COMPUTATIONAL MODELING OF HEAT TREATING PROCESSES BY USE OF HT-MOD AND ABAQUS

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Abstract— **This paper presents an overview of mathematical approaches for modeling heat treating process, mainly concerned by coupling heat conduction with phase transformation, prediction of microstructure and material hardness, as well as estimation of heat transfer coefficients. The program HT-mod developed by the authors is briefly described. An analysis of distortions and residual stresses by a combination of HT-mod and ABAQUS Software is outlined. The performance of vegetable oils (castor, soybean and mineral oil) as quenchants are summarized as an application example. Comparison between measured and predicted hardness and microstructure of AISI 4140 bars is provided for validation of the methodology proposed for modeling heat treating processes. On average, good agreement was obtained.**

Keywords— **heat treatment, steels, numerical simulation, microstructure, optimization.**

I. INTRODUCTION

Heat treatment is an integral part of the manufacturing processes of today's steel components. A heat treatment cycle will typically involve heating up and cooling down components. Both aspects of the cycle affect the shape, geometry, microstructure and mechanical state of the components in the sense that they will cause the component to expand and contract. The thermal stresses induced by the resulting temperature gradient may be large enough to cause fracture of the part, or to exceed the elastic limit resulting in permanent residual stresses and gross distortions in the component.

Computer simulation has become a powerful tool for analysis, assisting in the design and optimization of heat treating processes to achieve the desired as-quenched and tempered mechanical properties of steel. Computational modeling deals with coupled phenomena of heat transfer, phase transformation, electromagnetic induction, diffusion of carbon and other chemical elements within the matrix, as well as thermo mechanical behavior of components in response to a heat treatment. A literature review regarding modeling and simulation in this field was presented by Totten *et al.* (2004).

Heat treatment of steel involves heating the steel to an elevated temperature, typically the austenitizing temperature, often with subsequent quenching into a vaporizable liquid medium such as water, oil or aqueous polymer quenchant. Figure 1 is a typical cooling curve which shows the three most common heat transfer mechanisms observed during conventional immersion cooling in water. Upon initial immersion, the part is surrounded by a vapor film where full-film boiling or vapor-blanket cooling occurs. When the temperature decreases to the Leidenfrost temperature, the vapor film (vapor blanket) collapses and surface wetting by the liquid occurs by a nucleate boiling process due to lateral heat conduction relative to the surface. When the surface temperature decreases to a temperature less than the boiling point, nucleate boiling ceases and convective cooling begins.

Cooling power of liquid quenchants can be expressed by using cooling curve data of standard probes, like JIS silver probe or ISO INCONEL 600 probe (Totten and Clinton, 1993). For the computer simulation of heat treating processes, accurate values of heat transfer coefficients (HTC) or heat fluxes must be provided as boundary values conditions at the surface of the workpiece. These parameters are estimated from cooling curves data by use of *a lumped-heat-capacity metho*d or by *an inverse method.* The first one is suitable for estimating HTC from JIS silver probe data (Bi< 0.1, Biot number), and the second one from ISO INCONEL 600 probe data (Biot number > 0.1) (Narazaki *et al.*, 1998; Chen *et al.*, 1997).

This paper presents a review of the work developed by the authors for modeling heat treating process, mainly dealing with the coupling between heat conduction, phase transformation, prediction of microstructure and material hardness as well as the estimation of HTC by use of the *inverse method* applying the Finite Element Software **HT-Mod** (Heat Treating Modeling)**.**

HT-Mod was applied to estimate the heat transfer coefficients of a wide variety of quenchants, like polyalkylene glycols and UCON solutions (Sánchez Sarmiento *et al.*, 1996a, b). Recently, Penha *et al.* (2005, 2006) studied the effect of fresh and used mineral oil and bath temperatures (40, 60, 80 and 100°C) on cooling time-temperature performance of a Inconel 600