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Transient and residual thermal stresses in quenched cylindrical bodies

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Abstract

To predict residual and thermal stresses which occur during water quenching of solid cylindrical rod and ring cross-sectioned steel tubes, a finite element technique has been used. The variations of residual stresses on different surfaces and cross-sections, e.g. in the radial, axial and tangential directions have been examined, and the effect of internal diameter of tubes on residual stress was investigated. The results show that the residual stresses act as a compressive force along the cooling surface and then by moving away from the surface begin to decrease and reverse their sign, near the centre of the cylinder are subjected to tensile stresses. Because of the reversal of the sign of stress, the effective stress goes to a minimum at some distance from the frontal surface and this may be vital since lower plastic deformation may cause cracking failure. As in solid cylinder, in cylindrical tubes also, the frontal and the upper cooling surface has significant effect on the stress distribution. From the comparison of the residual stress distributions of solid cylinder and cylindrical tubes and using their individual stress maps it was seen that they vary considerably along different cooling surfaces, especially at the frontal surface. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Steel rods and tubes with various wall thicknesses have been widely used in industry as connecting and rotating components, rolling equipment, generator shafts, pressure vessels, etc., and therefore most of the time their mechanical properties are strictly required in detail. In order to enable those parts to work within the safety limits a large variety of heat treatments are conducted. However, in most of the cases when the safety factors are determined, the residual and thermal

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stresses, which occur after heat treatment and remain in the shaft together with some distortions, are not often taken into account. Since the cylindrical rods are the basic form of many mechanical components, they are mostly used for residual stress analysis and for quenching cracks depending on geometrical differences, quenching conditions and properties of material effects. Experimental, analytical and numerical methods were used to calculate residual stress and distortion. Since, analytical methods even for simple geometry have very complex equations and so their solutions, and experimental methods require considerable time and labour, it is difficult to predict the effects caused by changes in constituent materials, dimensions, cooling rates, etc., based on the results of these studies. Meanwhile, the analysis enables the effects caused by changes in these conditions to be predicted if proper initial material characteristics and boundary conditions are assumed. To analyse the development of residual stress by approximate solution, several computer programs were written. In recent years finite element method, which is one of the most powerful numerical methods, has been used to predict the residual and thermal stresses. Several researchers [1–3] showed that the finite element method could be used to simulate the real processes by comparing the results with some experimental data. Influences on development of thermal and residual stresses in quenched steel cylinders of different dimensions were studied by Schröder [1] through a finite element program. The residual stress distribution in the convex surface of the cylinders along a generating line was shown over the quarter of cross-section and the influence of diameter and quenching conditions was discussed. It was shown that the quenching over the frontal surface has large influence on the residual stress distribution. The residual stress was found to be constant only over about one-third of the cylinder length. Fletcher and Lewis [2] used a finite element technique to examine the effect of free edge on thermal stresses in water-quenched steel circular plates of high hardening ability. They introduced some kind of correction factors in the edge-affected region to save on computer time. They also showed that the resulted stress in the circular disc during the early stages of water quench varies in a rather complex manner close to the unloaded circumference of the disc. Kamamato et al. [3] have analysed residual stresses and distortion of large low-alloy steel shafts due to quenching. The results showed that the transient stresses affect each other, and that residual stresses and distortion are strongly related to the transformational behaviour. The residual stresses in quenched cylindrical bars were measured by the boring out technique [4]. In another similar work Yu [5] presented his own residual stress results numerically and compared them with Buhler's results. Although numerous works exist in literature, it was seen that residual stress for steel tubes was not given adequate attention, and most was focused mainly on solid cylinders. Toparli and Aksoy [6] analysed residual stresses during water quenching of cylindrical solid steel bars of various diameters by using finite element technique. They computed, as well, the transient temperature distribution for solid bars with general surface heat transfer. Fa-rong and Shang-li [7] carried out ADINA/ADINAT programme to analyse the transient temperature and residual stress fields for a metal specimen during quenching. They modified the elastic–plastic properties of specimen according to temperature fields. Yamada [8] presented a method of solving uncoupled quasi-static thermoelastic problems in perforated plates. In their analysis a transient thermal stress problem is solved for an infinite plate containing two elliptic holes with prescribed temperature. In another study the transient thermal stress problem of a rectangular slab, which possesses both thermal and elastic orthotropy was investigated [9]. Gurney [10] studied residual stresses in a large circular disc caused by local heating and cooling at its centre.