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UNSTEADY STATE COMPUTER SIMULATION OF 2 CHROMIUMSTEEL AT 925°C AS AUSTENITIZING TEMPERATURE TO DETERMINE THE LOWEST HARDNESS POINT (LHP)

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Abstract

Quenching of steels in general has been and continues to be an important commercial manufacturing process for steel components. Temperature histories must be performed to obtain more accurate transformation kinetics; an adequate tool has been produced for investigating the impact of process history on metallurgy and material properties.

Modelling of axisymmetric industrial quenched steel bar was based on the finite element software ANSYS Workbench. Taking into account the cylindrical shape of the specimen, a 2D axisymmetric model has been adopted to predict temperature history, then the hardness of the quenched ste*el bar at any point (node). Hardness in specimen points was calculated by the conversion of calculated characteristic cooling time for phase transformation $t_{8/5}$ to hardness.

The lowest hardness point [LHP] determined, where it's exactly inside the heat treated quenched steel bar at the half of the length at the centre of the bar, experimentally impossible task using manual calculation techniques. Earlier methods only used hardness calculated at the surface, which is higher than LHP this has negative consequence which can result to the deformation and failure of the component.

The temperature history needs to be properly understood in order to efficiently produce high quality components. The model can be employed as a guideline to design new cooling programs for achieving the desired microstructure and mechanical properties such as hardness at any point (node). Temperature of 925 ^{o}C as austenitizing temperature has been used.

Key words: Heat Treatment; Quenching; Axisymmetric Steel Bar; Finite Element Software ANSYS Workbench; Unsteady State Heat Transfer.

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Introduction

Quenching is a heat treatment usually employed in industrial processes in order to control mechanical properties of steels such as toughness and hardness. The process consists of raising the steel temperature above a certain critical value, holding it at that temperature for a specified time and then rapidly cooling it in a suitable medium to room temperature. The resulting microstructures formed from quenching (ferrite, cementite, pearlite, upper bainite, lower bainite and martensite) depend on cooling rate and on chemical composition of the steel [2].

Quenching of steels is a multi-physical process involving a complicated pattern of couplings among heat transfer. Because of the complexity (thermal-mechanical-metallurgical) theory and non-linear nature of the problem no analytical solution exists. However, numerical solution is possible applying finite element software ANSYS Workbench [1].

During the quenching process of the steel bar, the heat transfer is in an unsteady state as there is a variation of temperature with time [3]. The heat transfer analysis in this paper will be carried out in 3D. The three dimensional analysis will be reduced into a 2D axisymmetric analysis to save cost and computer time. This is achievable because in axisymmetric conditions, there is no temperature variation in the theta ( ) direction, the temperature deviations are only in R and Z directions. In this paper software ANSYS technique is used to compute the lowest hardness point (centre node).

It is clear that the 1st point (node) will be completely cooled after quenching (surface node) because it is located on the surface touched by the cooling medium, then the other points (nodes) on the radial axis to the centre, respectively will be cooled and the last point will be completely cooled after quenching (centre node).

It means that the maximum hardness will be measured on the surface node subjected to fast cooling, then the hardness decreases from the surface node on the radial axis to the centre node of the quenched steel bar, respectively. This means that the lowest hardness point of the quenched steel bar will be detected at the centre node.

The hardness lowest point (LHP) should be expected inside the heat treated quenched steel bar at the half of the length at the centre of the bar (centre node). To prove this statement experimentally is an almost impossible task using manual calculation techniques. Also the earlier methods only used hardness calculated at the surface (surface node), which is higher than the lowest hardness point (centre node). This might have negative consequences resulting to the deformation and failure of the component.

It will be more important to know the lowest hardness point (centre node) once the radius of the quenched steel bar will increase because the lowest hardness point will be lower than the hardness on the surface (surface node). This means that increasing the radius of the bar is inversely proportional to the hardness at the lowest point (centre node), while the hardness on the surface (surface node) will be the same.

No published information are available till date on this aspect. This paper represents a contribution towards understanding of steel behaviour at elevated temperature during quenching at the lowest hardness point (centre node) of the steel bar. We believe that the results of this paper might be very useful to obtain the hardness of the lowest point of the steel bar in order to reach the maximum benefit against the deformation and failure of the component..

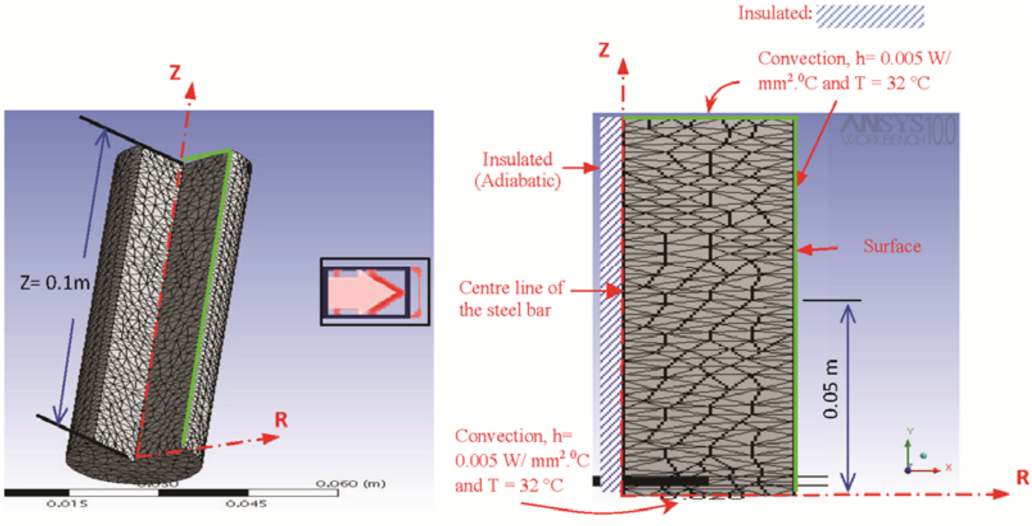
Two dimensional modeling and analysis

Taking into account the cylindrical shape of the specimen, a two dimensional axisymmetric model has been adopted; for symmetry reasons only one half of the rectangular work-piece is been modeled. The steel bar cross section is created on the work plane on the R and Z axis; applying opportune boundary conditions into the symmetry cross section. To determine the temperature history of the heated steel bar, we will input the data of the steel bars and the quenching fluid into the software for analysis. The data input for the steel are Young Modulus, specific heat, thermal conductivity of the steel bar, initial temperature of the steel bar, dimensions, number of elements of meshing. For the fluid, the data input are the ambient temperature and the convective coefficient of the quenching medium. A time dependant function must exist in a transient (unsteady state) thermal analysis.

Meshing is applied on the steel sample from under the Mesh menu in the computer software graphical user interface.

We can choose the type of element to be generated.

The mesh geometry is shown in Fig. 1(a) and (b).



a) *b)*

Fig. 1. Mesh geometry.

The type of analysis is Transient Heat Transfer, the elevated temperature of the steel set as the initial condition. The time step must be the same with the range defined. After analysis, the output results will be obtained from the many post-processing features offered by the software.

Predicting the hardness of the 2 types of steel

The steel bar was heated up to 925°C, then quenched in water, sea water and oil consequently the hardening of the steel is calculated. In this study, we choose to calculate the cooling time between 800oC and 500oC. Where, 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) [4-11].

The time for selected nodes to cool from 800°C to 500°C will be calculated from the temperature-cooling time data given by the software simulation as shown in Table 1. In some cases, to obtain more accurate results, the calculations for the time at the selected temperature will be determined using interpolation method as shown in Case 1 below.

In this paper computer simulations (transient) will be run for two types of chromium steel, i.e. AISI-SAE 8650H and AISI-SAE 5147H at 925°C as austenitizing temperature. Quenching was performed in water, sea water and in oil to the ambient temperature 32°C. The temperature distribution on the radial axis at Z = 50mm as shown in Fig. 2 will be determined.

As was previously mentioned, this analysis will be conducted for the steel bar at 2-D axisymmetric. The steps analysed will be applicable and a comparison between the hardness of the two types of steel will be drawn.

The steps to be followed to achieve this objective are hereby summarised below:

Step 1: Calculation the cooling time for all cases

Step 2: Determine the Jominy distance for all cases

Step 3: Predict the hardness of quenched steel bar for the cases

Step 4: Comparison of hardness by using different medium

Step 5: Plot the hardness vs. nodes graph for all cases

After the simulation, the output data are the temperature-cooling time table/graph. From the results obtained, the calculations for the cooling time at different nodes at the selected temperature will be determined using interpolation method as shown in Case 1 below.

From the cooling time obtained from Interpolation method, the cooling rate of the nodes will also be determined. The cooling time at these nodes will then be used as a data input in the standard Jominy Distance – cooling time Table to determine the Jominy distance of the steel at each selected node. The Jominy distance will be determined directly from the standard Jominy distance – cooling rate Table. The hardness of the steel bar will be calculated by using the output of the Jominy distance, i.e. the Jominy distance at selected nodes will be inputted into the hardness-distance Jominy curve. From this curve, we will determine the hardness at every node of the steel bar even the lowest hardness point on the centre. The hardness values at the nodes obtained for all cases from the Jominy standard tables/graphs will be computed into hardness - nodes graph for comparison.

Fig. 2 shows the selected nodes on the steel sample at Z= 50 mm

Case 1: Quenching of AISI-SAE 8650H [900 0C water, sea water and oil cooled]

Step 1: Simulation using ANSYS v10.0 of the nodes W_1 to W_5

By using the data input below, simulation will be carried out applying ANSYS v 10.0. The outputs obtained from the simulation are the temperature–time curve Table 1 and Fig. 4 at the selected nodes W1 to W5.

Material: (AISI-SAE 8650H)

Dimension: 100mm (length) x 12.5mm (radius)

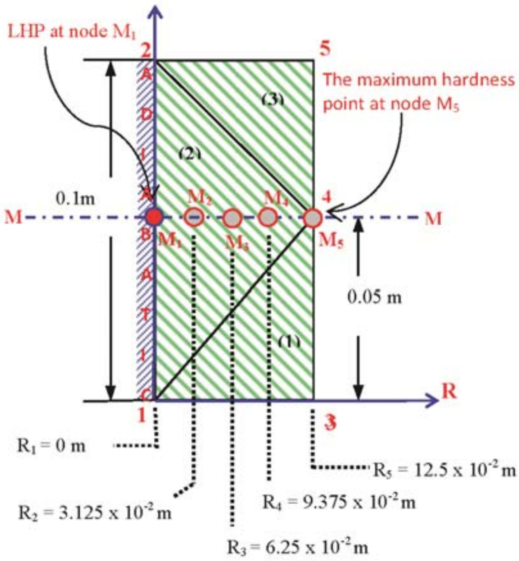


Fig. 2 Selected nodes at Z = 50

Analysis type:	Transient thermal
Total end time:* :	364 s
Number of elements:	474 elements
Quench medium:	Water
Element shape :	Triangular
Elevated temperature:	925^0C
Ambient temperature:	$32\ ^0C$
Film coefficient of water:	$5000\ W/m^{20}C$

Property of the steel at elevated temperature:

Thermal conductivity:	$28.8 W/m\ ^0C$
Specific heat:	$511\ J/kg.^0C$
Young Modulus:	90 Gpa

* The total end time was achieved by trial and error as a data input in ANSYS, the simulation was applied until the hot steel bar at the given temperature of 925^0C reaches the given ambient (fluid) temperature of 32^0C.

The above data will be used as a data input to simulate by ANSYS and the output.

Fig. 3a shows the temperature distribution just before the steel bar becomes completely cooled and Fig. 3b refers to the temperature distribution at the moment that the entire steel bar becomes completely cooled after 364s.

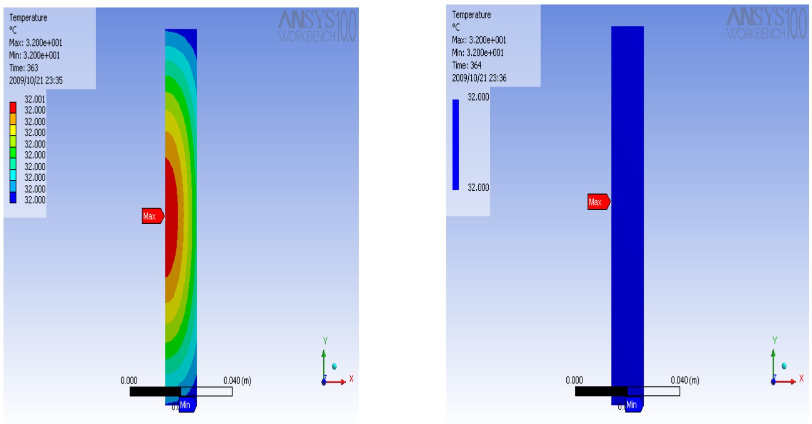


Fig. 3a shows the temperature distribution just before the steel bar becomes completely cooled; Fig. 3b shows the temperature distribution at the moment that the entire steel bar becomes completely cooled after 364s.

Table 1 shows the portion of the temperature history table at the nodes W_1 to W_5. The data from this table will be input in Step 2 of Case 1 in order to calculate the cooling time and cooling rate at these nodes.

Table 1 Portion of the temperature history Table at the nodes W_1 to W_5.

Time (s)	W_1-T (°C)	W_2-T (°C)	W_3-T (°C)	W_4-T (°C)	W_5-T (°C)
0.0	925.0	925.0	925.0	925.0	925.0
0.56	899.05	896.25	873.91	803.21	685.17
1.12	895.84	887.58	840.96	740.74	601.75
1.68	889.5	874.44	807.92	691.59	550.17
2.24	879.81	858.04	776.98	651.82	512.71
2.8	867.05	839.51	748.43	618.77	483.39
3.92	834.59	799.22	697.66	566.12	438.96
5.04	796.67	757.65	653.37	524.73	405.48
6.16	756.63	716.65	613.76	490.15	378.23
9.52	639.83	603.44	513.34	408.11	315.28
10.08	621.72	586.25	498.62	396.44	306.43
14.0	507.99	479.0	407.8	325.12	252.6
14.56	493.55	465.42	396.36	316.18	245.87
157.92	32.09	32.09	32.07	32.06	32.04
161.28	32.08	32.07	32.06	32.05	32.04

To calculate the cooling time, t_c, time for the (nodes) to cool from 925^0C to 800 0C is recorded and deducted by the time for the sample to cool down to 500^0C.

$$t_c=t_{800}-t_{500}$$

The hardness of the nodes W1 to W4 will be compared with the hardness at the surface.

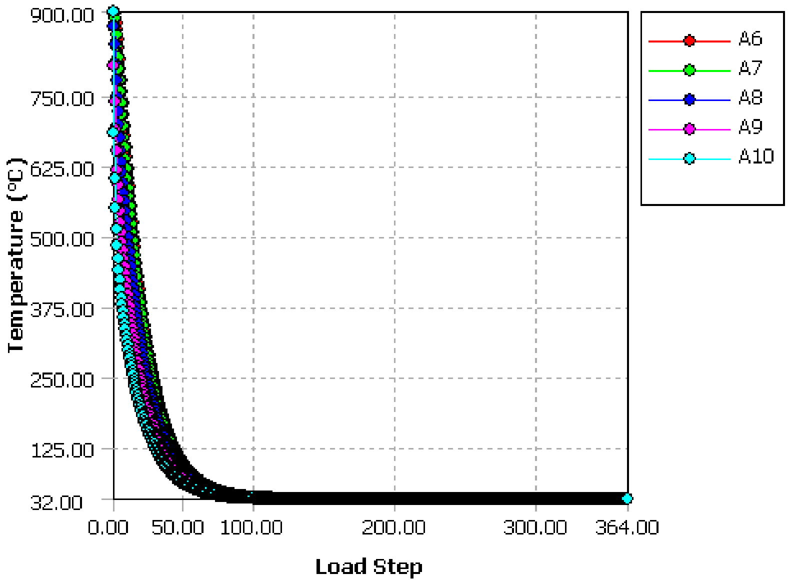


Fig. 4 Temperature-time curve at the nodes W_1 to W_5

Step 2: Calculating the cooling time required

For calculating the time taken for node W_1 at 800°C from Table 1 interpolation method was applied:

a) Calculate the time at 800^0C by using Interpolation.
b) Calculate the time at 500^0C by using Interpolation.
c) Calculate the cooling time $t_c = t_{500°C} - t_{800°C}$
d) Calculate the cooling time in same way for the other selected nodes.
e) To interpolate the t800 value in a table or chart t_1, t_3, T_1, T_2 and T_3 need to be known.

Node W_1 : $t = 3.92$s when $T = 834.59^0$C
Node W_1 : $t = t_{800}$ when $T = 800^0$C
Node W_1 : $t = 5.04$s when $T = 796.67^0$C

Solving for t_{800} by interpolation method:

$$\frac{t_{800} - t_1}{t_3 - t_1} = \frac{T_{800} - T_1}{T_3 - T_1}$$

Thus:

$$t_{800} = \frac{(T_{800} - T_1)}{(T_3 - T_1)}(t_3 - t_1) + t_1 \qquad \therefore t_{800} = 4.942 \text{ s}$$

For calculating the time taken for node W_1 at 500°C:

$$\frac{t_{500} - t_1}{t_3 - t_1} = \frac{T_{500} - T_1}{T_3 - T_1} \quad \text{Thus,} \quad t_{500} = \frac{(T_{500} - T_1)}{(T_3 - T_1)}(t_3 - t_1) + t_1 \qquad \therefore t_{500} = 14.310\text{s}$$

Cooling time, tc at node W_1 = 14.310 - 4.942 = 9.368s

For nodes W_2 to W_5, the cooling time at 800 and 500 as shown in Table 2 will also be calculated using the above method.

Table 2 shows rate of cooling and the time taken for the selected five nodes to cool from 925°C to 800°C and from 925°C to 500°C

Nodes	W_1	W_2	W_3	W_4	W_5
Cooling time (s)	9.338	9.327287	8.648262	5.767045	2.826323
Cooling Rate °C /s	32.12414	32.16369	34.68905	52.01971	106.1449

Step 3: Calculating the Jominy distance from Standard Jominy distance vs. cooling time curve

Cooling time, tc obtained from step 2 will now be substituted into the Jominy distance versus cooling time curve to get the corresponding Jominy distance. Jominy distance can also be calculated by using polynomial expressions via polynomial regression via Microsoft Excel or by the standard Table.

In this paper the standard Table [Cooling rate at each Jominy distance (Chandler, H., 1998)] will be used. [12]

Then Jominy distance of nodes W_1 to W_5 will be calculated by using the data from [Cooling rate at each Jominy distance (Chandler, H., 1998)] via interpolation.

Let J_{dA1}= Jominy distance at node W_1

Thus: J_{dA1} = 9.344mm

By repeating the process that has been mentioned above, the Jominy distance for each node can be calculated as shown in Table 3.

Table 3 Cooling time, cooling rate and Jominy distance for the nodes W_1 to W_5

Node	Cooling time,	Cooling rate	J-distance (mm)
W_1	9.338	32.12414	9.344
W_2	9.327287	32.16369	9.338
W_3	8.648262	34.68905	8.928
W_4	5.767045	52.01971	7.205
W_5	2.826323	106.1449	4.818

Step 4: Predict the hardness of the quenched steel bar

The HRC can be calculated by interpolation by using the Practical date Handbook, the Timken Company 1835 Duebex Avenue SW Canton, Ohio 44706-2798 1-800-223, www.timken.com which showed the relation for this type of steel between the J-Distance and the HRC, and then HRC can be computed as the following:

HR_{CW1} = 58.492

By repeating this process, the HRC for each node can be calculated as shown in Table 4 and Fig. 5.

Table 4 Cooling time, cooling rate, Jominy distance and HRC, water cooled for the nodes W_1 to W_5

Node	Cooling time,	Cooling rate	J-distance (mm)	HRC
W_1	9.338	32.12414	9.344	58.675
W_2	9.327287	32.16369	9.338	58.681
W_3	8.648262	34.68905	8.928	59.068
W_4	5.767045	52.01971	7.205	60.231
W_5	2.826323	106.1449	4.818	60.982

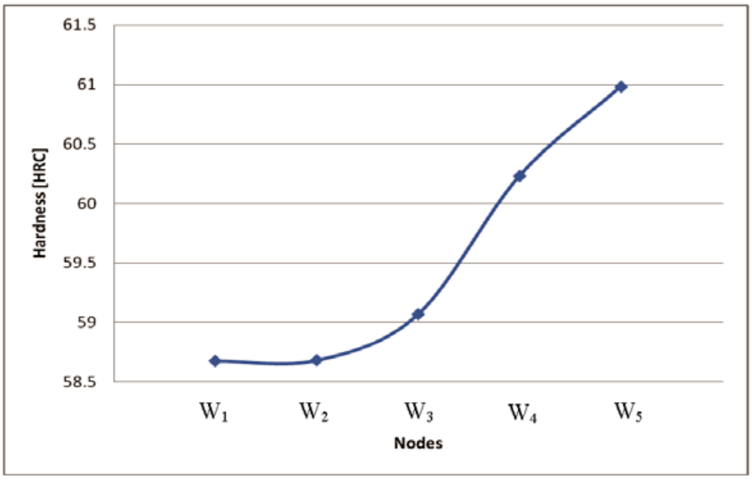


Fig. 5 The hardness at the nodes W_1 to W_5

By repeating the process that has been mentioned above, quenching of AISI-SAE 8650H [925^{0}C sea water cooled and oil cooled] will be shown in Figs. 6 and 7, respectively.

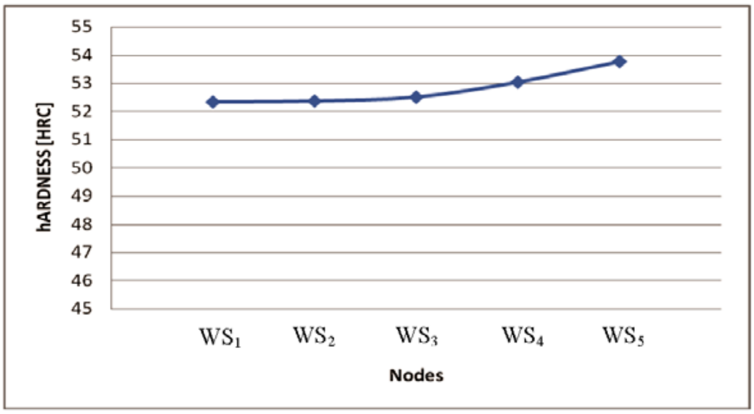


Fig. 6 The hardness at the nodes $(SW)_1$ to $(SW)_5$

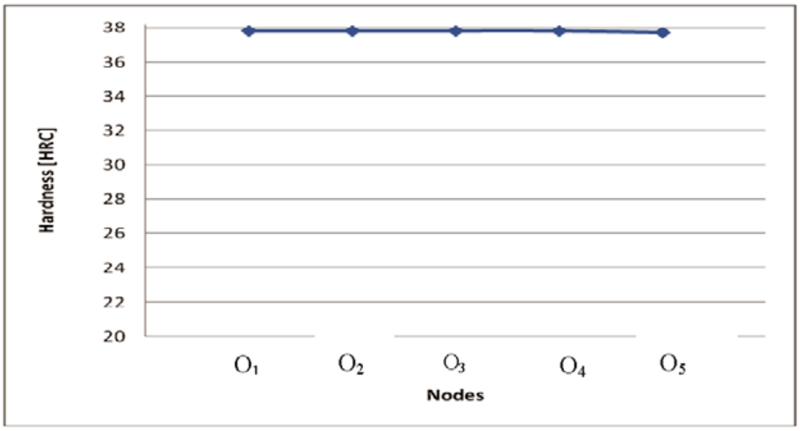


Fig. 7 The hardness at the nodes O_1 to O_5

Case 2: Quenching of AISI-SAE 5147H [925 °C water, sea water and oil cooled]

The HRC of AISI-SAE 5147 water, sea water and oil cooled shown in Fig. 8

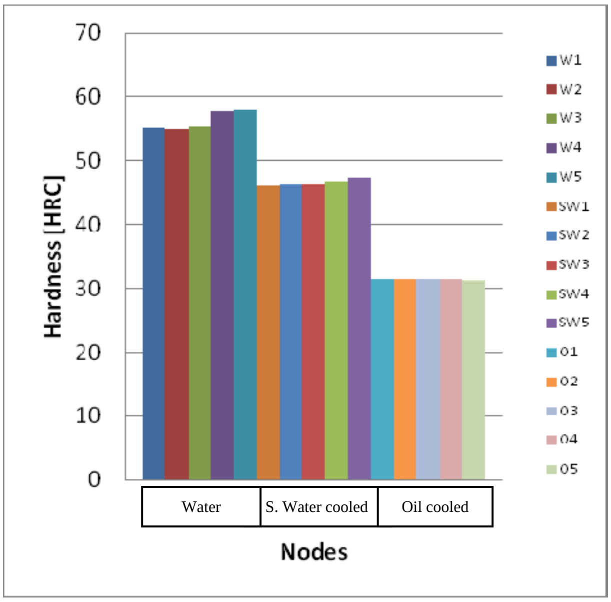


Fig. 8 The HRC of AISI-SAE 5147H. Water, sea water and oil cooled

HRC comparison of AISI-SAE 8650H and AISI-SAE 5147H steel at 925°C as austenitizing temperature in different medium is shown in Fig. 9

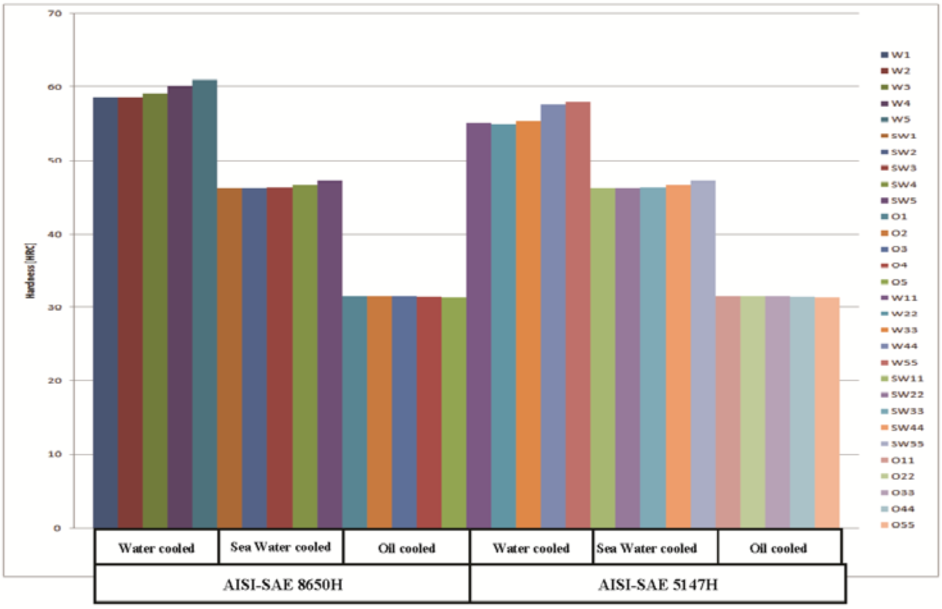


Fig. 9 HRC comparison of AISI-SAE 8650H and AISI-SAE 5147H

Discussion

The AISI-SAE 8650H steel

The common name of this steel is Nickel Chromium Molybdenum Steel.

The selected 5 nodes of this steel are as follows:

[Nodes W_1-W_5 water cooled, 925^0C],
[Nodes SW_1-SW_5 sea water cooled, 925^0C],
[Nodes O_1-O_5 oil cooled, 925^0C],

This steel shows high hardness ability because of the following alloy composition:

- [0.47-0.55 %C] carbon has a major effect on hardness. Carbon is the primary hardening element in steel. Hardness increases as carbon content increases.
- [0.35-0.75 Cr] chromium is commonly added to steel to increase corrosion resistance and oxidation resistance, to increase hardenability.
- [0.35-0.75 Ni] nickel increases the hardenability and impact strength of steels.
- [0.15-0.25 Mo] molybdenum increases the hardenability of steel.

The AISI-SAE 5147H steel

The common name of this steel is Chromium steel.

The selected 5 nodes of this steel are:

[Nodes W_{11}-W_{55} water cooled, 925^0C],

[Nodes SW_{11}-SW_{55} sea water cooled, 925^0C],
[Nodes O_{11}-O_{55} oil cooled, 925^0C],

It shows less hardness than the AISI-SAE 8650H steel because this steel contains:

- [0.45-0.52 %C], as explained above, the carbon content has a major effect on steel properties. Carbon is the primary hardening element in steel.
- [0.0.8-1.25 Cr], as explained above, chromium is commonly added to steel to increase corrosion resistance and oxidation resistance, to increase hardenability,

This steel does not contain molybdenum and nickel and thereby has less hardness ability than the AISI-SAE 8650H steel.

Conclusions

The explanations and graphs shown above are the comparison of HRC, HRC versus selected 5 nodes for 2D-axisymmetrical, for AISI-SAE 8650H and AISI-SAE 5147H steels quenched from at 925°C as austenitizing temperature in three different quenching medium water, sea water and oil.

The highest hardness of 60.982 HRC was obtained in steel AISI SAE 8650H at node W_5 [925^0C] when quenching was performed in water. On the other side, the lowest hardness of 31.3 HRC was obtained in AISI SAE 5147H steel at node O_{11} [925 ^0C] when quenched in oil. The results showed that AISI SAE 8650H steel is harder than AISI SAE 5147H steel in the entire quenched medium [water, sea water and oil]. As for the quenching medium, the steel quenched in water has the highest hardness compared to the sea water and oil. The steel quenched in oil has the lowest hardness if compared to water and sea water.

It was found that the maximum hardness was obtained at the surface of the sample bar due fastest cooling rate, then the hardness decreases from surface from the radial axis direction to the centre of the quenched steel bar. This means that the lowest hardness point [LHP] of the quenched steel bar will be on half the length at the centre as documented by our results.

This paper will be very useful to know LHP of the steel bar in order to obtain the maximum benefit against the deformation and failure of the component under certain conditions.

Acknowledgements

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