Hardness and impact energy absorbed produced by Q&T steel and DQ&T steel

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Abstract. Hot rolled plate steel is heat treatable steel made in Indonesia for commercially developed to Quenched and Tempered Steel. This steels made by PT. Krakatau Steel (Persero) Cilegon, Banten, Indonesia. The aim of this study to improve the hardness and energy impact through heat treatment of double quench + temper. The method used is heating up to 900°C (maintained for 30 minutes and cooled by water) for fives specimen hot rolled plate steel and produce the quenched 900 steel (Q⁹⁰⁰ steel). Four Q⁹⁰⁰ steel specimens were heated at 750°C, 800°C, 850°C, and 900°C (maintained for 30 minutes) each. Then five specimens (include Q⁹⁰⁰ Steel) are tempered at 150°C (maintained for 30 minutes) and produced Q⁹⁰⁰ & T Steel, Q⁹⁰⁰+750 & T Steel, Q⁹⁰⁰+800 & T Steel, Q⁹⁰⁰+850 & T Steel, Q⁹⁰⁰+900 & T Steel. Results of the study were changes in microstructure, hardness and impact energy. Hardness and impact energy absorbed of Q⁹⁰⁰+750&T Steel higher than Q⁹⁰⁰&T Steel.

1. Introduction
In recent years there has been an increasing need for quenched and tempered steels (Q&T Steels) used for highly-stressed structures, including application in construction of military (ballistic resistant) and non-military equipments, because of their high hardness and energy absorbing properties and excellent toughness [1-5]. Conventionally, high hardness of steels can be produced by quenching and tempering heat treatment process. This is caused by phase transformation of steel during quenching processes, where the lattice structure of steel changes immediately from a face-centered cubic γ phase to a body-centred tetragonal martensite [6].

In low-alloy steels and iron-carbon alloys, however, carbon diffusion cannot be suppressed, and to generate useable high-strength microstructures, is even promoted by low-temperature tempering. Hardness and general carbon-dependent features of hardened microstructural systems in steels [7]. Low-carbon martensite, the martensite units form in the shape of lath, grouped into larger sheaves or packets. Its substructure consists of high densities of dislocations arranged in cells, and is superficially similar to that developed in iron by a heavy cold-working process [6]. Since steel is a polycrystalline substance, containing various microstructures such as prior austenite, martensite and ferritic grain boundaries [8]. While the formation of martensite can be induced if the steel is austenitized and then cooled at a sufficiently high rate in order to avoid the formation of ferrite, pearlite and bainite [9].
Steels were processed by quenching and tempering in order to obtain the target mechanical strength [10]. In order for Q&T Steel to have high hardness performance, they need to have martensite structures. Martensite structure can be formed during quenching process heat treatment, and the hardness of a fully martensite structure is determined only by the carbon content of (low-carbon) steels and it is equal to the maximum hardness of steels [11]. The grain sizes are primarily dependent on the temperature and the time of quenching for the austenitized region. Finer grains can be obtained by heating at the lowest possible temperatures that still exceed the austenizing temperature. However, for the steel to be sufficiently hard, it is necessary to form a solid solution of carbon with the martensite structure. The diffusion speed increases as the heating temperature goes up. Therefore, the amount of solid solution increases as the heating temperature goes up. In addition, the heating temperature during quenching needs to take into account both the amount of solid solution and the grain refinement [12]. Refinement of microstructure in quenched and tempered martensitic steels is expected to improve both strength and toughness especially the latter [13].

This study focuses on developing a heat-treatment method can improve the hardness and impact energy absorbed using re-quenching in quenched hot rolled plate steel at a temperature of austenite.

In addition, re-quenching transforming the retained austenite failed to martensite structure. Because the start temperature of austenite grows with the most refined grain structure, and expected fine martensite structure can be obtained. Quenched steel needs to be treated are subjected to tempering in order to obtain ductility and residual can be reduced, and Quenched and Tempered Steel (Q&T Steel) can be obtained. The transformation temperature (Ar₃) is related to the chemical composition as shown in equation 1. Martensite start temperature (Mₛ) are statistically related to the chemical composition of low-alloy steels as shown in equation 2 [14 & 15].

\[
Ar₃ \left(°C\right) \sim 910 - (310C) - (80Mn) - (80Mo) - (55Ni) - (20Cu) - (15Cr) \\
\text{used in steel} 0.2\% - 0.8\% \text{carbon}
\]

\[
Ms \left(°C\right) = 561 - 474C - 33Mn - 17Ni - 17Cr - 21Mo
\]  

\[
M_F = 175 \degree C - 265 \degree C \text{ lower of } M_s
\]

The hardness depend on austenite temperature, and ductility depend on temper temperature (Tₜ). Tₜ must be lower than Mₖ to avoid decomposition of the martensite structure and reduce the residual stress. Industrially, to preserve as much of the strength of as-quenched martensite as possible, tempering is performed at low temperatures, between 150 °C and 200 °C [7]. After tempering the hardness profile becomes more homogeneous due to the tempering effect of the microstructure [16], because before tempering distribution of austenite grains was heterogeneous in the microstructure [17]. Quenching prevents the formation of ferrite or pearlite and allows the formation of bainite or martensite [18], and the impact toughness and fracture toughness increase significantly with increasing the quenching temperature, respectively [19]. While the parameters of heat treatment have a strong influence on hardness is tempering [20].

2. Material and Method
The material used is Hot Rolled Plate Steel (thick = 10 mm) produced by PT. Krakatau Steel (Persero) Cilegon, Banten, Indonesia.

Heat treatment used consist of conventional and proposed study based on Figure 1 and 2 for heat treatment. The procedure of the study showed in Figure 3. The method used is heating up to 850°C (maintained for 30 minutes and cooled by water) for fives specimen hot rolled plate steel and Q₈₅₀ Steel produced. Four Q₈₅₀ steel specimens were heated at 750°C, 800°C, and 850°C (maintained for 30 minutes). Five specimens (include Q₈₅₀ Steel) are tempered at 150°C (maintained for 30 minutes) and
Q_{850}+T Steel, Q_{850+750}+T Steel, Q_{850+800}+T Steel, and Q_{850+850}+T Steel. These specimens are heated using Nabertherm Furnace. Following step of experiment include: First set up hot rolled plate steel specimen 20 mm × 20 mm × 10 mm in size and tested using the spectrometer (by using Optical Emission Spectrometer Machines ARL type 3460) to obtain the chemical composition. Second set up specimen (Q_{850} steel, Q_{850+750} Steel, Q_{850+800} Steel, Q_{850+850} Steel, Q_{850}+T steel, Q_{850+750}+T Steel,

**Figure 1. Heating process [22]**

Q_{800+800}+T Steel, and Q_{850+850}+T Steel) machined in size 3 mm × 3 mm × 1 mm for metallograph and microhardness (in Vickers) observation using Nikon Epiphot Metallograph and ZWICK Type Zhu Machines respectively. The microstructures etched by using 97% alcohol + 3% HNO₃. Third set up the

**Figure 2. Heat treatment process were used in this study**
specimen above machined in size 10 mm × 10 mm × 55 m for Charpy Impact Energy using WOLPERT Type PW 30/15 Impact Tesing Machines [21].

3. Results and Discussion

Results of study are: chemical elements, metallographic, impact energy and micro Vickers hardness are shown in Table 1, Figure 4, 5 and 6 respectively.

Based on carbon content (= 0.2923%) that HRP Steel classified as heat-treatable steels [23]. The temperature of transformation Ar3 ≈ 665°C and martensite start Ms ≈ 357°C can be found by formula 1 - 3. Martensite finish temperature MF = 91°C - 182°C lower than Mf.

Table 1. Chemical compositions of HRP steel

| Element | C  | Cr  | Mn  | Mo  | Ni  | P  | S  | Si  |
|---------|----|-----|-----|-----|-----|----|----|-----|
| wt%     | 0.293 | 0.550 | 1.412 | 0.193 | 0.279 | 0.014 | 0.008 | 0.329 |

Figure 3. Flow chart for experiment procedure of this study

Figure 4. HRP Steel (288 VHN = 274 BHN)

Figure 5. Q850 Steel (530.3 VHN = 499 BHN)
Figure 4 shows the microstructure in HRP Steel. Structures dominated by ferrites, pearlitic, and little austenite austenites. Bright color indicates the austenites and small ferrites, and the dark color is pearlite structures. Elongated structures due to the rolling process when plate steel made in the factory. The elongated structure light and dark color producing uneven hardness of the specimen.

Figure 5 shows $Q_{900}$ Steel. The needle-like known martensite structures. Martensite structures produced by the transformation of austenite structures during the quenching process. There is small austenite not transform to martensite structures during quenching by the covered bubbles on the specimen. Bubbles covered causes heat transfer rate from the specimen to the water decreased, and the bubbles as insulators. Slow cooling cause the austenite transformation to martensite cannot fully. Figure 6 shows $Q_{850+750}$ Steel and the bright and dark colors is austenite and pearlite structure respectively. Figure 7 shows $Q_{850+800}$ Steel and coarser, and needle-like structure appears. There is austenite structure fail to transform into martensite. Figure 8 shows $Q_{850+850}$ Steel and the coarser structure than $Q_{850+800}$ Steel.

Figure 8. $Q_{850+850}$ Steel (540.75 VHN = 509 BHN) Figure 9. $Q_{850+800}$ Steel (530 VHN = 499 BHN)
Figure 12. Q_{850+850} & T Steel (509 BHN)

Figure 13. Hardness

Figure 14. Charpy impact

Figure 9 – 12 shows Q_{850+750} & T Steel, Q_{850+800} & T Steel, and Q_{850+850} & T Steel are tempered steel at 150°C. Tempered quenched steel reducing residual stress decreased and ductility increased.

Figure 13 shows the average hardness of HRP Steel, Q_{850} & T Steel, Q_{850+750} & T Steel, Q_{850+800} & T Steel and Q_{850+850} & T Steel. The highest hardness was obtained at Q_{850 + 800} & T Steel is 515 BHN.

Figure 14 shows the impact energy absorbed by specimen through the Charpy Impact Test. The highest impact energy absorbed was obtained in Q_{850 + 800} & T Steel is 44 Joule.

4. Conclusion

From the study has been done from the beginning to the end can be concluded as follows:

- The hardness and impact energy absorbed of conventional Q_{850} & T Steel specimen is 499 BHN and 42.2 Joule respectively.
- The highest hardness and impact energy absorbed of proposed Q_{850+800} & T Steel specimen is 515 BHN and 44 Joule respectively.
- The grain structures of proposed Q_{850+800} & T Steel specimen smaller than conventional Q_{850} & T Steel visually. Smaller grain structure have higher ductility than coarser one.

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References

[1] Reddy G, Madhusudhan, Mohandas T 1996 Ballistic performance of high-strength low-alloy steel weldments Journal of Materials Processing Technology 57 23-30

[2] Reddy, G Madhusudhan Reddy, Mohandas T, Papukutty 1999 Enhancement of ballistic capabilities of soft welds through hardfacing International Journal of Impact Engineering 22 775-791

[3] Magudeeswaran G, Balasubramanian V, Reddy, Reddy G, Madhusudhan 2008 Hydrogen induced cold cracking studies on armour grade high strength, quenched and tempered steel weldments, Internatio-nal Journal of Hydrogen Energy 33 1897 – 1908

[4] G Magudeeswaran, V Balasubramanian, G Madhusu-dhan Reddy 2009 Effect of Welding Consu-mables on Fatigue Performance of Shielded Metal Arc Welded High Strength, Q&T Steel Joints Materials Engineering and Performance 18

[5] M Balakrishnan, V Balasubramanian, G Madhusudhan Reddy 2013 Effect of hardfaced interlayer thickness on ballistic performance of armour steel welds Materials and Design 44 59–68

[6] Woei-Shyan Lee and Tzay-Tian Su 1999 Mechanical properties and microstructural features of AISI 4340 high-strength alloy steel under quenched and tempered conditions Journal of Materials Processing Technology 87 198–206

[7] Krauss, George 1999 Martensite in steel: strength and structure Materials Science and Engineering A273–275 40–57

[8] Chikara O, Kikuo M, Hirokazu N 2004 Improving Rolling Contact Fatigue Life of Bearing Steels Through Grain Refinement NTN Technical Review 71

[9] Silva, Eduardo P, Pedro M C L P, Marcelo A S 2004 On the micron -mechanical coupling in austenite–martensite phase transformation related to the quenching process International Journal of Solids and Structures 41 1139–1155

[10] A Di Schin, C Guarnaschelli 2009 Effect of microstructure on cleavage resistance of high-strength quenched and tempered steels Materials Letters 63 1968–1972

[11] Toshinobu N, Nobusato K 2012 Effect of quenching rate on hardness and microstructure of hot-stamped steel Journal of Alloys and Compounds

[12] K O Lee, S K Hong, Y K Kang, H J Yoon and S S Kangi 2009 Grain Refinement in Bearing Steels Using A Double Quenching Heat-Treatment Process International Journal of Automotive Technology 10 697–702

[13] M H Khani Sanij, S S Ghasemi Banadkouki, A R Mashreghi, M Moshrefifar 2012 The effect of single and double quenching and tempering heat treatments n the microstructure and mechanical properties of AISI 4140 steel Materials and Design 42 339–346

[14] Sampath 2007 How to Choose Electrodes for Joining High - Strength Steels Welding Journal 26 – 28

[15] Messler, Robert W, Jr 2004 Princile of Welding (Processes, Physics, Chemistry, and Metallurgy) WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 547

[16] G Luxenburger, M Bockelmann, P Wolf, F Hanus, R Cawelius, J Buchholz 2004 High strength quenched and tempered (Q&T) steels for pressure vessels International Journal of Pressure Vessels and Piping 81 159–171

[17] S A Etesami, M H Enayati, Ali Ghatei Kalashami Austenite formation and mechanical properties of a cold rolled ferrite martensite structure during intercritical annealing Materials Science & Engineering 682 296–303

[18] Vivek T, Adarsh P, Zuber M, Chandrashekhari I. Bha 2014 Prediction of quench severity of various quench media based on hardness and microstructure studies International Journal of Innovative Research in Advanced Engineering 1 2278-2311

[19] Shao-lei L, Yi-long L, YunJiang, YuLiang, Ming Yang, Yan-liang 2016 Effect of quenching temperature on martensite multi-level microstructures and properties of strength and toughness in 20CrNi2Mo steel Materials Science & Engineering A676 38–47
[20] Yurianto, Pratikto, Rudy S, Wahyono and A P Bayuseno 2018 Quenching and tempering parameter on Indonesian hot rolled plate steel for armour steel 05001 MATEC Web of Conferences 204

[21] _____, ASTM E23 – 07a, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, (2007).

[22] Callister, William D Jr 2007 Materials Science and Engineering (An Introduction), John Wiley & Son, Inc.160

[23] Jefferson T B 1972 Metals and How to Weld Them, Welding Engineer Publication, Inc 111 – 113; 163 –164