ISSN: 0128-7680
Pertanika J. Sci. & Technol. Supplement 9(2): 259-267 (2001)

Finite Element Analysis of Steel Quenching Process

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ABSTRACT

The finite element method (FEM) is employed to investigate the residual stress state and the variation of internal stresses in the St50 cylinder bar quenched from 600 to 0°C. Thermal analysis is first performed to obtain the cooling curves for the core and surface of the bar, this is followed by a full structural analysis. The results obtained from the computer simulation are compared with those experimentally determined values that are available in the literature and there appears to be a good measure of agreement. The study found that at the initial stages of the quenching process, the residual stresses were tensile at the surface and compressive in the core, however, towards the end of the quenching process, the tensile residual stresses switched to the core and compressive residual stresses at the surface.

Keywords: Finite element analysis, quenching, residual stress

INTRODUCTION

In manufacturing operations, many parts are formed into various shapes by applying external forces to the workpiece. When workpieces are subjected to deformation that is not uniform throughout the workpieces, they develop *residual stresses.* These are the stresses that remain within a part after it has been formed and all external forces have been removed. In heat treatments, the uneven cooling invariably introduces residual stresses.

There are two types of stress distributions in the residual stress pattern: the *compressive* residual stresses and the *tensile* residual stresses. Tensile residual stresses in the surface of a part are generally considered to be undesirable, since they lower the fatigue life and fracture strength of the part. This condition occurs because a surface with tensile residual stresses sustains lower additional tensile stresses from external forces than a surface that is free from residual stresses. This condition is particularly true for brittle or less ductile materials where fracture takes place with little or no plastic deformation preceding fracture. Tensile residual stresses can also lead to stress cracking or stress-corrosion cracking of manufactured products over a period of time.

On the other hand, compressive residual stresses on a surface are generally desirable. In fact, in order to increase the fatigue life of components, compressive residual stresses are imparted to surfaces by techniques such as shot peening and surface rolling in the mechanical surface treatment processes.

If a phase transformation occurs during the cooling process in quenching, the residual stress pattern becomes more complicated, and less predictable. The stresses are influenced by the volume change and the temperature range in which this occurs. With so many variables affecting the value of residual stress, it is impossible to predict the desirable output.

Due to the problems mentioned above, researchers have identified a method to improve the situation by integrating finite element analysis (FEA) into the prediction of the residual stress.

Several studies have been conducted on the prediction of residual stresses occurring during quenching. Yu (1977) calculated the residual stresses in rotationally symmetric bodies considering temperature, phase transformation and elastic-plastic deformations. Hildenwvall (1979) predicted the residual stresses for carburized steels during quenching. Denis *et al.* (1985) concluded that transformation plasticity has a marked effect on residual stress distribution, and reviewed the main effects of stress on phase transformation, metallurgical and mechanical interactions. Inoue *et al.* (1992) developed a finite element code for simulation of various heat treatment processes based on the thermo-mechanical theory. Gur *et al.* (1996) develop and implement an efficient finite element model for predicting all relevant process-parameters during and after quenching of components. In their study, both numerically and experimentally methods are being performed to determine the residual stress.

The purpose of the present study is to develop an efficient finite element model that is capable of analyzing the quenching process and thus predicting the residual stress state during the quenching process.

It is the intention of the study to model and simulate the quenching behavior of steel by using the commercial available FEA Software. The model is used to predict the cooling curves of the core and the surface for quenching of St50 cylinder bar from 600 to 0°C in the thermal analysis. After that, the structural analysis is performed to predict the residual stress state in the St50 cylinder quenched from 600 to 0°C and the variation of internal stress state during quenching of St50 cylinder from 600 to 0°C.

PROCEDURE

Quenching Process Theory

The process of cooling a steel bar quenched from high temperature into a liquid at low temperature. The temperature-time curve of a point inside or on the surface of the part can be divided into three regions. The high-temperature stage involves a relatively slow heat transfer rate due to the hot part vaporizing some of the fluid to form a continuous gaseous blanket between the steel and the cooling fluid. As the steel cools, however, the nucleate boiling region is entered in which the vapor forms discrete bubbles, which are removed rapidly from the surface, allowing fresh fluid to contact the surface. During this stage, the cooling rate is at its highest. When the temperature is sufficiently low, boiling ceases; heat is then transferred by conduction and convection in the fluid and the rate of heat transfer decreases.

Figure 1 illustrates the temperature gradient at the surface of the steel is shown. (Brooks 1979). In such quenching processes, the relative importance of the three stages depends upon a number of factors, such as the surface condition of the part and the flow pattern of the fluid past the part. In general, it is the second stage that is most important because the cooling rate is at its highest. A quantitative measure of ability of the quenching medium to extract heat is desired, so that for a known geometry and size of a part, the cooling rate can be estimated at any position in the part.

In heat treatment, the uneven cooling invariably introduces residual stresses. In some application, these counteract the external applied stresses, and hence some surface treatments and heat treatments are designed specifically to develop certain residual stress.

Quenching Stresses

To illustrate the formation of residual stresses, a description will be presented of the

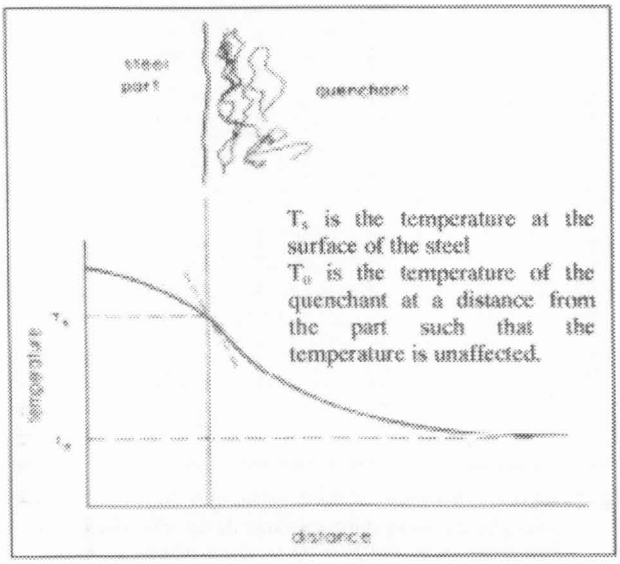

Fig. 1. Temperature distance curve from the center of a steel part into the quenchant (Brooks 1979)

development of the stress distribution during quenching a homogeneous metal, which does not undergo any phase transformation. Let the sample be a cylinder at a high temperature T_h, which is to be quenched into a medium at a lower temperature T_f.

Figure 2 illustrates the longitudinal residual stress across the diameter at various stages in cooling. At the high temperature, T_h the temperature is uniform and there are no residual stresses (Figure 2a). The cylinder is then placed in the quenchant, which is at temperature T_f. The surface cools to T_l, but the center is still at T_h. At temperature T_l, the bar should contract to length l1. If the center of the bar (still at temperature T_h) completely restrains the surface (at T_l) from contracting, then the surface is to long and is in tension (Figure 2b). However, the surface will pull on the center and place it in compression. Hence the actual stress distribution at this stage, with the surface at T_l and the center still at Th, is the surface in tension and the center in compression (Figure 2c). If the yield strength of the material is not exceeded at a position along the diameter, then the bar will cool to T_l, with no final residual stresses. That is, the center will cool allowing the surface and the center to contract to the final length l1, at temperature T_f. However at stage (c), if the stresses are sufficiently high, both the center and the surface begin to deform plastically. The strength of the center is less than the surface because it is at higher temperature, but here, it is assumed that deformation occurs equally in both sections. The cylinder then undergoes stress relaxation, and the stresses begin to vanish (Figure 2d). Now, in this state, the relaxed length is l1, which is the unstressed length or the surface, for it is at T_f. However, the center, upon cooling to T_l, will contract to length l2 if unrestrained. Thus, from stage (d) on, the center cools and contracts, placing the surface in compression. The surface prevents the center from attaining the length l2, and hence it remains in tension. The final stress distribution is the center in tension and the surface in compression (Figure 2e).

In a steel quenching process, the higher temperature will develop the greater residual stresses and the faster cooling (water quench) will also cause larger stresses.

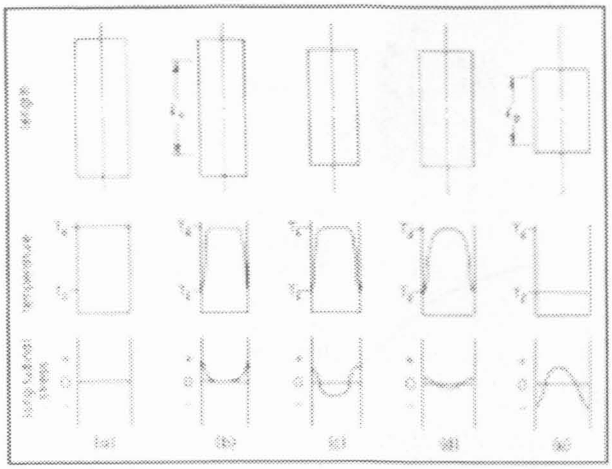

Fig. 2. Schematic illustration of the development of longitudinal thermal stresses in a cylinder during cooling. At (a), the cylinder is at high temperature, and from (b) to (e) the cylinder is cooling.

Mathematical Formulation

Thermal interactions and elasto-plastic deformation are the two basic phenomena involved in the mathematical model for quenching. Computations are first performed with determining the temperature distribution. This distribution is influenced by the quenching severity of the medium, thermal conductivity, heat capacity and latent heat due to phrase transformation. Quenching severity is characterized by the convective heat transfer as a function of temperature at the specimen surface. The initial stresses are computed by means of an elasto-plastic analysis (below equations are from Gur et al. 1996).

Prediction of Temperature Field

Quenching process is a transient heat conduction problem with convective boundary conditions. Hence, for an isotropic material and axisymmetrical geometry

$$\lambda\left[\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}=\frac{\partial^2}{\partial z^2}\right]T-\rho c\frac{\partial T}{\partial t}=\frac{\partial L}{\partial t}=0 \tag{1}$$

is valid, where T stands for temperature, t – time, r – radial displacement, λ – thermal conductivity, ρ – density and c_p – specific heat.

$$[H]\{T\}+[C]\left\{\frac{dT}{dt}\right\}+\{Q\}=0 \tag{2}$$

After standard procedures of finite element discretization, equation (1) be reduced on elemental basis to:

Prediction of Internal Stress State3

Stresses are expressed in terms of strain rates which can be obtained from the velocity field. The elastic strain tensor is given by:

$$\varepsilon_{ij}^{e} = \frac{1}{E}\left[(1+v)\sigma_{ij} - \delta_{ij} v \sigma_{h}\right] \tag{3}$$

where e^{ij} is the strain tensor, E is Young s modulus, v is Poisson's ratio, σ_{ij} denotes the nominal stress tensor, σ_h is the hydrostatic stress and δ_{ij} is Kronecker's delta.

Finite Element Analysis

A cylindrical solid steel shaft was selected as the model, with a diameter of 50mm. This steel was of St50 grade. This model was heated up to its austenizing temperature (600°C) and was quenched in the water quenchant at 0°C. This cylinder was quenched as similar to the procedures used in the *Yu* (1977) study.

The quenching process in this study is assumed to be a linear transient (thermal) analysis. A constant convective heat transfer coefficient was chosen throughout the whole cooling range of the quenching process as reported by Yu (1977) and no phase transformation was considered. The thermal analysis output was used as the nodal temperature loading inputs in the structural analysis. The material data were also taken from the study of *Yu* (see Table 1).

Model Discretization

A 2D axisymmetric solid continuum element with enhanced strains was selected to perform this structural analysis in the quenching process. This element name is QAX4M in LUSAS. This isoparametric element with an assumed strain field can be formulated and applied over a unit radian segment of the structure, and the loading and boundary conditions are axisymmetric. The element is numerically integrated. There is four numbers of nodes and each node has two degree of freedoms.

In this project, the solid cylindrical steel shaft was defined and assigned as a 'surface features' (which is draw as a 2D rectangular shape). The surface feature was mesh as a axisymmetric solid element and the linear order quadrilateral element shape was selected. This computation was conducted with 100 axisymmetrical elements (see Figure 3).

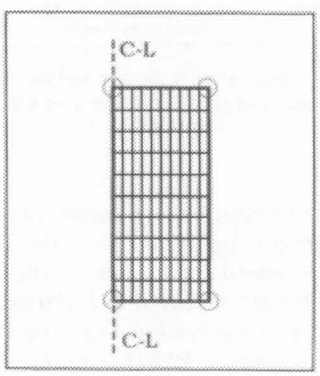

Fig. 3. 100 axisymmetrical elements mesh

Material Property Specification

The surface features were assigned as an elastic isotropic material. The steel cylinder was of St50 grade. The material properties were assigned to the surface features and the input data are from Table 1.

TABLE 1
Material data for St50 steel

T, °C	E,Gpa	ν	Y,Mpa	H,Gpa	α, 1/°C
0	206	0.3	349	0	$14.1*10^{-6}$
200	206	0.3	294	0	$14.1*10^{-6}$
600	206	0.3	58	0	$14.1*10^{-6}$

heat transfer coefficient = 43.16 J/ms°C
heat capacity = 4525170 J/m^3°C
hc = 16760 Jm^{2}s°C (surface temperature)

Temperature Loading Definition

The cooling curve data from Figure 4 were applied as nodal temperature loading in the structural analysis. These data were assigned to both the core and surface of the surface feature (model).

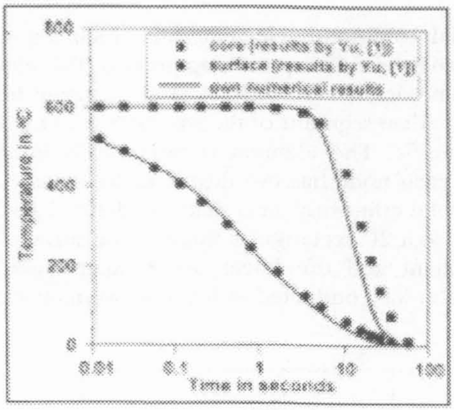

Fig. 4. Cooling curves of the core and the surface for quenching of St50 cylinder from 600 to 0°C.

Transient Control Analysis

Transient Control was used to control the solution procedure for transient analysis where time effects are significant. In this project, the default transient control was defined and assigned to the related load cases in the previous nodal temperature loading assignments. This study was conducted with 100 axisymmetrical elements and an average time of 0.01 sec. Average computational time on Pentium 166Mhz 64 RAM was about half an hour for 9000 time steps. MYSTRO post-processing was used to view and analyze the result file produced by LUSAS.

The residual stress contours of effective stress, axial stress, tangential stress and radial stress were obtained according to the desired time period throughout the quenching process (0, 3.4, 22, 28, 38, 60 and 90 seconds). Various values of residual stresses were obtained along the cross section of the steel cylinder. Graphs of residual stress vs. distance from the cylinder core; residual stress at the core and surface of the cylinder vs. time; and residual stress vs. normalized area (r/R)2 were plotted.

Variation of Internal Axial Stress during Quenching

Two different sets of data were obtained during the quenching process from 600 to 0°C, which are the residual stress in the core and at the surface of the cylinder. These are plotted into a graph residual stress versus time in Figure 5.

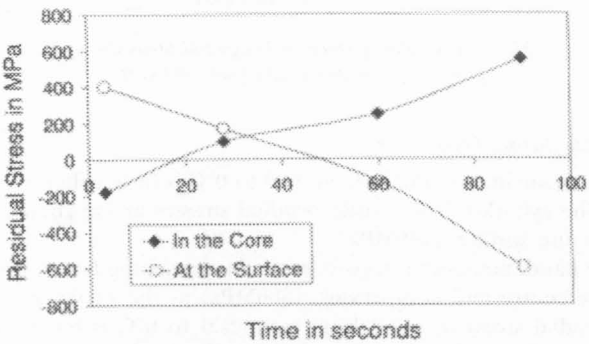

Fig. 5. Variation of Internal Axial Stress during Quenching of St50 Cylinder from 600 to 0°C

At the initial stages in the quenching process (at 3.4 seconds), it was found that the residual stress was tensile at the surface and compressive in the core. It was later found that the compressive residual stress in the core switched into tensile residual stress after 20 seconds and increased constantly up to approximately 600MPa at 90 seconds.

On the other hand, the tensile residual stress at the surface switched into the compressive residual stress after approximately 53 seconds, at a much slower rate. This further decreased to 400MPa into compressive residual stress at 90 seconds.

Variation of Internal Tangential Stress during Quenching

Likewise, data obtained during quenching from 600 to 0°C are plotted to form two lines, residual stress in the core and residual stress at the surface of the cylinder (Figure 6).

In the initial stage of the quenching process, it was found that the residual stress was compressive in the core and tensile at the surface of the cylinder. Likewise, at the end of the quenching process, the compressive residual stress in the core has switched to tensile, and the tensile residual stress at the surface had switched to compressive residual stress. The switch from tensile to compressive residual stress was at a much slower rate than that of the compressive to tensile residual stress, with a difference of 30 seconds.

Thus, Figures 5 and 6 indicate that the axial and tangential residual stress show similar distribution. However, at the end of the quenching process, axial stress reveals higher values than the tangential residual stress in the core of the cylinder.

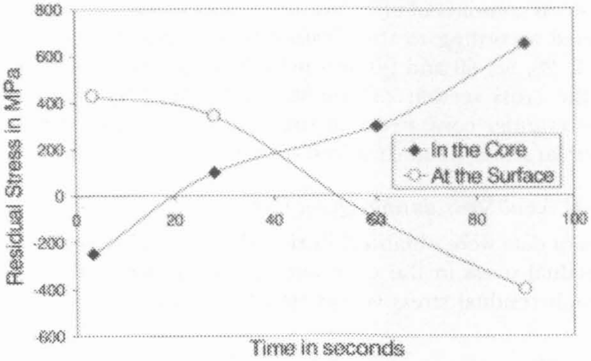

Fig. 6. Variation of Internal Tangential Stress during Quenching of St50 Cylinder from 600 to 0°C

Residual Stress State during Quenching

Effective stress contour in quenching from 600 to 0°C is in tensile region for the entire cross-section of the cylinder. The tensile residual stresses are in their peak in the core (280MPa) and at the surface (400MPa).

On the other hand, tangential stress contour in quenching from 600 to 0°C is tensile (600 MPa) in the centre and compressive (800MPa) at the surface of the cylinder.

Finally, the radial stress in quenching from 600 to 0°C is tensile in the core but decreasing to zero when nearing the surface. No compressive residual stress can be found.

The data collected are plotted onto the same graph (Figure 7) so that the residual stresses after quenching are given as a function of normalized area $(r/R)^2$, where R is the outer radius of the specimen. Tangential and axial stresses show similar distribution, that is, tensile in the core and compressive at the surface. Surface radial stress vanishes in accordance with the boundary condition. Verification of the final results obtained with other researchers are showed in the same figure. The studies found that the results are in good agreement with the results in the literature.

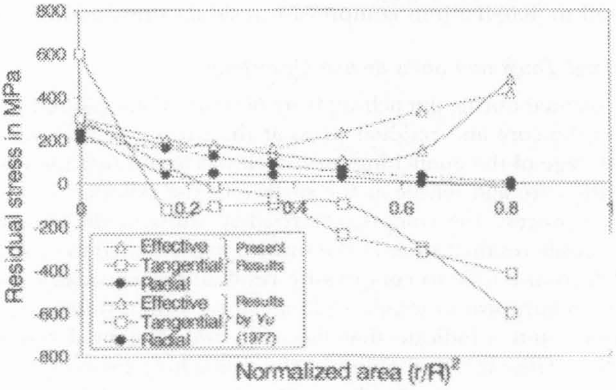

Fig. 7: Residual Stress State in the St50 Cylinder Quench from 600 to 0°C

CONCLUSIONS

In this project, the quenching process is carried out only as a numerical model using commercial finite element software. Selected results of other researchers (using both numerically and experimentally methods) are adopted to serve as benchmarks for the verification of the model and results.

An efficient finite element model for predicting the variation of internal axial stress and tangential stress in the core and at the surface of the cylinder at different time periods has been developed. The effective, tangential, axial and radial stresses produced at the end of quenching of St50 cylinder from 600 to 0°C along the cross-section of the cylinder was obtained and compared.

The study found that at the initial stages in the quenching process, the residual stress was tensile at the surface and compressive in the core. But it was later found at the end of the quenching process that the tensile residual stress was switched to the core and compressive residual stress at the surface. This was also true for both axial and tangential residual stress during quenching of St50 cylinder from 600 to 0°C. The radial stress in quenching from 600 to 0°C is tensile in the core but decreasing to zero when nearing the surface. No compressive residual stress can be found.

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