Computer Simulation to Determine LHP of 4 Different Types of Transient Industrial Quenched Molybdenum Steel Bars

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Abstract—Simulation of hardness distribution in quenched specimens has been investigated using three-dimensional finite element (FE) analyses which reduced into a 2-dimensional axisymmetric analysis based on Ansys Software capable of predicting temperature history; evolution hardness of four different types of Molybdenum steel bars during thermal processing of materials in quenching process is presented. The Jominy test results are used to estimate specimen hardness. specimen points hardness used to be determined through conversion of evaluated characteristic cooling time for phase transformation t8/5 into hardness. The lowest hardness point (LHP) of each quenched Molybdenum steel bar has been determined to be in mid its length in the center. Experimentally, it is quite impossible to determine this hardness value, and earlier approaches could only assess surface hardness. Normally, this value of hardness at the surface is greater than (LHP), that, under certain conditions might lead to component failure and deformation. The model can be employed to establish a cooling method to attain the required microstructure as well as mechanical properties, which include hardness.

Keywords — Ax-Symmetric Steel Bar, Heat Treatment, Modeling, Simulation, Transient Heat Transfer Quenched Steel Bar.

I. INTRODUCTION

In econometrics, Quenching is a heat treatment that is commonly used for industrial operations in order to adjust the mechanical properties of steel, for example, hardness and toughness [1]. Steel quenching is a multi-physics mechanism that involves a complex mode of heat transfer couplings. Due to complexity, there is no analytical solution exists to coupled (thermal, mechanical, and metallurgical) theory and the nonlinear nature of the trouble. however, another solution is possible by finite element software analysis called numerical solution [2]. Heat transfer during quenching operation of steel specimen is in an unsteady state, where the temperature variation with time [3]. Analysis heat transfer of a 3-dimensional model could be simplified to a 2-dimensional axisymmetric analysis to reduce cost and computing time limit [2],[4],[5],[12],[17]. This is possible in axisymmetric analysis, because no temperature variation in direction of theta (θ), the deviations of temperature only in the directions of (r) and (z) [1], [4], [5], [18]-[20].

In this research, numerical analysis was utilized to compute the lowest hardness point (LHP) of four different types of Molybdenum steel bars during thermal processing of materials in the quenching process. It is obvious that the first node W1 should be totally cooled after quenching since it is in touch with the medium of cooling, followed by the remaining points (W1, W3, W2, and W3) on the radial axis to the center respectively. Also, node W1 to be entirely cooled after quenching will be LHP. LHP has been determined, where it is exactly in heat treated quenched steel sample in mid-length at the center of the bar, which practically is almost impossible mission using manual computation techniques. Additionally, previous approaches only utilized hardness determined at the surface, which is higher than LHP, which has negative consequences that could result in component failure and deformation.

The present research proposal aims to make a significant contribution to comprehending the behavior of steel at elevated temperatures when cooling at the steel bar's lowest hardness point (center node).

This paper will be very beneficial in determining the LHP of steel bars to maximize the advantage of anti-bending, deformation, and component failure.

II. TWO DIMENSION MODELING AND ANALYSIS

Considering the specimen's cylindrical configuration, a two-dimension ax-symmetrical model has been chosen. Then, just one-half of the rectangular workpiece has been modeled due to symmetry concerns [2],[4],[5],[12],[17].

The steel specimen cross section is formed in the work plane along the R and Z axes by including appropriate boundary constraints into the symmetry cross-section. Mesh option on computer program graphical user interface is used to apply meshing to the steel bar. Also, we have control over the type of element that is produced. Mesh geometry is represented in Fig. 1a and 1b.

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III. DETERMINING THE HARDNESS OF THE 4 SAMPLES OF STEEL

In this research, we decided to estimate cooling time between 800°C – 500°C [6-9]. Because the typical cooling time for phase change in the majority of structural steels is between 800 – 500 °C (time t_b/s) [10-17].

Computer simulations (transient) for four samples of steel, Molybdenum steel 4032H, 4037H, 4042H, and 4047H [AISI- SAE], will be run in this work, with 1000 °C as the austenitizing temperature for each. Afterward, quenched in water, seawater& oil to ambient temperature (32 degrees Celsius). The temperature distribution of the 5 selected nodes on the radial axis at Z = 50 mm as illustrated on Fig.2 will then be obtained.

A. Simulation of Quenching AISI-SAE 4037H For Nodes W1 – W5, 1000°C Water - Cooled Simulation Results

The simulation will be performed using ANSYS v 10.0 with the data supplied as shown below. The results are temperature variation with time for the chosen nodes W1 to W5, which are represented in Table I.

Type of analysis; (2-D) thermal analysis-transient
Elements number: 474 elements
Total end time: 471s
Material: AISI-SAE 4037H
Dimension: 100 mm (on Z) × 12.5 mm (on R)
Quench medium: Water
Shape of the element: Triangular
Elevated temperature: 900°C
Temperature of the ambient: 32 °C
* Water film coefficient: 5000 W/m². °C
Steel properties at elevated temperature:
Elastic Modulus: 90 GPa
Specific heat: 660 J/kg. °C
Thermal conductivity: 28.8W/m. °C
*In this research, heat transfer coefficient (h) is provided by Steel Industries (Sabah) SdnBhd, which based on steel bar's surface temperature. Once (h) available, it has therefore been possible to simplify cooling chamber convection without taking the complexity of forced convection into account.

The entire end time was determined by trial and error as data was delivered to ANSYS, and the simulation was run till the hot steel sample at 900°C reached a required temperature of 32°C (ambient temperature).

The aforementioned information will be utilized as data delivered to simulate by the ANSYS program in order to calculate the temperature history of each node as it is clear on Figs. 3a, 3b, Fig. 4, and Table I.
Fig. 3a illustrates the distribution of temperature shortly before the steel specimen becomes entirely cooled after the 470s. Fig. 3b depicts the distribution of temperature when the steel specimen has cooled completely after 471 seconds (moment of completely cooling).

Fig. 1. Mesh geometry; a). Mesh geometry of the model, b). Axi-Symmetric of the model (rectangular).

Fig. 2. illustrates selected points on steelspecimen at Z=0.05 m, where [LHP] at node W1.
Fig. 3. Temperature distribution; a). The steel bar before completely cooled, b). The steel bar after completely cooled.

Fig. 4. Curve of temperature versus time at points W1–W5, water-cooled.

| TABLE I: TEMPERATURE HISTORY AT NODES W1–W5, WATER COOLED |
|------------------------------------------------------------|
| t(s) | W1 - T °C | W2 - T °C | W3 - T °C | W4 - T °C | W5 - T °C |
|------|-----------|-----------|-----------|-----------|-----------|
| 0    | 900       | 900       | 900       | 900       | 900       |
| 0.56 | 899.6     | 898.7     | 893.1     | 854.7     | 739.36    |
| 1.12 | 898.2     | 895.2     | 880.4     | 811.7     | 663.41    |
| 1.68 | 895.6     | 889.3     | 863.4     | 774.6     | 612.75    |
| 3.16 | 874.1     | 857.2     | 804.9     | 688.5     | 519.09    |
| 3.92 | 863.2     | 843.6     | 785.6     | 665.7     | 498.83    |
| 5.04 | 837.6     | 814.1     | 748.6     | 626.1     | 464.15    |
| 5.6  | 823.3     | 798.6     | 730.9     | 608.5     | 449.51    |
| 6.16 | 808.5     | 782.9     | 713.9     | 592.2     | 436.2     |
| 6.72 | 793.2     | 767.0     | 697.4     | 576.8     | 423.96    |
| 9.52 | 715.3     | 689.2     | 621.5     | 510.3     | 373.38    |
| 10.1 | 700.0     | 674.2     | 607.6     | 498.5     | 364.71    |
| 15.0 | 586.4     | 564.4     | 507.6     | 416.3     | 305.28    |
| 15.1 | 573.6     | 551.9     | 496.4     | 407.2     | 298.79    |
| 17.4 | 524.7     | 504.9     | 454.3     | 373.0     | 274.41    |
| 17.9 | 513.1     | 493.8     | 444.3     | 365.0     | 268.68    |
| 18.5 | 501.8     | 482.9     | 434.6     | 357.1     | 263.1     |
| 19.0 | 490.8     | 472.3     | 425.2     | 349.4     | 257.64    |
| 20.4 | 32.09     | 32.09     | 32.08     | 32.06     | 32.05     |

B. Calculating The Cooling Time Required

Interpolation method is adopted in this section (1).

\[ t_c = t_{800} - t_{500} \] (1)

Then \( t_{800} = 6.473 \text{sec} \) and \( t_{500} = 18.575 \text{sec} \),

Cooling time, \( t_c \) at node \( W_1 = 18.575 - 6.473 = 12.10210 \text{sec} \).

The cooling time for the selected nodes is shown in Table II.
C. Determine Quenched Steel Hardness

The cooling rate at each Jominy distance [16] standard table, should be utilized in this study to compute the Jominy distance, with results provided on Table III, rate of cooling (ROC) can be calculated from (2).

$$\text{ROC} = \frac{800\, ^\circ C - 500\, ^\circ C}{t_f} = \frac{800\, ^\circ C - 500\, ^\circ C}{t_{cool} + t_{first}} \text{C/sec}$$ (2)

Practical Date Handbook, Timken Company at 1835 Duebex Avenue SW in Canton, Ohio, 44706-7981-800-223, will be employed to compute HRC, and results are illustrated in Fig. 5 and Table III.

IV. QUENCHING OF AISI-SAE 4032H, 4042H AND 4047H [1000 °C WATER - COOLED]

In the same manner, as it has been demonstrated above to determine HRC of specimen AISI-SAE 4037H water-cooled, so for samples, AISI-SAE 4032H, 42H and 47H calculated too, then the HRC comparison for the nodes W1 and W5 on the centers and surfaces respectively of the four types of steel computed as shown in Fig. 6.

All specimens AISI-SAE 4032H, 37H, 42H and 47H of steel were quenched in water at 900°C as austenitizing temperature. By comparing the results of hardness; the highest hardness shown in 4th specimen 47H at the surface (node W5), it was 55.62 HRC. In contrast, lowest hardness noted in the 1st sample AISI SAE 4032H at mid the length in the Centre (node W1), the lowest hardness determined was 20.2 HRC. Noticed that the highest hardness of quenched steel bars occurred at the surface that was rapidly cooled, so the hardness declined from the (node W5) at the surface on the radial axis toward (node W1) at the center. As shown by the results, lowest hardness point (LHP) of quenched bars of steel will be in mid-length at the center. This research may be beneficial in determining LHP for steel bars to attain the most advantage against deformation, bending, and failure.

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