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Effect of austenitizing and tempering on impact resistance of a hot rolled high strength steel

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Abstract

The aim of this study is to investigate the effect of heat treatments on the impact properties of hot rolled high strength steel and describes the effect of tempering temperature and quenching media on the microstructure, hardness, and impact resistance of plates. In the present study a high strength steel was austenitized at 900 °C with different quenching medium and followed by tempering at 300 °C, 500 °C. After thermal treatments, the values of Charpy impact resistance, hardness, and microscopic structure were evaluated from mechanical and metallographic analysis of metals respectively. The change of mechanical properties and microstructure of the metal with the existence of heat treatment with the ballistic performance of high-strength steel. Experimental results showed that tempering at 500 °C for 2 hours after water quenching medium it provides the best mechanical properties in conjunct on with an improved in microstructure.

Keywords: Hot rolled, High strength steel, Impact resistance.

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1. Introduction

Metals as well as alloys, composites, polymers and ceramics can be used as armor materials in structural protection technology. Concepts such as hardness, strength and impact energy are the main and most important characteristics of the ballistic performance of certain materials [1].

Amongst all materials, ultra-high strength steels are the most extensively used metallic armor today. They have a great association between high strength, high toughness and excellent hardness, weldability and heat treatment, which makes them a favorite in ballistic applications [2].

For a long time, this type of steel has been used as an armor application due to its high strength, excellent toughness and reasonable cost [3]. This resulted in increased search for different treatment methods such as heat treatments, cold rolling, etc. to increase HSS strength, hardness and toughness, thus helping to reduce armor weight and cost. Previous studies have well discussed the effect of heat treatment on improving the mechanical properties of metals [4 - 7].

The armor weight on combat vehicles has always been restricted due to its weight, which with increasing threat levels has become a real and serious problem. Therefore, armor materials that provide greater ballistic protection with a slight increase in weight are being researched and developed [8].

In general, quenching and tempering is an effective method for the production of high-strength steel reinforcement (HSS), with an increased impact toughness of all structures resulting from heat treatment, the forms of the martensitic phase at the highest level of strength in steel. However, due to the great internal stresses associated with the martensitic transformation, the martensitic phase is rarely used in an untampered state. Tempering treatment after quenching increases both ductility and toughness [9].

In recent times, defense industries have been trying to discover and develop materials with excellent ballistic performance under any specific threat [10,11]. The hardness property is an important and major feature of the materials used in the armor field [12-14]. Sangoy and Meunier [15] reported that high hardness of given armor steel directly determines the ballistic performance.

Many studies on the impact resistance of the steel revealed that relationship exists between impact energy of the steel and ballistic performance [16,17]. In addition, toughness is another important property of armored materials under a dynamic attack of projectiles with high kinetic energy. It is generally considered that high-strength armor steel will be very useful to withstand ballistic impacts without breaking down [18]. The current study is trying to find the optimal heat treatment conditions that produce better impact resistance with high ballistic performance for a hot rolled high strength steel.

2. Experimental Procedure

2.1. Materials

The main alloying element of received hot rolled high strength steels in the Table 1. Sixteen samples in the form rectangular cross section area with dimensions of 6.4 cm length, 1.2 cm width and 0.4 cm thick. Using cutting tools to make hardness, microstructure and impact samples. the steel samples which were heat treated. The rough grinding process was done with zero grinding paper. After rough grinding samples was checked either its or thickness and surfaces are flat, then samples were placed over anvil and adjust anvil. A steel hardened ball of 10 mm diameter is used in Brinell hardness test according to ASTM E10. The applied load 3000 kg for 10 seconds, removed load an impression has been made. The diameter of impression was measured with low magnification of microscope.

Table 1 The chemical composition of the experimental steel (Wt. %)

C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Ai**	**Co**	**Cu**
0.11	0.84	1.68	< 0.0030	0.0025	0.022	0.0058	< 0.0080	0.039	< 0.0085	0.0077
Ti	**V**	**W**	**Pb**	**Sn**	**Mg**	**As**	**Zr**	**B**	**Nb**	**Fe %**
0.043	0.0049	0.045	0.026	0.012	< 0.0015	0.095	< 0.0030	0.0041	< 0.0050	97.1

2.2. Heat treatment and mechanical testing

Hardening involves heating of steel to 900 °C, keep it for one hour at a suitable temperature until all perlite is converted to austenite, then quickly extinguish it in water or oil. The temperature at which the austenitizing occurs depends on the percentage of carbon in the steel used according's to ASM Handbook, Volume 4A: Steel Heat Treating Fundamentals and Processes [19]. The heating time should be increased to ensure full metal conversion to austenite and rapid cooling to ensure certain properties of materials are obtained.

16 Samples were prepared from steel and put it in the muffle at 900 °C temperature and for an hour (all samples), then the samples furnace quenched in water or oil, 8 samples quenched in water and 8 samples quenched in oil, then the samples were prepared to tempering.

The 16 samples put in the furnace, 8 samples at 500 °C, 4 of them at 1 hour and the other at 2 hours then put other 8 samples in the furnace at 300 °C, 4 samples at 1 hour and the other samples soaked at 2 hour, then the samples were removed from the furnace and then they are left them to cool in the air, then tested by Brinel Hardness (BH), Charpy impact test and the microscopic examination to determine the values of hardness, impact resistance and microstructure after the normalizing process.

2.3. Metallographic Examinations

The samples taken from the experimental HSS before the impact test prepared by metallographic examination. All samples were prepared by grinding with 250, 600, 1000 and 1200 µm emery paper respectively, then, the ground surface was polished with 3 µm diamond, etching was carried out with nital (3 % of HNO_3) to characterize the microstructure.

Samples that were prepared were examined using electron microscopy (SEM) - Examination of S5O, SEM, Japan-made - for fixing the etched surface Microscopic structure features. The Energy dispersive spectroscopy (EDS) attached to SEM to evaluate the chemical composition in the microstructure.

3. Results and Discussion

3.1. Hardness

The hardness of the material was evaluated as a function of heat treatment. The results are presented in Table 2. For samples treated by oil quenching medium, the hardness increases continuously with decreasing tempering temperature from 181.67 BHN at 500 °C to 275.66 BHN at 300 °C for the same tempering time (2 hours), while the hardness increases with decreasing tempering time from 181.67 BHN at 2 hours to 196.00 BHN at 1 hour for the same tempering temperature (500 °C).

The samples which treated by water quenching media, the value of hardness decrease when decreasing the tempering time as shown in Table 2, from 417.67 BHN at 2 hours to 390.00 BHN at 1 hour for the same tempering temperature 300 °C, while at tempering temperature 500 °C, the value of hardness decrease when increasing tempering time from 1 hour to 2 hours as shown in Table 2 from 265.00 to 236.67. The best hardness value is 417.67 BHN at 300 °C for 2 hours after water quenching. The HSS hardness is known to depend heavily on the martensitic phase present in the microscopic structure. The highest hardness in HSS corresponded with high carbon content in the martensitic phase. When austenitizing temperature increases, the amount of dissolved carbon in the austenite solution increased, which resulted in a higher carbon content of martensitic phase after quenching. The higher carbon content of martensitic phase, the higher the hardness of martensitic phase [20]. However, after quenching, the martensite phase appears in microstructure, this martensite phase is characterized by high hardness and brittleness, and therefore not suitable for engineering applications. So mechanical properties including ductility and toughness are improved by conducting a tempering treatment, as the microstructure changes from martensite phase to tempered martensite phase with the best mechanical properties and engineered acceptance in applications.

Table 2 Hardness of a hot rolled high strength steel for various conditions.

Type of heat treatments	**BHN**
Austenization 900 °C, 1h, oil quenching, tempering 500 °C, 2h	181.67
Austenization 900 °C, 1h, water quenching, tempering 500 °C, 2h	236.67
Austenization 900 °C, 1h, oil quenching, tempering 500 °C, 1h	196.00
Austenization 900 °C, 1h, water quenching, tempering 500 °C, 1h	265.00
Austenization 900 °C, 1h, oil quenching, tempering 300 °C, 2h	275.66
Austenization 900 °C, 1h, water quenching, tempering 300 °C, 2h	417.67
Austenization 900 °C, 1h, oil quenching, tempering 300 °C, 1h	287.50
Austenization 900 °C, 1h, water quenching, tempering 300 °C, 1h	390.00

3.2. Impact Testing

The Charpy impact energy is measured as function of heat treatment conditions. The impact energy appears quite sensitive to heat treatments conditions, Table 3, it can be noted that by varying heat treatment conditions, a range of impact energies can be achieved. Figure 2 shown the samples after quenched in water and in oil respectively. while Figure 2 Sample after impact test performed. Charpy energy gives excellent indication of the energy required to initiate a crack. The Charpy impact energy variation in the range of (40-90) J depending on tempering temperature and tempering time.

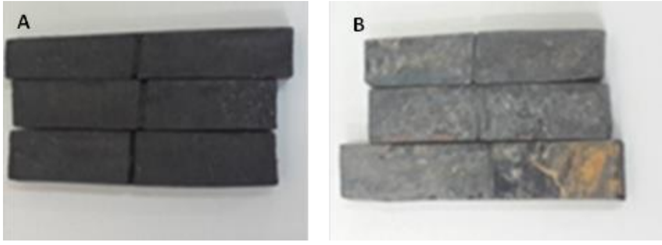

Fig. 1 pictures for 3 samples quenched (A) in water and (B) in oil.

Fig. 2 Sample after impact test performed.

With increasing in tempering temperature, impact energy increases for fixed tempering time. In the same manner with increasing tempering time, the Charpy impact energy increases when the quenching medium change from oil to water for the same tempering temperature. The mechanical properties of the tempered samples showed that the impact resistance increases with the increase in the time of the tempering treatment, as the absorbed energy increases as well. So, the sample after tempering treatment provides a good mixture of mechanical properties because these processes reduce the brittleness by increasing the ductility and toughness. At the same time, it leads to a decrease in hardness when the tempering time increases [21]. The best heat treatment conditions are 500 °C, 2 hours, after water quenching and the value of impact energy is 90 J.

Table 3 Impact test of a hot rolled high strength steel for various conditions.

NO.	Tempering Temperature (°C)	Quenching medium	Time (hour)	Impact Energy value (J)
1	500	Oil	1	65
2	500	Oil	2	85
3	500	Water	1	70
4	500	Water	2	90
5	300	Oil	1	40
6	300	Oil	2	53
7	300	Water	1	45
8	300	Water	2	81

3.3. Evaluation of Microstructure

From the micrographs it can be seen that increase in tempering temperature affects directly on the microstructure of the high strength steel (Fig. 3 A-E). All the microstructures exhibit lath martensitic structure. However, roughening of lathes with an increase in the tempering temperature can be clearly distinguished from the micrographs. This showed that tempering temperature improved the degree of tempering of the martensite, softening the matrix and decreased its resistance of plastic deformation. Enhancement of hardness and impact resistance by control of microstructure of HSS [22].

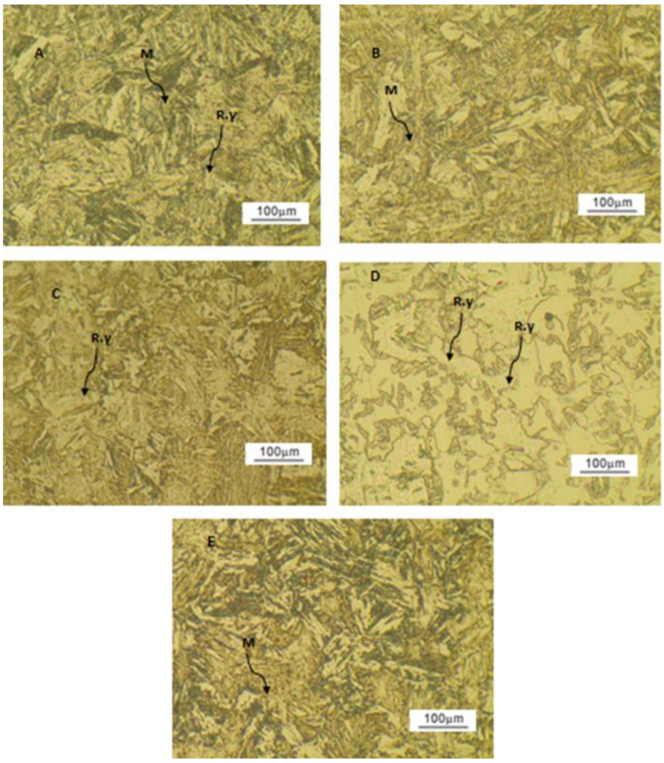

Fig. 3 Microstructures of untreated and heat-treated samples showing variation in microstructure of untreated sample and tempered samples with etching (a) untreated (b) tempered at 300 °C, water quenching, 2hr., (c) tempered at 300 °C, oil quenching, 2hr. (d) tempered at 500 °C, water quenching, 2hr. (E) tempered at 500 °C, oil quenching, 2hr. * M: Martensite , R. γ : Retained Austenite.

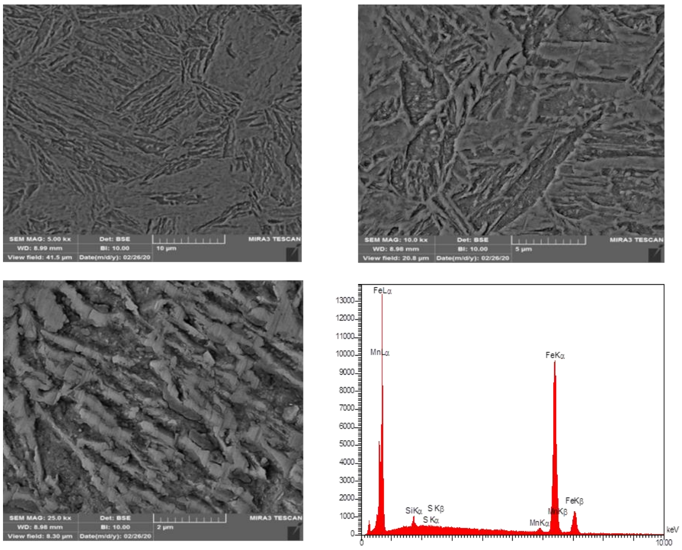

Fig.4 Scanning electron microscope images with EDS analysis of high strength steel without any heat treatment.

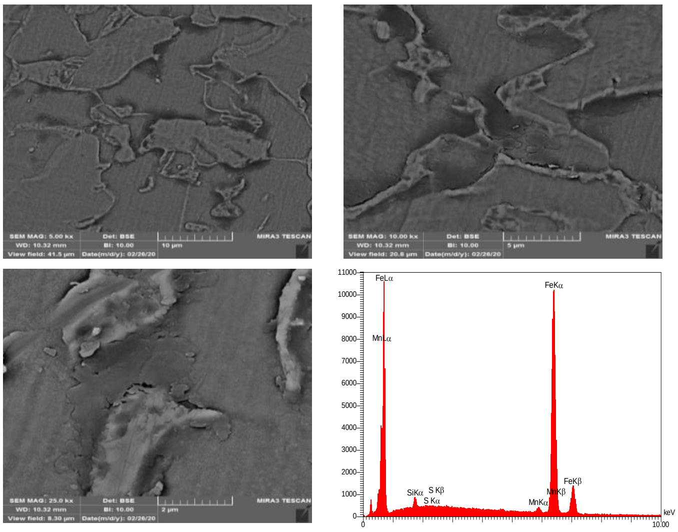

Fig. 5 Scanning electron microscope images with EDS analysis of high strength steel after austenization at 900 °C, 1h, water quenching, tempering 300 °C, 2h.

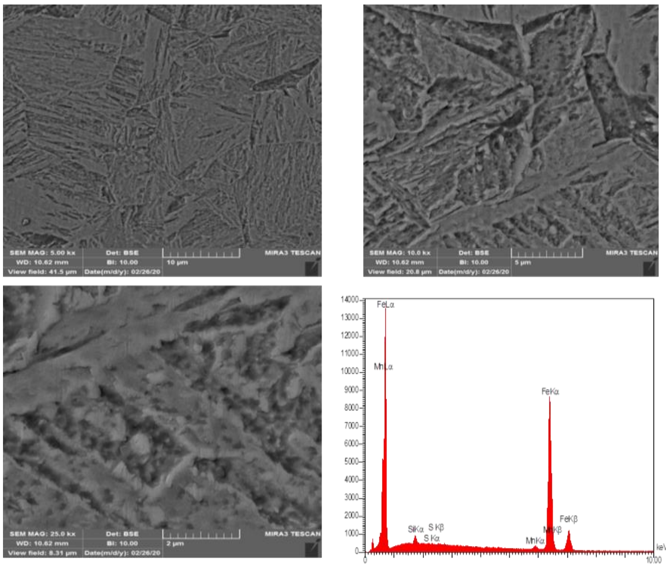

Fig. 6 Scanning electron microscope images with EDS analysis of high strength steel after austenization at 900 °C, 1h, water quenching, tempering 500 °C, 2h.

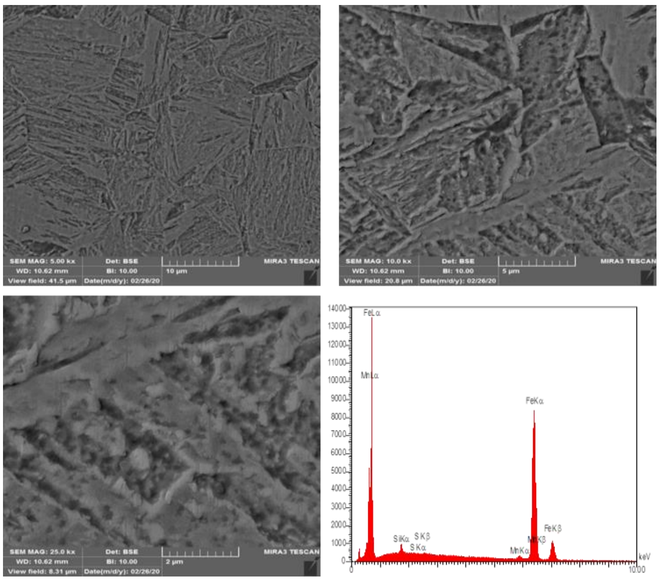

Fig. 7 Scanning electron microscope images with EDS analysis of high strength steel after austenization at 900 °C, 1h, oil quenching, tempering 300 °C, 2h.

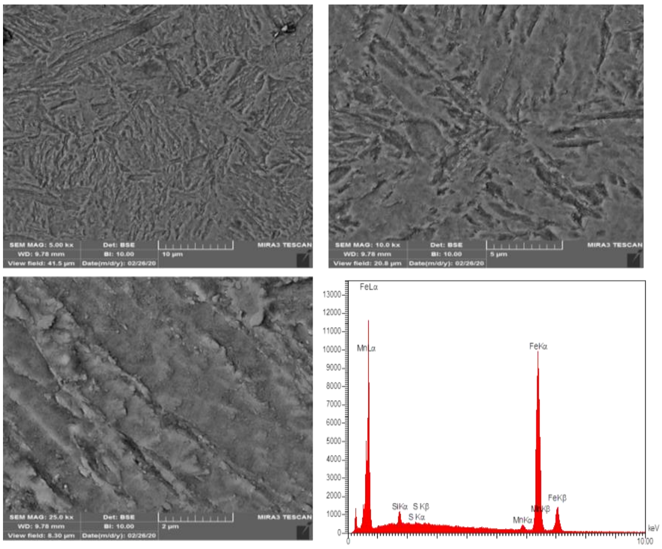

Fig. 8 Scanning electron microscope images with EDS analysis of high strength steel austenization at 900 °C, 1h, oil quenching, tempering 500 °C, 2h.

The hardness and Charpy impact energy are measured as a functions of tempering temperature, the mechanical properties after quenched condition are also evaluated for comparison. The impact energy of the HSS appears to be quite sensitive to the tempering temperature. It can be seen that by changing the tempering temperature, a wide range of impact energies and hardness can be obtained. The hardness appears to decrease with an increase in the tempering temperature.

The impact energy of the quenched sample increase when tempering temperature increase. An optimum combination of hardness, impact resistance is essential for excellent ballistic performance which can be achieved by controlling heat treatment (heating temperature, heating rate, holding time and cooling process).

The heat treatment (quenching and tempering) of HSS leads to refining the grains by converting the martensitic phase, which formed by quenching. Carbon atoms remain dissolved by force (trapped) in the solid solution and are not allowed to diffuse outside the crystal structure of austenite, because the cooling is rapid and over a short period which leads to the martensitic structure, which is a brittle structure (poor mechanical properties), therefore it requires conducting heat treatment (tempering). The main objective of this tempering is to reduce the internal stresses resulting from the hardening of the samples as well as improve the ductility and fracture toughness by converting the martensitic phase to the retained martensitic phase [23] as shown in Figs. 4-8, which leads to improving the hardness value by matching with impact strength. Mainly higher concentration of Mn which investigated by EDS were observed also as shown in Figs. 4-8 in retained austenite island. The retained austenite undergoes martensitic transformation it enhances the impact resistance of HSS [24].

Improve mechanical properties of HSS with homogenous structure resulted in good resistance to the crack propagation.

In the present HSS in these combinations of austenitizing at 900 °C with water quenching followed by 500 °C tempering for 2 hours, Charpy Impact energy improved to a higher value about 90 J.

4. Conclusions

1. The impact energy of the high strength steel appears to be quite sensitive to the tempering temperature.
2. The impact energy of the quenched sample increase when tempering temperature increase.
3. The hardness shows a decreasing trend with an increase in tempering temperature for the same austenitizing temperature.

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