The effect of heat treatment on the hardness and impact properties of medium carbon steel

Noor Mazni Ismail, Nurul Aida Amir Khatif, Mohamad Aliff Kamil Awang Kecik, Mohd Ali Hanafiah Shaharudin
Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Malaysia
E-mail: drmazni@ump.edu.my

Abstract. This paper covers the effect of heat treatment on the mechanical properties of medium carbon steel. The main objective of this project is to investigate the hardness and impact properties of medium carbon steel treated at different heat treatment processes. Three types of heat treatment were performed in this project which are annealing, quenching and tempering. During annealing process, the specimens were heated at 900°C and soaked for 1 hour in the furnace. The specimens were then quenched in a medium of water and open air, respectively. The treatment was followed by tempering processes which were done at 300°C, 450°C, and 600°C with a soaking time of 2 hours for each temperature. After the heat treatment process completed, Rockwell hardness test and Charpy impact test were performed. The results collected from the Rockwell hardness test and Charpy impact test on the samples after quenching and tempering were compared and analysed. The fractured surfaces of the samples were also examined by using Scanning Electron Microscope. It was observed that different heat treatment processes gave different hardness value and impact property to the steel. The specimen with the highest hardness was found in samples quenched in water. Besides, the microstructure obtained after tempering provided a good combination of mechanical properties due to the process reduce brittleness by increasing ductility and toughness.

1. Introduction
Heat treatment is a process that involves a combination of time-controlled heating and cooling operations of metal without changing the product shape that will produce desires mechanical properties and to observe the microstructure after heat treatment (D.A.Fadare, 2011). Heat treatment is used to improve the mechanical properties of the metal alloys. Basically, the product performance will improve when the strength of material increased (Ashih Bhatjea, 2012). It can be divided into three main processes namely annealing, quenching and tempering. In general, the procedure of heat treatment process consists of three stages. First stage is heating the material. Second, hold the temperature for a period of time and third, cool down the metal to room temperature. The treatment of medium carbon steel with heat can significantly changes the mechanical properties, such as ductility, hardness and strength. Heat treatment of steel slightly affects other properties such as its ability to conduct heat and electricity as well. A variety of methods exist for treating steel with heat. The carbon and manganese content in medium carbon steel make quenching and tempering the most common method of heat treatment for this type of steel. This process generally involves repeatedly heating the steel to less than 1,333°F (about 723°C), and cooling it rapidly by quenching it in a liquid
such as oil or water. The temperature and time of this process allows the manufacturer to precisely control the final properties of the steel.

Meanwhile, the definition of medium carbon steel based on Serope Kalpakjian book (Serope Kalpakjian, 6th Edition, 2010) and Rajan et al. (1988) basically refers to iron alloy with more than 0.25% to 0.65% of carbon. This type of steel provides a good balance between strength and ductility, and it is common in many types of steel parts. Iron consists of a crystal lattice of iron atoms that allow the atoms to slide past each other, making pure iron relatively soft. The carbon in steel reduces this tendency, making medium carbon steel harder than iron. Additional elements such as chromium, manganese, tungsten and vanadium can also act as hardening agents in steel. The precise proportion of these elements determines the specific properties of the steel. Additional carbon makes the steel harder but also more brittle, so manufacturing carbon steel requires a balance between hardness and ductility. The most common uses of medium carbon steel are in heavy machinery, such as axles, crankshafts, couplings and gears. Steel with carbon content between 0.4 and 0.6 percent is commonly used in the railroad industry to make axles, rails and wheels.

2. Materials and methodology
The chemical composition of medium carbon steel samples used for this investigation is given in Table 1.

| Element         | Content (%) |
|-----------------|-------------|
| Carbon, C       | 0.34        |
| Iron, Fe        | 0.60        |
| Manganese, Mn   | 0.44        |
| Phosphorous, P  | 0.21        |
| Sulfur, S       | 0.03        |
| Chromium, Cr    | 4.78        |
| Copper, Cu      | 0.08        |
| Nickel, Ni      | 0.15        |
| Molybdenum, Mo  | 1.61        |
| Vanadium, V     | 0.51        |

This project started by preparation of specimen of medium carbon steel about 14 samples. The sample was cut with dimension 55mm x 10mm x 10mm that follow standard dimension for Charpy impact test ASTM E23. Then, it will divide into two parts which are heat-treated and non-heat treated. For non-heat treated only two sample of medium carbon steel is used to observe the microstructure, perform the hardness test and impact test.

The method will continue for heat-treated experiment. For this part the specimen is prepared about 12 samples for heat treatment. The sample will undergoes heat treatment process which are annealing, quenching, and tempering. After this several process the samples were undergoing sample testing process. The samples will undergo microstructure analysis using metallurgical microscope. Then, Rockwell hardness test by referring to American Society for Testing and Materials (ASTM E18)
standard. Moreover, the samples also undergoes Charpy impact test follow (ASTM E23) and the fracture surface is observe using camera. After get the result, the project was concluded by comparing the data and the result was analysed.

3. Result and discussion

3.1 Microstructure

The microstructure provided by the manufacture is in the soft annealed condition. This material is easy to machine with cutting tools and the microstructure suitable for hardening. The soft annealed microstructure contain of soft matrix in which carbide are embedded. In medium carbon steel this carbide are iron carbides. Higher carbide content means higher carbon compound and therefore higher resistance to wear. This investigate medium carbon steel were ground, polished, and etching using nital etching solution to observe the microstructure for non-heat treated. The specimen was observed and the microstructure for non-heat-treated showed a combination of ferrite and pearlite as shown in Figure 1.

Pearlite is usually a lamellar combination of ferrite and cementite (Fe₃C). It is formed by eutectoid decomposition of austenite upon cooling by diffusion of C atoms, when ferrite and cementite grow contiguously, C precipitating as Fe₃C between laths of ferrite at the advancing interface, leaving parallel laths of Fe and Fe₃C which is pearlite.

![Figure 1. Microstructure of Non-heat Treated Steel (10X)](image)

Ferrite forms by the slow cooling of austenite, with the associated rejection of carbon by diffusion. Ferrite has a good strength and moderate ductility. These ferrites are ferromagnetic. They are not heat treatable and have excellent corrosion resistance, moderate formability, and relatively inexpensive.

Figure 2 represents the microstructure of medium carbon steel after quench in water. Before quench in water the specimen were anneal with 900°C for 1 hour and at that time microstructure become austenite. Annealing means changes of crystal structure from ferrite to austenite. From that figure it shows the formation of martensite. When the specimen of medium carbon steel are rapidly quenched from austenite temperature to room temperature in medium of water, the austenite will decompose into a mixture of some medium carbon martensite and fewer pearlite but if the specimen is not quenched sufficiently rapidly, the carbon atom will allow the reforming of ferrite p, pearlite or bainite from austenite. At this stage, the microstructure is hard; hence increase in hardness and tensile strength but reduction in ductility of the material.
Besides that, martensite hardness depends on the carbon content of the steel. This is because the higher carbon content, the higher the hardness.

\[ \text{Figure 2: Microstructure of Hardened Medium Carbon Steel (10X)} \]

However, martensite is too brittle and cannot be used directly after quench for any application. Martensite brittleness can be reduced by applying a post-heat treatment known as -tempering. Tempering is necessary to increase ductility and toughness of martensite. Some hardness and strength is lost after tempering treatment. The microstructure of medium carbon steel become tempered martensite. The microstructure of tempered at 600 °C is shown in Figure 3. The microstructure shows the formation of recrystallized ferrite grains with graphite flakes site in martensite matrix. That’s mean the tempered martensite consist of carbide precipitated. This particle can increase hardness during high tempering temperature.

\[ \text{Figure 3: Microstructure of Tempered Medium Carbon Steel (10X)} \]

Therefore, by increase in tempering temperature, the hard constituent of martensite is being transformed to comparatively soft troos tite or also called as tempered martensite that have better combination of mechanical properties.
3.2 Hardness

Hardness is refers to the ability of metal to resist permanent indentation, usually by indentation or known as penetration when in contact with an indenter under load. (ASM Handbook, 2000). In addition, the hardness is the resistance to scratching, cutting or abrasion. Hardness is one of the mechanical properties of metal which is when a load is applied it will gives the ability to resist being permanently, and deform. The higher the metal hardness will cause the higher resistance need to deform.

Table 2: Result of Hardness after Quenching with Hardness after Tempering

| CONDITION       | HARDNESS (HRC) |     |
|-----------------|---------------|-----|
|                 | Water         | Air |
| After Quenching | 11.85         | 8.95|
| After Tempering | 9.01          | 8.77|

Figure 4: Graph of Comparison Result for Hardness Value vs Different Heat Treatment

The graph in Figure 4 plotted the hardness (HRC) against heat treatment process. This bar graph shows the result from Table 2. As can be seen from the graph, the hardness of medium carbon steel after quenching is higher than the hardness of sample after tempering. This happen because quench hardening is a mechanical process in which steel are strengthened and hardened. That’s mean the quenching is the process to improve the hardness while tempering is the treatment to improve the
toughness and ductility. Therefore during tempering the hardness will decrease and the toughness
improve and materials become more ductile.

Besides that, from the result obtain it is concluded that the hardness of medium carbon steel after
quench in water is higher than quench by open air. This is because water is fast quenching rate and the
best quenching media than air and oil to produce the excellent tool performance. Water is one of the
most efficient quenching media where maximum hardness is acquired. However, there is a small
chance that it may cause distortion and tiny cracking.

The variation of hardness of medium carbon steel at various tempering temperatures in the range of
300°C to 600°C is shown in Table 3.

| Tempering temperature, °C | Hardness, HRC (Water) | Hardness, HRC (Air) |
|---------------------------|-----------------------|--------------------|
| 300                       | 10.08                 | 9.72               |
| 450                       | 9.14                  | 8.52               |
| 600                       | 7.80                  | 8.06               |

Table 3: Result of Hardness with Increasing Tempering Temperature

Figure 5: Graph of Hardness, HRC vs Tempering Temperature, °C

The graph from Figure 5 shows that hardness decrease as tempering temperature increase for both
different quenching media. This is because by tempering the process of quenched medium carbon steel
could be modified to decrease hardness and increase ductility and impact strength gradually. Besides
that, this happen also due to transformation of martensite to tempered martensite.

3.3 Impact Test
After heat treatment with different tempering temperature this 14 specimen consist of heat treated and
non-heat-treated will undergoes Charpy impact test. The fracture surface obtain is shown as in Figure
7 using camera.
Figure 6: Specimen after Impact Test

Figure 7: Fracture Surface After Impact

Table 4: Result of Impact Test

| TEMPERING TEMPERATURE (°C) | ABSORBED ENERGY (J) |
|----------------------------|---------------------|
|                            | WATER   | AIR    |
| 300                        | 10.8    | 11.9   |
| 450                        | 11.2    | 13.5   |
| 600                        | 13.3    | 19.5   |
The mechanical properties of tempering samples showed that the toughness in J is increased as tempering temperature increase. When tempering temperature increase, the absorbed energy also increases. Therefore the specimen after tempering provides a good combination of mechanical properties because these processes reduce brittleness by increase ductility and toughness. At the same time reduce hardness when tempering temperature increase.

**4. Conclusion**

From this study, it can be concluded that the experimental study successfully the first objective in this study, which is to perform heat treatment on medium carbon steel. The first objective was needed to fulfil the second and third objectives of this study.

According to research study of the microstructure of medium carbon steel by using metallurgical microscope, the result shows that the annealed specimen with mainly ferrite structure gave the lowest hardness value but highest ductility and toughness value. However, after quenching the microstructure shows the formation of martensite. This martensite shows that the hardness increase and specimen is too brittle and not suitable for any application. Then, tempering is necessary to increase ductility and toughness of martensite. After tempering at high temperature 600°C the microstructure changed from martensite to tempered martensite and also found the formation of recrystallized ferrite grains. Then, according to the result, the hardness value after quenching in water which is 11.85 HRC shows the higher hardness than cooling by open air which is 8.95 HRC. This is due to the water is the best media for quenching treatment because it is cooled rapidly. However, the hardness is changed when specimen undergoes tempering process at different temperature. The hardness after tempering is decreased when tempering temperature increased. Through this tempering the hardness of medium carbon steel begins to drop then the toughness of a material increase as the absorbed energy increase.

Lastly the objective to investigate the impact toughness of medium carbon steel also achieved. Based on the result obtained, the toughness of steel increase as the absorbed energy increases when tempering temperature increase. This result shows that the microstructure obtained after tempering provides a good combination of mechanical properties because this process reduce brittleness by increase ductility and toughness and at the same time reduces hardness when temperature increase.
5. References

[1] Ashish Bhateja, Aditya Varma, Ashish Kashyap, Bhupinder Singh. 2012. “Study of the effect on the hardness of three sample grades of tool steel after heat treatment process”, *International Journal of Engineering And Science (IJES)*, Volume 1, Issue 2, pages 253-259.

[2] Alawode, A.J., 2002, Effects of cold work and stress relief annealing cycle on the mechanical properties and residual stresses of cold-drawn mild steel rod. M. Eng. Thesis, Mechanical Engineering Department, University of Ilorin, Nigeria.

[3] A. N. Isfahany, H. Saghafian and G. Borhani, “The effect of heat treatment on mechanical properties and corrosion behaviour of AISI420 Martensitic Stainless Steel,” *Journal of Alloys and Compounds*, Vol. 509, No. 9, 2011.

[4] Adnan, Calik 2009. Effect of cooling rate on hardness and microstructure of AISI 1020, AISI 1040 and AISI 1060 steels. *Int J of Physics Sciences*, vol. 4(9), pp. 514 – 518.

[5] B.S.Motagi, Ramesh Bhosle 2012, “Effect of heat treatment on microstructure and mechanical properties of medium carbon Steel”. *International Journal of Engineering Research and Development*, Volume 2, Issue 1, July.

[6] D.A.Fadare, T.G.Fadara, O.Y.Akanbi, 2011 Effect of heat treatment on mechanical properties and microstructure of NST 37-2 Steel, *Journal of Minerals & Materials Characterization & Engineering*, Vol. 10, No.3, pp.299-308.

[7] Eric O., Sidjanin L., Miskovic Z. I 2004 Microstructure and toughness of cu- ni- mo austempered ductile iron; materials letters, Volume 58, Pages 2707 – 2711.

[8] E. F. Strobel, N. A. Mariano, K. Strobel and M. F. Dionízio, 2012 “Effect of the heat treatment in the resistance corrosion of a martensitic stainless steel CA6NM,” 2nd Edition, *Mercosur Congress on Chemical Engineering*.

[9] F. M. F. Al-Quran and H. I. Al-Itawi, 2010 “Effects of the heat treatment on corrosion resistance and micro hardness of alloy steel,” *European Journal of Scientific Research*, Vol. 39, No. 2.

[10] Harpreet Singh, Er.B.S.Ubhi, Er. Harvinder Lal. 2013”Improvement in the corrosion rate and mechanical properties of low carbon steel through deep cryogenic treatment”, *International Journal of Scientific & Technology Research* Volume 2.