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Unsteady State Thermal Behavior of Industrial Quenched Steel Bar

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Abstract: Heat transfer is very important in steel industries because heating is an economical way to alter a steel component's properties to suit the end user's requirement. Heating interrupted by quenching is a well-known procedure to treat steel components. Much work had been done on changing the mechanical properties of the steel component and little on the fundamental of the process, which is the heat transfer between the quenching medium and steel component. Theoretically, we should be able to predict hardness at any points of steel provided that the relationship between its cooling rate and hardness and the temperature field and its evolution with time are known. Nevertheless, based on metallurgy literature, steel such as hot rolled bar; the allowable hardness is 35HRC. In this paper, we will discuss the approach of finite element software ANSYS Workbench. The ANSYS simulation will be done in 1-D, 2-D and three dimensional. Beside that, the results will be verified by using ANSYS software. From the result, the hardness prediction can be used as a rough guideline to assist the quality engineer prior to production by comparing to a typical standard hardness value set. This will help to reduce the risk of trial and error during production. In this manuscript we discussed the hardness prediction of the quenched bar is difference according to its quenching media which for water have the highest value of 50.32 HRC, 25.46 HRC for stationary oil and the lowest hardness is 14.82 HRC for salt bath. Hardness increase as cooling rate increases.

Once the cooling temperature decreased, the steel bar will need to take longer time to quench. This was caused the hardness of steel bar decreased. The effect of quenchants media gives variable of hardness of steel bar by according to its cooling rate. As a conclusion, this paper has fulfilled all the objectives where the affected parameters have been identified to improve the workability of steel bar during cooling by using ANSYS software [1-D, 2-D and 3-D] owing to lower cost, safer and reliable procedure than experimental work.

Keywords: *Heat treatment, Temperature distribution, Hardness, heat transfer, Ansys workbench software, Finite Element, Steel, Quenchant media*

1. Introduction

This paper studied the thermal behavior of steel bar during quenching three dimensional. Where, we found that the temperature distribution obtained by finite element method and ANSYS Workbench are almost having the same results in one [1-D] and two-dimensional [2-D] solution as shown in Figs.1. and 2 respectively. Therefore ANSYS Workbench can produce the accurate result and it helps us save the time and money to analyze the problems. So, instead of wasting time and money, the best alternative solution is by doing the simulation. Therefore we can easily calculate the hardness distribution during cooling from the temperature distribution history by using Ansys Workbench.

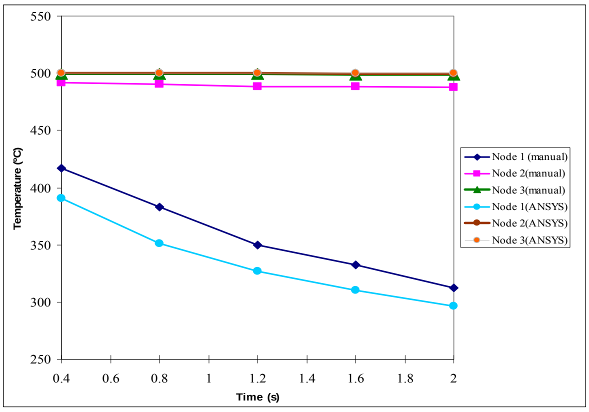

Fig.1. Comparison Result for water quenchant (1-D)

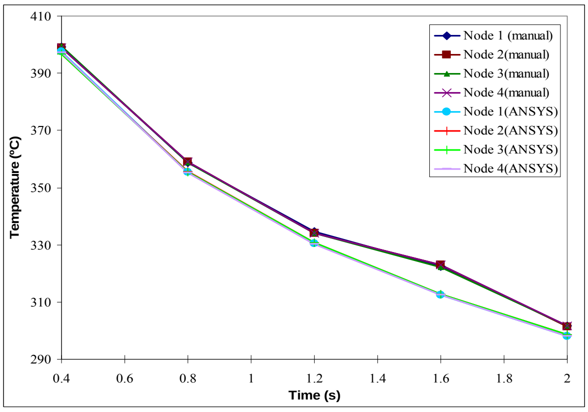

Fig.2. Comparison Result for water quenchant (2-D)

2. Problem and Solution

In manufacturing process, the material is in some way thermally and mechanically affected. Thus the effect on steel bar will be studied in order to determine the parameters of cooling process. After knowing the thermal effects and behavior of steel bar, controlling the cooling process becomes essential. The control of cooling depends on the heat transfer between steel bar and the quenching medium such as water, stationary oil, and salt bath. After know the heat transfer output data such as changes in thermal behavior according to time has been obtained, we can obtain a specific cooling time for the process. If the cooling time is too long, the steel bar will become low ductility. Consequently, it is possible to develop a 'virtual laboratory' for cooling process using mathematical model and computer simulation to increase the productivity and reliability of steel bar, whilst minimizing the costs and risk associated with the trial and error. Another possible method of studying the thermal behavior would be to study the hardenability of steel. The ability of steel to form martensite on quenching is referred to as the hardenability and through this property one can know the thermal behavior of the product during quenching as well. The use of TTT (Time-Temperature Transformation) diagrams could provide a good starting point for an examination of hardenability, but as they are statements of the kinetics of transformation of austenite carried out isothermally, they can only be a rough guide. Besides the temperature distribution, another property that can be obtained from the cooling time is the hardness of the product. The hardness of the product would be the measure of the effectiveness of the quenching process and can be determined using the several tests, such as the Grossman test and the Jominy end quenched test data via ASTM E140. In the Grossman test, the transverse sections are metallo-graphically examined to determine the particular bar which has 50% martensite at its centre. The diameter bar is designated at its critical diameter. A less elaborate approach would be the Jominy test in which a standardized round bar is used. It has been known after cooling process, steel will become very hard and low workability. Cooling time can be computed from temperature behavior. Using Bozo's method and with the availability of cooling time from temperature history, we can predict the hardness of quenched steel bar. This simulated hardness can be used as a guideline to make the quality of steel bar.

3. ANSYS Simulation of Steel Bar during Quenching in Three-Dimensional

Data Input: Material : AISI 4140, Dimension : 0.0125m radius and 0.1m length, Thermal conductivity 28.2 W/m. °C, Steel bar temperature : 500°C, Cooling water temperature : 40°C

Quenchants types : (Water, stationary oil and salt bath), Film coefficient : 6500 W/m^2. °C, Elements : 722 and End time : 100s @ 1.67min

3.1. Water Quenchants:

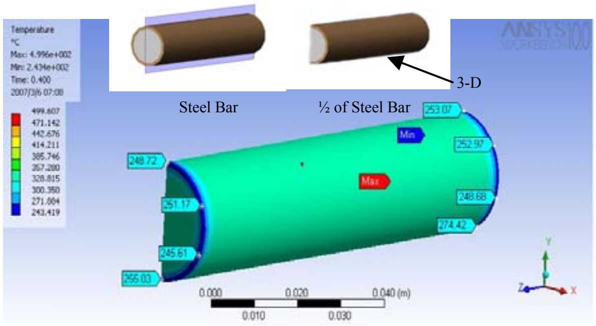

Fig.3. Result for 500 ºC Steel bar and 40 ºC at time step 0.4 second.

This is repeated for step 0.8, 1.2, 1.6 and 2 (s) the results shown in table.1. and Fig.4. shows temperature history until 100 second, water cooled

t(s)	Node 1 (ºC)	Node 2 (ºC)	Node 3 (ºC)	Node 4 (ºC)
0.4	248.72	251.17	245.61	255.03
0.8	190.62	191.72	193.23	196.78
1.2	160.01	161.44	160.13	166.24
1.6	139.73	141.5	139.53	144.15
0.4	253.07	252.97	248.68	272.42
0.8	189.78	192.3	191.74	199.54
1.2	161.29	161.14	169.83	165.38
1.6	142.44	147.94	138.25	157.03

Table.1. Result from ANSYS software in three-dimensional

From fig.4. Temperature will reach absolute 40 ºC after 100s. Each node has the same value of temperature due to its coordinate that located at the end of steel bar. Basically temperature is difficult to archive equilibrium value when it's come to heating or cooling. Heat is removed very slowly where boiling ceases and heat is removed by convection into the liquid. Temperature will highly decrease when the steel bar suddenly immersed into water which this explained the behavior of boiling phase which the stable vapor film will eventually collapses and cool quenchant comes into contact with the hot metal surface resulting in nucleate boiling and high heat extraction rates.

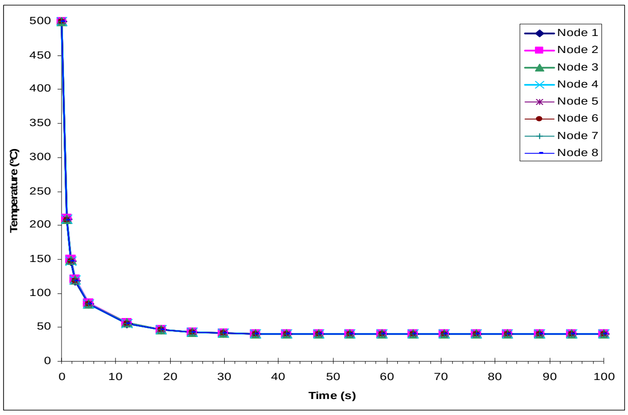

Fig.4. Temperature history until 100 second, water cooled

3.2. Stationary Oil Quenchants:

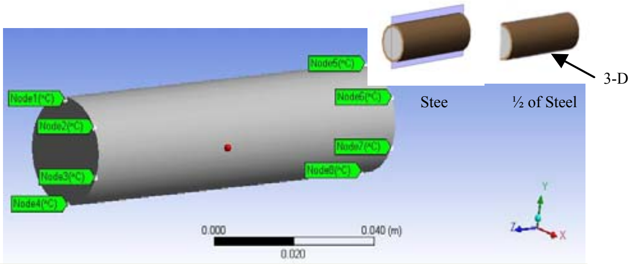

Figure.5. Nodes coordinates for 3-D stationary oil quenchant.

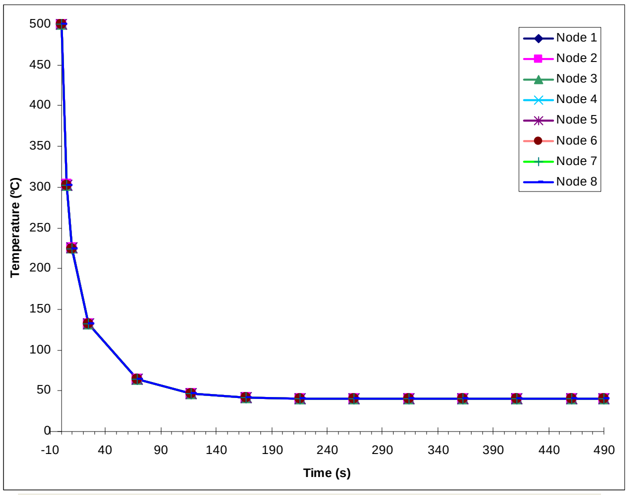

Figure.6. Temperature versus time for stationary oil quenchant

From Fig.6. temperature will reach absolute 40 ºC after 490 second (8.17 minute). Each node has the same value of temperature due to its coordinate that located at the end of steel bar. Quenching oil has different value of heat transfer coefficient if compared to heat transfer coefficients for water; this will give different value of cooling rate thus resulting difference hardness value. Similar with water case study, value for cooling rate are approaching zero at the end of the quenching process.

3.3. Salt Bath Quenchants

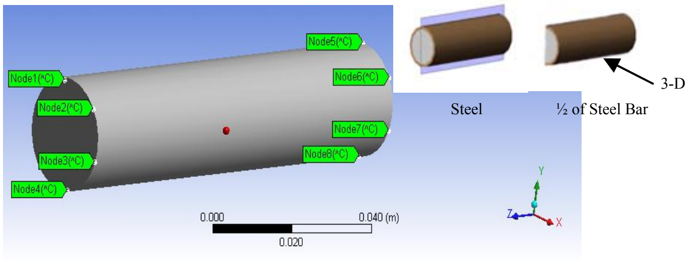

Figure.7. Nodes coordinates for 3-D salt bath quenchants

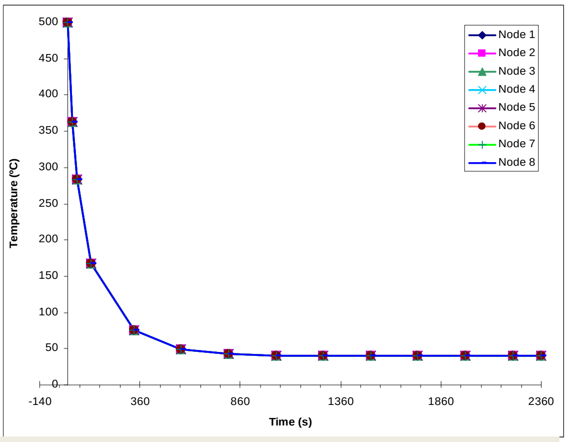

Figure.8. Temperature versus time for salt bath

From Fig.8. temperature will reach absolute 40 ºC after 2360 second (39.3 minute). Each node has the same value of temperature due to its, coordinate that located at the end of steel bar. Salt bath has different value of heat transfer coefficient if compared to heat transfer coefficients for water and oil; this will give different value of cooling rate thus resulting difference hardness value which will be discuss in the next chapter. Similar with water and oil case study, value for cooling rate are approaching zero at the end of the quenching process, and Fig.9. shows Cooling curves quenching in water, oil, and salt.

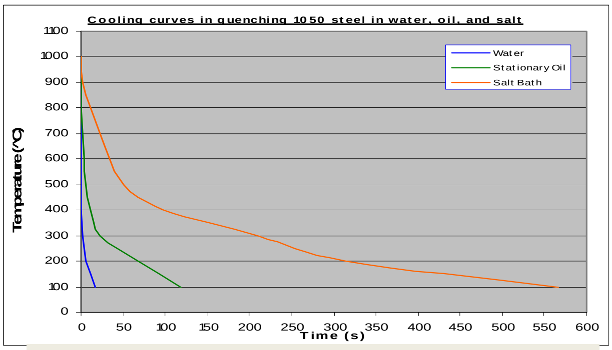

Figure.9. Cooling curves quenching in water, oil, and salt.

A plot of temperature vs. time for AISI 4140 steel bar, quenched in different fluids, is shown in figure.9. The steel bar quenched in water has the highest cooling rates and the bushing quenched in salt bath has the lowest cooling rate. Water has the fastest cooling time due to its largest heat transfer convection coefficients while salt bath has the smallest heat transfer convection coefficients compared to stationary oil. This variable end time can provide different type of hardness and ductility.

3.4. Discussion

The result when changing the quenchants media from water to stationary oil and salt bath with the comparison of result between each quenchants. From the result, we can say that ANSYS software and Finite Element Method manual calculation are in good agreement. So, instead of wasting time and money, the best alternative solution is by doing the simulation.

4. Hardness Prediction

Hardenability is defined as the ability for a ferrous alloy to form martensite when quenched from its austenizing temperature. Theoretically, hardness of a particular alloy is a function of its cooling rate. Thus, knowing the relationship between the cooling rate and hardness for a particular alloy should enable us to predict the hardness at a material point in a complicated part, provided that the temperature field and its evolution with time are known. However, the experiment shows that this predicted hardness is a lot greater than actual hardness. we need to know the cooling time, t_c, from 800°C to 500°C for a starting temperature of steel bar 1000°C. This is the time relevant for structure transformation in most structural steel. After get the cooling time, calculate the cooling rate, Jominy distance, Hardness of Rockwell C (HRC) and Vickers Hardness (HV).

4.1. Jominy Distance versus Cooling Time

One standard procedure that is widely utilized to determine hardenability is the Jominy end quench test as shown in Fig.10.

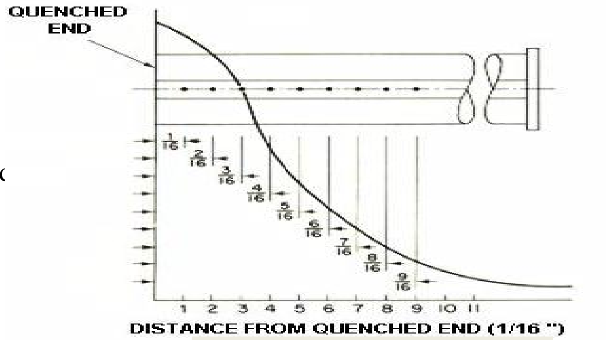

Figure.10. Jominy end quench test.

Since each distance along the quenched bar is equivalent to a certain actual cooling rate, one could just as well plot HRC hardness versus cooling rate as HRC hardness versus J-distance. This is exactly what is done on the ASTM graph paper.

Cooling Time, $t_c = t_{500\,^\circ\mathrm{C}} - t_{800\,^\circ\mathrm{C}}$ (4.1)

Cooling Rate, ROC $= \dfrac{T_{800\,^\circ\mathrm{C}} - T_{500\,^\circ\mathrm{C}}}{t_c}$ (4.2)

Jominy distance versus cooling time curve was regressed into the following polynomial equations (4.3)–(4.5) by Yeoh Chuan Shuan [2] via using Muller method. The J-distance can be determined from these equations based on its cooling time.

For ($0 \leq t_c \leq 12.86$): J-distance = $-0.057(t_c)^2 + 1.5492\,(t_c) + 0.3209$ (4.3)

For ($12.86 < t_c \leq 43.55$): J-distance = $-0.0025(t_c)^2 + 0.5026\,(t_c) + 5.0352$ (4.4)

For ($43.55 < t_c \leq 174.19$): J-distance = $0.001(t_c)^2 + 0.0631\,(t_c) + 18.633$ (4.5)

Where: J-distance =Jominy Distance and t_c = Cooling Time

4.2. Hardness versus Jominy Distance

The Jominy distance is input into hardness versus Jominy distance curve to get the hardness value. The hardness versus Jominy Distance curve was regressed by Yeoh (C.S Yeoh, 2002) using Muller method.

For (0mm ≤ J-distance<13.5mm): HRC=$0.2105(\text{J-distance})^2 - 5.5866\,(\text{J-distance}) + 54.791$ (4.6)

For (13.5mm ≤ J-distance<51.0mm): HRC=$0.0044(\text{J-distance})^2 - 0.4522(\text{J-distance}) + 22.664$ (4.7)

Where: HRC = Rockwell Hardness C and J-distance = Jominy Distance

4.3. Hardness Conversion

The conversion of Rockwell Hardness C (HRC) to Vickers Hardness (HV) can be done through calculations which were done by Yeoh Chuan Shuan [2] via using regressed polynomial equation.

For 29 HRC and below: HV = $0.0627\,(\text{HRC})^2 + 2.6399\,(\text{HRC}) + 161.68$ (4.8)

For 29 ≤ HRC ≤ 68: HV = $0.3199\,(\text{HRC})^2 - 15.664\,(\text{HRC}) + 496.71$ (4.9)

Where: HV = Vickers Hardness and HRC = Rockwell Hardness C

4.4. Result of J-distance, Rockwell Hardness C and Vickers Hardness

The sensitivity analysis of this paper was done in unsteady state condition, so we can predict the J-distance, Rockwell Hardness C and Vickers by assumed the cooling time via using the equations (4.1)-(4.9). Table below shows the relation among them.

Table.2. The result of J-distance, HRC and HV

Cooling Time, *t*(s)	Cooling Rate ($^oC/s$)	J-distance (mm)	HRC	HV
1	300.00	1.8131	45.3539	444.3132
2	150.00	3.1913	39.1063	373.3729
3	100.00	4.4555	34.0786	334.4190
4	75.00	5.6057	30.0889	315.0163
5	60.00	6.6419	26.9715	278.4939
6	50.00	7.5641	24.5773	264.4352
7	42.86	8.3723	22.7734	254.3175
8	37.50	9.0665	21.4435	247.1196
9	33.33	9.6467	20.4876	242.0830
10	30.00	10.1129	19.8223	238.6452
11	27.27	10.4651	19.3803	236.3919
12	25.00	10.7033	19.1110	235.0311
13	23.08	11.1465	18.6734	232.8391
14	21.43	11.5816	18.3243	231.1077
15	20.00	12.0117	18.0576	229.7953
16	18.75	12.4368	17.8704	228.8794
17	17.65	12.8569	17.7603	228.3428
18	16.67	13.272	17.2437	225.8452
19	15.79	13.6821	17.3006	226.1186
20	15.00	14.0872	17.1669	225.4767

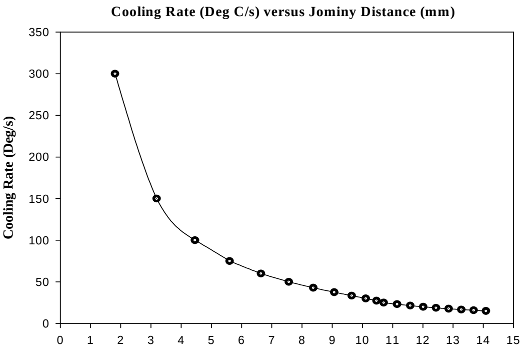

Figure 11. Graph cooling rate versus Jominy Distance

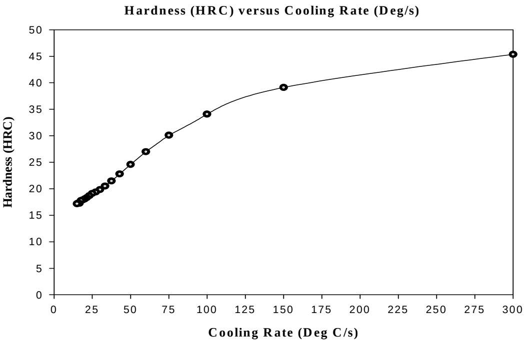

Figure 12. Graph hardness (HRC) versus cooling rate (C^o/s)

4.5. *Discussion*

The relation between the cooling rate, J-distance and the hardness. Fig.11. shows that when the distances of Jominy quench end increase, the cooling rate will decrease. This means that the surface of quench end have faster cooling rate than the center. While Fig.12. shows that hardness of the Jominy quench bar increase when the cooling rate increase. Fig.13. shows that the hardness near to the surface of the quench bar is higher, the center is lower. So the microstructure at the surface of quench bar will also be harder rather than center.

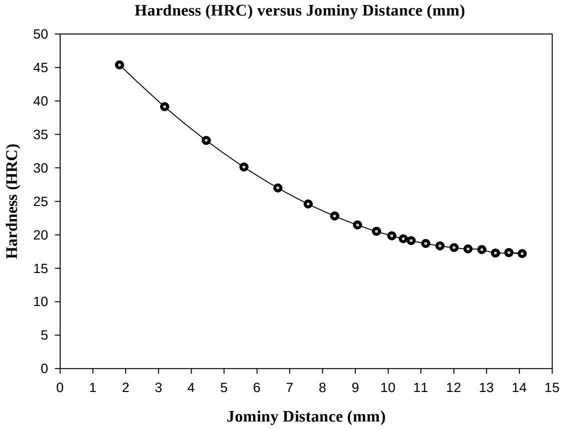

Figure.13. Graph hardness (HRC) versus Jominy Distance (mm)

4.6. *Calculation for hardness prediction for starting temperature of 1000ºC, water*

Hardness can be calculated via using the equations (4.1)-(4.9). The cooling time for steel bar to achieve 500ºC from 800ºC initial temperature of 1000ºC can be determine from three-dimensional case ANSYS 10.0 software.

i) Cooling Time
$t_c = t_{500^oC} - t_{800^oC} =$ 0.33487 – 0.005 = 0.32987 Sec

ii) Cooling Rate
Cooling Rate, ROC = $(T_{800^oC} - T_{500^oC}) / t_c = [798.16^OC - 503.78^OC] / 0.32987$ Sec
Thus ROC = 892.41 ^OC / Sec

iii) Jominy Distance: for ($0 \le t_c \le 12.86$)
J-distance = $-0.057(t_c)^2 + 1.5492(t_c) + 0.3209 = 0.8261$ mm

iv) Hardness: for (0mm ≤ J-distance ≤ 13.5mm)
HRC = $0.2105\,(\text{J-distance})^2 - 5.5866(\text{J-distance}) + 54.791 = 50.32$

v) Hardness Conversion HV: for $29 \le HRC \le 68$
HV = $0.3199(HRC)^2 - 15.664(HRC) + 496.71 = 518.52$

4.7. Calculation for hardness prediction for starting temperature of 1000ºC, oil

i) Cooling Time
$t_c = t_{500}{}^{o}C - t_{800}{}^{o}C = 6.442 - 0.84196 = 5.6$ Sec

ii) Cooling Rate
Cooling Rate, ROC = $(T_{800}{}^{o}C - T_{500}{}^{o}C) / t_c = [799.41^{O}C - 500{,}53^{O}C] / 5.6$ Sec
Thus ROC = 53.4 ^{O}C / Sec

iii) Jominy Distance: for ($0 \le t_c \le 12.86$)
J-distance = $-0.057(t_c)^2 + 1.5492(t_c) + 0.3209 = 7.2089$ mm

iv) Hardness: for (0mm ≤ J-distance ≤ 13.5mm)
HRC = 0.2105 (J-distance)^2 – 5.5866(J-distance) + 54.791 = 25.46

v) Hardness Conversion HV: for 29 HRC and below
HV = 0.0627(HRC)^2 -2.6399(HRC) + 161.68 = 269.53

4.8. Calculation for hardness prediction for starting temperature of 1000ºC, salt bath

i) Cooling Time
$t_c = t_{500}{}^{o}C - t_{800}{}^{o}C = 55 - 11.687 = 43.313$ Sec

ii) Cooling Rate
Cooling Rate, ROC = $(T_{800}{}^{o}C - T_{500}{}^{o}C) / t_c = [804.9^{O}C - 494.14^{O}C] / 43.313$Sec
Thus ROC = 7.17 ^{O}C / Sec

iii) Jominy Distance: for ($12.86 \le t_c \le 43.55$)
J-distance = $-0.0025(t_c)^2 + 0.5026(t_c) + 5.0352 = 22.114$ mm

iv) Hardness: for (13.5mm ≤ J-distance ≤ 51,0mm)
HRC = 0.0044 (J-distance)^2 – 0.4522(J-distance) + 22.664 = 14.82

v) Hardness Conversion HV: for 29 HRC and below
HV = 0.0627(HRC)^2 -2.6399(HRC) + 161.68 = 214.57

Table.3. The result of J-distance, HRC and HV for different types of quenchant.

Quenchants	Cooling Time, *t_c* (s)	Cooling Rate (ºC/s)	J-distance (mm)	HRC	HV
Water	0.33	892.41	0.8261	50.32	518.52
Stationary Oil	5.6	53.4	7.2089	25.46	269.46
Salt Bath	43.31	7.17	22.14	14.82	214.57

4.9. Discussion

Hardness increases as cooling rate increases. Theoretically, we should be able to predict hardness at any points on an alloy provided that the relationship between its cooling rate and hardness and the temperature field and its evolution with time are known. Nevertheless, based on metallurgy literature, steel such as hot rolled bar; the allowable hardness is 35HRC.

5. General Discussion

The result of the sensitivity analysis on the quenched bar was simulated in three dimensional model. The predicted hardenability of steel bar on various cooling time for water quenchants was discussed. In order to increase a productivity and workability of steel bar by quenching, the hardness of steel bar must below the 35HRC.

6. Conclusion

1. The hardness prediction of the quenched bar is difference according to its quenching media which for water have the highest value of 50.32 HRC. Hardness increase as cooling rate increases. Nevertheless, based on metallurgy literature, steel such as hot rolled bar; the allowable hardness is 35HRC.

2. From the result, the hardness prediction can be used as a rough guideline to assist the quality engineer prior to production by comparing to a typical standard hardness value set. This will help to reduce the risk of trial and error during production.
3. As a conclusion, this paper has fulfilled all the objectives where the affected parameters have been identified to improve the workability of steel bar during quenching.

7. Recommendation for Further papers

There are many potential future works which can be carried out to modify or expand the models. The following are recommended for further manuscripts:

i. We have to change the other parameter so that we can achieve allowable hardness for quenched steel bar.

ii. Applying temperature history on different type of heat treating, such as normalizing, annealing, stress relieving, and surface hardening.

iii. Continue to study the alternative methods of quenching such austempering, martempering, isothermal quenching, Aus-bay quenching, Spray quenching, Fog quenching, Cold die quenching, Press quenching, Vacuum quenching, Fluidized bed quenching, HIP quenching, Ultrasonic quenching, and Quenching in electric and magnetic fields.

iv. Perform the Jominy end quenched test experimentally to get the hardness for the Jominy distance more than 51mm.

v. Extending the model to other shape of steel bar such as square, rectangular and triangular steel bar.

vi. Applying bending and grinding to steel bar to see the effect of stress relief due to heat treating of steel.

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