MODELING THE EFFECT OF RADIUS ON TEMPERATURE HISTORY OF TRANSIENT QUENCHED BORON STEEL

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Abstract
One-dimensional (1D) model of an axisymmetric unsteady state industrial quenched boron steel 50B46H bar based on finite element method (FEM) has been applied to investigate the influence of process history on its material properties. The effect of four different radii on its temperature history is determined. The model can be employed as a guideline to design cooling approach to achieve desired microstructure and mechanical properties such as hardness. A computer program of the model is developed, which can be used independently or incorporated into a temperature history software named (LHP)-software to continuously calculate and display temperature history of the boron steel bar and thereby to study the effect of radius on temperature history. The developed program based on (1D) FEM model has been verified by comparing its results with commercial finite element software results. The comparison indicates its validity and reliability.

Keywords: steel, quenching, FEM, unsteady state heat transfer

1 Introduction

Mathematical models are used particularly in the natural sciences and engineering disciplines (such as thermal engineering, heat treatment of unsteady state industrial quenched steel bar as in this work).

A mathematical model is an abstract model that uses mathematical language to describe the behaviour of a system.

A model may help to explain a system and to study the effects of different components, and to make predictions about behaviour; in this paper modelling the effect of radius on temperature history of transient quenched boron steel as shown in **Fig. 1** is studied.

Models allow us to predict behaviours or results that are as yet unseen or unmeasured such as LHP is unseen and unmeasured before as shown in **Fig. 1**.

The key steps in modelling process are shown in **Fig. 1**.

Mathematical modelling is a method of simulating real-life situations with mathematical equations to forecast their behaviour.

In this manuscript the heat transfer analysis is carried out in three dimensions (3D). The (3D) analysis is reduced to a 1-D axisymmetric analysis to save cost and computer time. This is achievable because in axisymmetric conditions, the temperature deviations are only along radius (R) while there is no temperature variation in the (□) and (Z) directions. The Galerkin weighted residual technique is used to derive the verified mathematical model [1-6].

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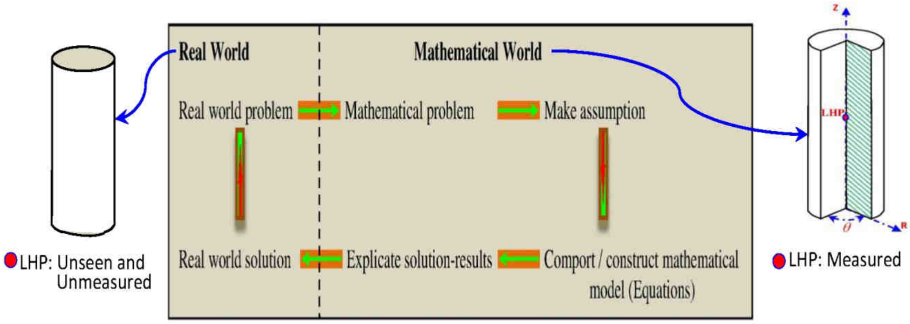

Fig. 1 Key steps in modelling process.

2 Application

2.1 Calculation the temperature history

The present developed mathematical model is programmed using MATLAB to simulate the results of the temperature distribution with respect to time in transient state heat transfer of the industrial quenched boron steel bar. The cylindrical boron steel bar has been heated to 850°C, then is being quenched in water with T_{water} = 32°C and convection heat transfer coefficient, hwater = 5000W/m^2·°C. The temperature history at any point (node) of the cylindrical steel bar after quenching is being identified in **Fig. 2** up to **Fig. 5**. The cylindrical bar was made from boron-50B46H, with properties as mentioned below.

Thermal capacity, ρ_c (J/m^3·°C),

$$0 \le T \le 650,\ \rho_c = (0.004 \cdot T + 3.3) \cdot 10^6,$$

$$650 < T \le 725,\ \rho_c = (0.068 \cdot T - 38.3) \cdot 10^6,$$

$$725 < T \le 800,\ \rho_c = (-0.086 \cdot T - 73.55) \cdot 10^6,$$

$$T > 800,\ \rho_c = 4.55 \cdot 10^6,$$

Thermal conductivity, k (W/m·°C),

$$0 \le T \le 900,\ k = -0.022T + 48,$$

$$T > 900,\ k = 25.5$$

In our case Eq. (27) becomes

$$[K]^{(G)}\{T\}^{(G)} + [C]^{(G)}\{\dot{T}\}^{(G)} = \{F\}^{(G)} \quad (22.)$$

$$[K]^{(G)} = [k_c]^{(1)} + [k_c]^{(2)} + [k_c]^{(3)} + [k_c]^{(4)} + [k_h]^{(4)} \quad (23.)$$

$$[C]^{(G)} = [c]^{(1)} + [c]^{(2)} + [c]^{(3)} + [c]^{(4)} \quad (24.)$$

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$$\{F\}^{(G)} = \{F\}^{(4)} \tag{25.}$$

With the input data and boundary conditions provided, a sensitivity analysis is carried out with the developed program to obtain the temperature distribution at any point (node) of the quenched boron steel bar.

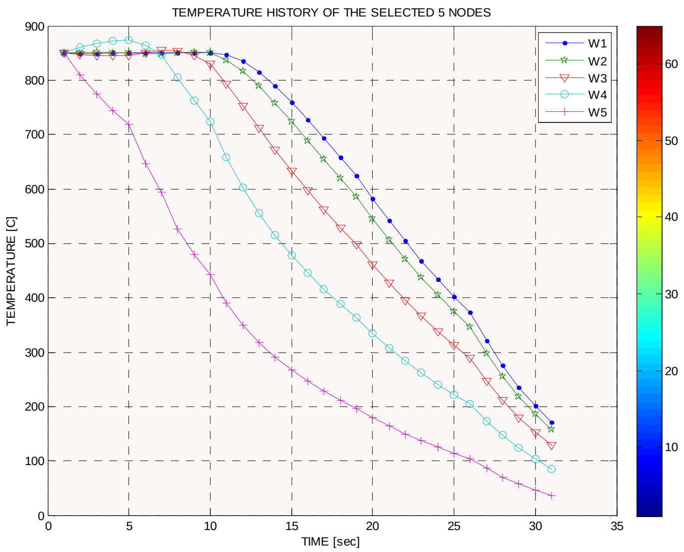

Fig. 2 Temperature history along WW cross-section when the radius equal 12.5 mm.

By the same way the temperature history of the 5 selected nodes has been obtained when the radii 25, 50 and 100 mm is determined respectively.

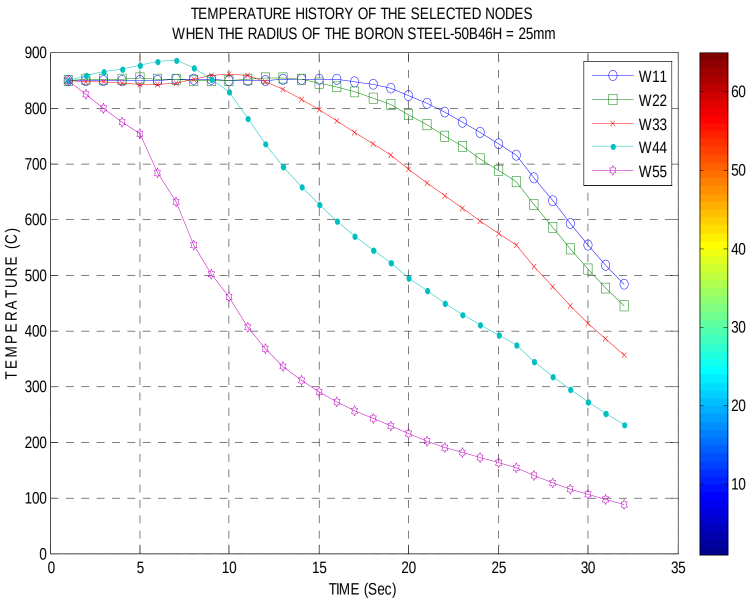

Fig. 3 Temperature history of the selected nodes when the radius equal 25 mm

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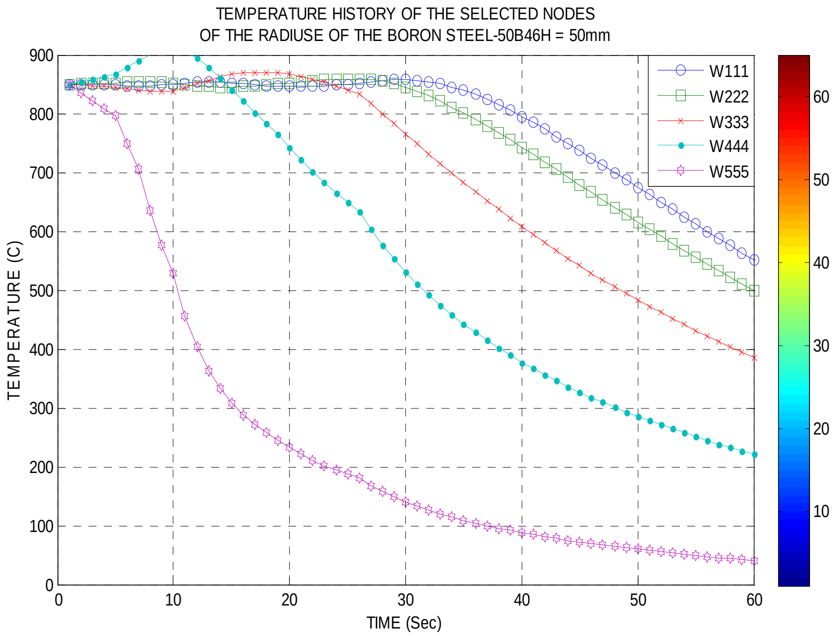

Fig. 4 Temperature history of the selected nodes when the radius equal 50 mm.

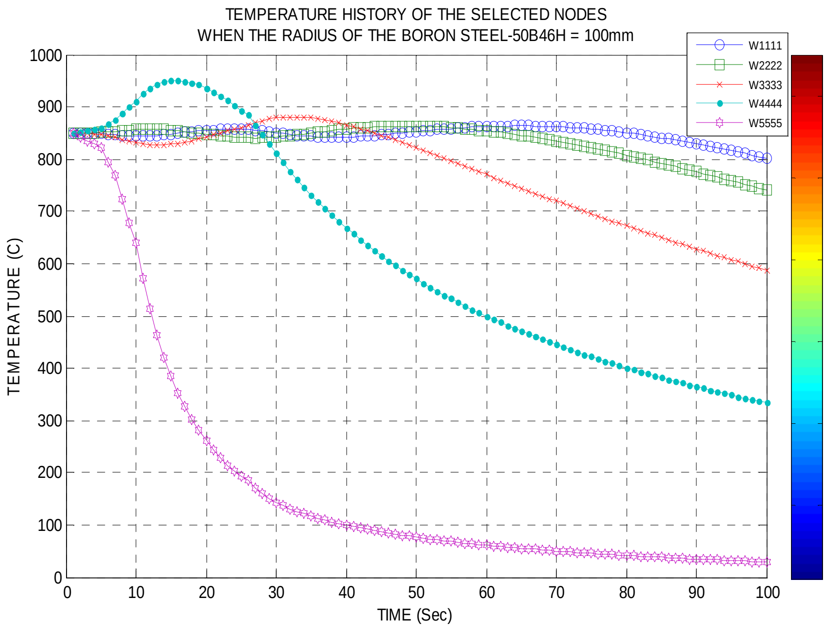

Fig. 5 Temperature history of the selected nodes when the radius equal 100 mm.

3 Mathematical model verification

The same data input for the steel properties and boundary condition used in the mathematical model when the radius equal 12.5 mm is applied to the ANSYS software to verify the

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temperature simulation results. The temperature distribution from the ANSYS analysis is depicted figuratively as shown in **Fig. 6** and **Fig. 7**.

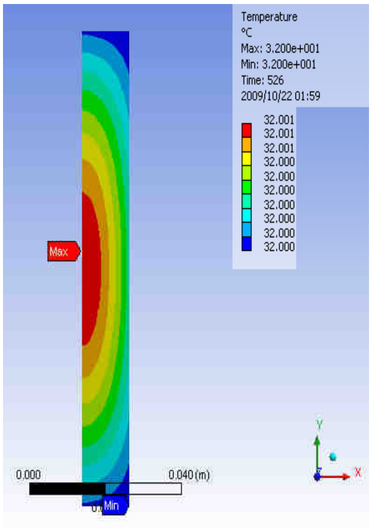

Fig. 6 The temperature distribution

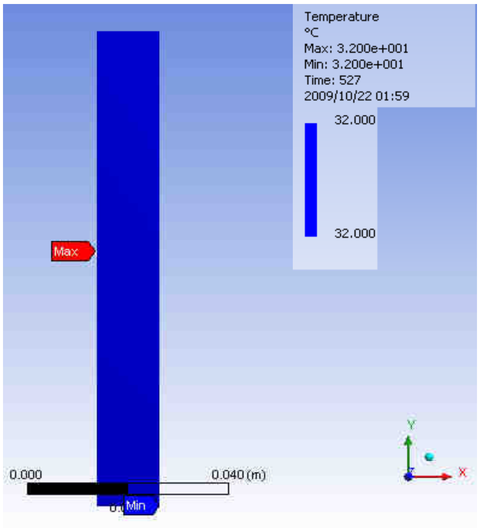

Fig. 7 The temperature distribution

The temperature time graph from the ANSYS analysis is depicted as shown in **Fig 8**.

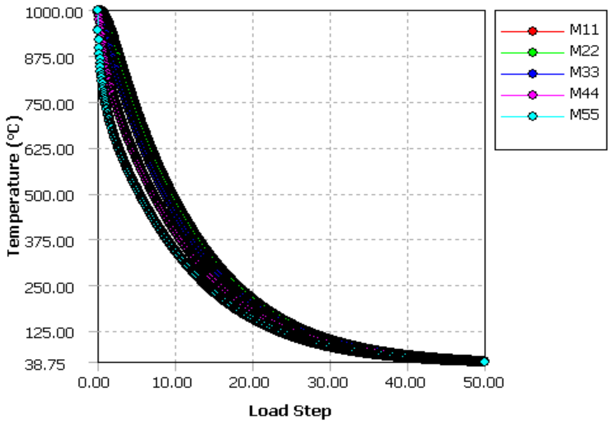

Fig. 8 Temperature-time history.

From the graphs, it can be clearly seen that the temperature history of the quenched steel bar have the same pattern. The heat transfer across the steel bar is uniform. As known during quenching, there are two important temperatures [800°C and 500°C] to calculate the cooling time [7, 8-10]. Because the characteristic cooling time, relevant for structure transformation for most structural steels, is the time of cooling from 800 to 500°C (time t8/5) [7, 11-17]. Then important mechanical properties such as hardness can be computed. In the mathematical model for the node W5 in the surface when the radius equal 12.5 mm, we found that it takes 2.3 sec

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during quenching from 850oC to 800oC and it takes 7.8 sec during quenching from 850°C to 500°C then the cooling time t_c = 5.5 sec.
While in ANSYS for the same node M55, we found that the cooling time t_c = 2.294191 sec. And for the nodes on the centres W1 and M11, it was found that t_c = 9.8 sec and 14.202646 sec for the mathematical model and ANSYS respectively. From the cooling time (t_c) the hardness of the boron steel-50B46H determined as in reference [2], it was found that by mathematical model when t_c = 5.5 sec the hardness = 52.808 and when tc = 9.8 sec the hardness = 44.953, while by Ansys when t_c = 2.294191 sec the hardness = 57.215 and when t_c = 14.202646 sec the hardness = 43.623. From the above, it can be seen that there is a strong agreement between both results.
The difference between all the results of the mathematical model and the ANSYS simulations can be accounted due to the fact that the ANSYS software is for commercial purpose, and thereby has some automated input data. On the other hand the developed mathematical model is precisely for a circular steel bar axisymmetric cross section. However, there is strong agreement between both results and thereby the result is validated where, the comparison indicated reliability of the proposed model.

4 Conclusions

It is clear from our results that the node on the surfaces cools faster than the nodes at half the length at the centre; this means that the mechanical properties such as hardness will be different. Where the hardness on the surface nodes will be higher than the hardness on the center nodes The results showed that the node on the surface will be the 1st to be completely cooled after quenching because it is in the contact with the cooling medium then the other points (nodes) on the radial axis to the centre respectively while the last point that will be completely cooled after quenching will be at centre of half length. Hence, lowest hardness point will be at half the length at the centre of the quenched industrial boron steel bar. Experimental calculation of lowest hardness point is an almost impossible task using manual calculation techniques. Also the earlier methods only used hardness calculated at the surface, which is higher than lowest hardness point, which has negative consequence and can result in the deformation and failure of the component.

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