may be used to calculate the node-based HTC distribution [15]. However, no currently commercially available CFD code is designed to calculate accurate HTC distribution data. The current CFD prediction of heat transfer and temperature distribution of a quenched part is not accurate particularly in liquid quenching because the complicated interaction and heat transfer phenomena between liquid and the hot part are not fully understood and represented in the state-of-the-art fluid flow and heat transfer code.

In this paper, an iterative modification method is developed to calculate zone-optimal heat transfer coefficients. The casting surfaces are divided into several zones based on geometry similarity and quench orientation. The transient

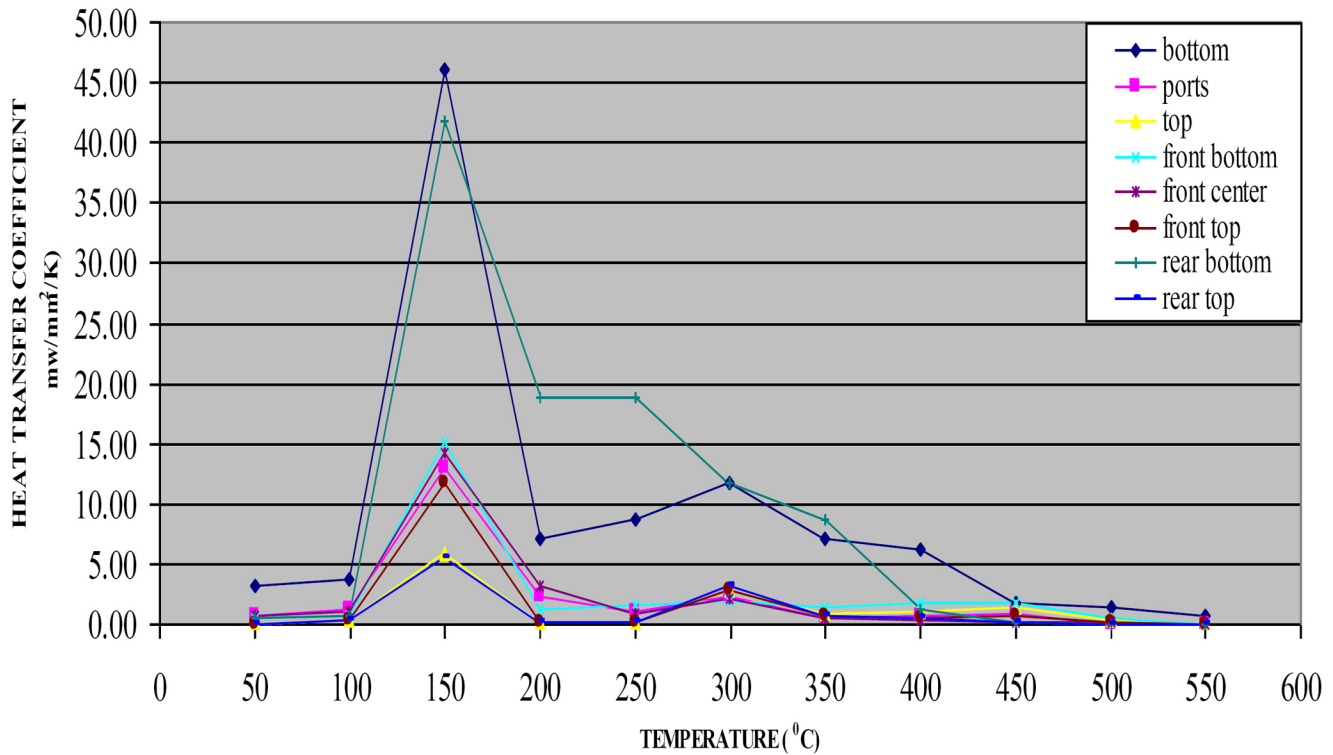


Figure 2. Temperature dependent HTC values inversely calculated for different locations in a cylinder head during water quench.

heat transfer is calculated using heat transfer software such as ABAQUS with a set of temperature-dependent heat transfer coefficient values assumed for different surface zones. During the course of heat transfer coefficient optimization, the temperature- and zone-dependent heat transfer coefficients are determined using a gradient method and the calculated thermal history during the quench is compared with the experimentally measured temperatures of the related locations in the casting. The whole optimization process iterates until the difference between the calculated thermal history and the experimental measurements is minimized. In the inverse calculation, the objective function is expressed as:

$$Error = \sum_{i=1}^N \sqrt{\sum_{j=1}^M (T_{i,j}^{calc} - T_{i,j}^{expt})^2} \quad (1)$$

where $T_{i,j}^{calc}$ and $T_{i,j}^{expt}$ are the calculated and experimental temperatures at the j^{th} time step of the i^{th} thermocouple. M is the total number of comparisons made for a thermocouple, and N is the total number of thermocouples.

Fig. 2 shows examples of the temperature-dependent heat transfer coefficients optimized for different zones of an aluminum cylinder head quenched vertically in water. It is seen that different zones have different heat transfer

coefficients and high heat transfer coefficients are seen between 100 °C and 200 °C for all zones.

MATERIAL CONSTITUTIVE MODEL

Material constitutive behavior plays an important role in development of residual stress and distortion during quenching. The low yield stress materials tend to have lower residual stress and possible high distortion. A mechanical threshold stress (MTS) model [16] is adopted and modified to simulate the constitutive behavior of aluminum casting during quenching. In the model, the total strain is simply divided into elastic, plastic, creep and other thermal strains due to phase transformation like precipitation hardening in heat-treatable cast aluminum alloys. The plastic strain is described by time-independent plastic model while the creep strain is characterized by creep law. The thermal strain due to phase transformation is described by precipitation hardening model. As shown in Eqn. 2, the flow stress is the sum of three components: an elastic stress modeling yielding, a plastic stress evolving with strain hardening, and a thermal stress modeling possible precipitation hardening during quenching.

$$\frac{\sigma}{\mu(T)} = C_e(\dot{\epsilon}, T) \frac{\hat{\sigma}_e}{\mu_0} + C_p(\dot{\epsilon}, T) \frac{\hat{\sigma}_p}{\mu_0} + C_{ppt}(\dot{\epsilon}, T) \frac{\hat{\sigma}_{ppt}}{\mu_0} \quad (2)$$