Study the effect of cooling medium on the torsion resistance and hardness of medium carbon steel

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Abstract: In this paper, the effect of the cooling medium on the strength of torsion and hardness is discussed. The specimen used in this study is of medium carbon steel grade. The carbon percentage was determined as 0.55% C through the Arl spectroscopy instrument. The specimen dimension is 6 mm in diameter, gauge length is 76 mm and the total length is 144 mm. Different cooling mediums such as water, air, furnace atmosphere and oil were used to determine the effect of cooling speed on mechanical properties, specifically the torsion strength and hardness. In all treatments, the holding period was 30 minutes. From the results, cooling in the furnace atmosphere had the greatest impact on the resistance of the torsion of the carbon steel from other cooling methods. The non-heat-treated sample was the least resistant between the samples whereas the water-cooled sample had the highest in terms of their scratch resistance according to the results of the hardness device.

1. Introduction

Some researchers had investigate the effects of heat treatment on the mechanical properties of the medium carbon steel [1-3]. For instances, samples of medium carbon steel were tested after heated at 9000ºC and soaked for 60 minutes in a muffle furnace and quenched in oil, while other researchers studied the effect of tempering and austenizing on the tensile strength and the toughness of the fracture on the 300M steel. The results showed that an appropriate heat treatment could be used to improve toughness and tensile strength properties in the same process. There was 20 % of the practical examination leads to the non-loss of tensile property by increasing austenizing temperature from 871 to 982 and more [4]. In addition, some researchers investigated a practical work to study the effect of hardness and roughness on the torsion strength of low carbon steel (1020). The results showed that ductility decreases by increasing the roughness and hardness of the sample surface. On the other hand, shear strength increases with increasing surface hardness. The strength is found to increase with increasing hardness and roughness, and the reason for this is because of the high concentration of stresses due to the sharp surface shape [5].

The effect of the cooling mediums such as water, furnace and air on mechanical properties of different carbon steels was investigated. The steel was heated to 977ºC for four hours and the results showed that there was a clear difference in the microstructure of different carbon steels (0.2, 0.4 and 0.6% C) with the cooling medium. The hardness of the water-cooled specimen was increased for all various carbon steel [6]. Fadare et al. (2011) studied the effect of heat treatment on steel (37-2 NST) [7]. Different cooling mediums were used: water, air and furnace atmosphere. It was observed that there was increased hardness and yield, as well as tensile strength, with increased plastic deformation. On the other hand, the impact was reduced

due to the effect of hardening. The normalizing processes increase the tensile strength as well as hardness more in comparison to annealing processes. Relationship between tensile strength and hardness in sheet of steel containing martensite and ferrite phases was derived. The relationship could be used as an approximate value when applying a Vickers test on the samples, in which the accuracy of the results was approximately 10%. Moreover, researchers had also found a method to calculate yield and strain depending on Vickers hardness results and converted them to the Brinell hardness for more benefits to build a diagram between hardness and tensile strength for some metals [8]. Furthermore, some researchers also studied the effect of cooling medium (polymer polyethylene with change of concentration) on the mechanical properties (i.e. impact, tensile strength and hardness-HB) of low carbon steel [9]. The samples were quenched to 575°C and also 220°C for a half an hour, and it was found that polymer quenching has an excellent effect on the mechanical properties as a slow cooling. By increasing the polymer concentration, mechanical properties can be increased [9].

The effect of different types of heat treatments on mechanical properties such as Rockwell hardness and impact was also investigated. The cooling mediums used were water and air. The treatment of tempering and quenching were used in this research apart from hardening. SEM was used in the microstructure. The researchers found that the highest value of the hardness was from those water-cooled samples whereas the impact from those treated in a tempering method was the best [10]. Investigation on the effect of vanadium (0.28 and 0.15) % as an alloying element in medium carbon steel with different cooling mediums to test a mechanical property (hardness and microstructures) was conducted and the results showed that increased vanadium in steel caused an increasing of forms ferrite like acicular with low cooling. When cooling rate was above the critical temperature, the hardness also increased but with high cooling, vanadium had greater impact on the hardness [11]. A useful study by Verma and Kumar (2013) on medium carbon steel with 0.4% carbon to achieve properties like hardness, elongation and tensile test by a suitable heat treatment (tempering) about 900°C and cooled by water and then tempered on multi temp degrees. The results showed a decreasing value of hardness with high temperature of tempering, elongation would be increased with high temperature of tempering too. By increasing the time and temperature of tempering, strength of tensile have been lower value [12]. The tensile resistance under the influence of high heating and wear abrasive resistance of the medium carbon steel with tiny alloys was discussed in the published work of Gündüz and Acarer (2006). Heat treatment was used on specimens that were treated and without treatment. The researcher concluded that medium carbon tiny alloys have dynamic resistance of ageing strain due to the effect of dislocation and bonding atoms. Wear abrasive had also increased by heating up to 300°C [13]. In the meantime, mechanical properties like ductility and impact of the medium carbon steel bars under the influence of the heat treatment were discussed by Daramola et al. (2010). In this study, the samples were heated to 830°C until they reached the austenite zone. Using water as the quenching medium, the samples were heated again at 480°C. In this study a good impact resistance was found as well as ductility [14].

An investigation on heat treatments of 12CrMoV steel on its mechanical properties and also behavior of fracture was made whereby a sequence of heat treatment produced different results. Cooling mediums such as water, air and oil had an influence on some mechanical properties. It was noted that the impact been in a good state by oil quenching from 1050°C and then tempering on 700°C, while cooling by air from same temperatures produced a low impact resistance. An alpha phase was produced as a precipitate by heating temperature up to 1200°C [15]. Meanwhile, a carbon steel with less than 0.1% C was investigated by another study that focused on the effect of heat treatments on mechanical properties. After heating the samples, a tempering was applied in different temperatures with different cooling time. Strength and yield were lowest when the temperature of tempering was increased but the ductility property was enhanced [16]. Heating or cooling of a metal can change its micro structure, which causes variations in the mechanical and physical properties and affects the behavior of the metal in processing and operation. By using the heat treatment, metal properties can be improved for the application in engineering fields. There are different spare parts used for several different purposes collected from foreign countries in Spinning Mills available machine in Bangladesh. Spindle is an important part of spinning mills [17].

Previous research has examined mechanical properties such as tensile and bending and how they are affected after the heat treatment as well as cooling type. This current research is characterized by the study

of resistance to torsion and how to improve the different cooling types in addition to hardness. The aim of this study is to investigate the effect of cooling medium on some mechanical properties such as resistance to torsion and hardness of the medium carbon steel. The chemical test was carried out in advance and the dimensions of the samples used were: d = 6 mm, gauge length = 76 mm, total length = 144 mm. Multiple cooling modes (water, air, oil, and cooling inside the oven) were used in this research. Also, the number of cycles in the torsion test was calculated until the samples failed. The devices used in this study are torsion tester, electric oven and hardness test.

2. Theoretical calculations

2.1. Study of torsion
The forces in this test are inverse and parallel, and do not fall on the longitudinal axis of the body. Thus, a double beam will be generated by the twist on the longitudinal axis. The amount of the torque that is causing the torsion is equal to that of one of the opposing forces in the distance between them. If two equal forces are placed at the end of a rod and the other end is fixed, the determination of the duality arising from these two forces, which is equal to the sum of one of the two forces in the length of the distance between them and the effect of twisting the penis around its longitudinal axis. The value of torque and output of the effective weights is calculated from the following Eqn. 1, R = radius of pulley, m = weights and g = constant of acceleration. Furthermore, the shear stress and shear strain values are calculated by Eqn. 2 and Eqn. 3, respectively, with the twist of angle, $\emptyset$ is given in Eqn. 4. Last but not least, the value of modulus of rigidity is given by Eqn. 5.

$$T = m \, g \, R \tag{1}$$

$$\tau = \frac{16 \, T}{\pi d^2} \tag{2}$$

$$\gamma = \frac{r \emptyset}{L} \tag{3}$$

$$\emptyset = N \, d \, \frac{\pi}{180} \tag{4}$$

$$G = \frac{\tau}{\gamma} \tag{5}$$

2.2. Study of hardness (Brinell)
One of the methods or tests used to measure the hardness of a material is invented by the Swedish engineer John August Brinell, which is the test method of compressing a ball of hard steel or a ball made of tungsten carbide material on flat sample of the substance to be tested. In this test, the thickness of the sample shall be at least 10 times the depth of the trace (the mark left by the ball in the sample). After the diameter of the trace is set for the test, the hardness is calculated by using Eqn. 6 where BHN is the Brinell hardness number, P is the load in kg, D is the diameter of the ball used as a harder in millimeters and d is the diameter of the trace on the surface of the sample in millimeters.

$$BHN = \frac{2P}{\pi D \left(D - \sqrt{(D^2 - d^2)} \right)} \tag{6}$$

3. Experimental methodology
The aim of the experimental study that is presented in this work is to test the heat treatment. The temperature of the metal or alloy was raised to a certain temperature (850ºC). After that, the temperature was maintained
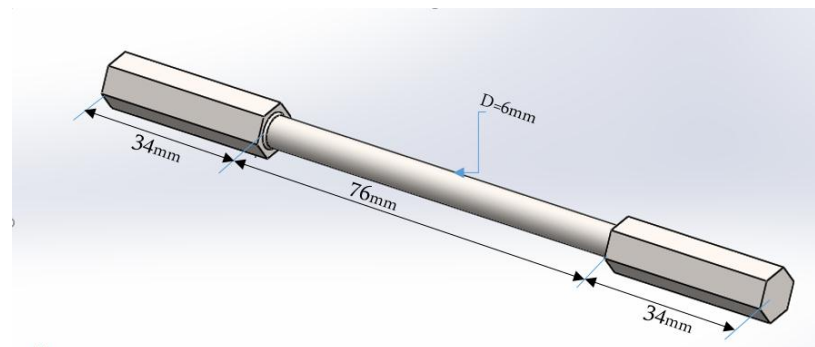
for an appropriate period of time. Next, the metal or alloy was cooled at a certain cooling rate. These three factors: the temperature at which the metal is heated, temperature holding time and cooling rate; have a significant impact on the properties to be achieved from the heat treatment. Therefore, these factors should be specified accurately. The hypo eutectoid steels are heated by 30°C above the upper critical temp (A3). The temperature is chosen according to the ratio of the carbon such that the ferrite phase is converted to an austenite.

3.1. Types of cooling medium
The cooling medium should have a relative advantage of absorbing the amount of heat in the first moments of the cooling process to ensure the Martensite phase. Then, a low cooling rate is necessary to prevent any deformation that may occur in the working area. The cooling media used were water, oil, salt, molten salt. Carbon steel with a carbon content of less than 0.25% is not acceptable for heat treatment. The higher the temperature of the cooling medium, the lower the cooling rate. To ensure this, large quantities of cooling medium should be used and the creation of spiral movements during the flipping of work pieces.

3.2. Metal selection
In this study, samples of medium carbon steel were used. Preparation of the steel samples (i.e. bar cutting and manufacturing process) was in accordance with ASTM standard specifications. The samples were in the following dimensions: diameter (6 mm), gauge length (76 mm), final length (144 mm); arranged for use in heat treatment. In general, as shown in Figure 1, the sample was a solid shaft with its end having a diameter greater than the center to avoid fracture at the end of the sample. After the chemical examination of the sample by using Arl spectrometer, the details obtained are presented in Table 1.

Figure 1. Specimen dimensions

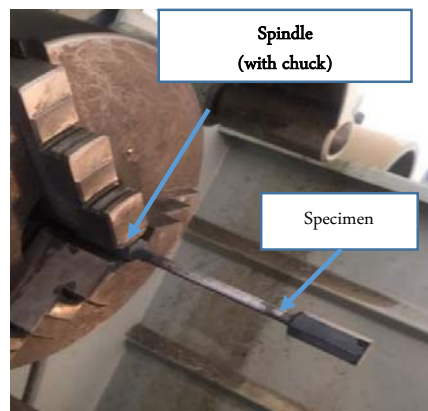**Table 1.** Chemical composition of medium carbon steel specimen

Element	C	Mn	Cr	Mo	Ni	Si	P
Weight fraction (W_t)	0.55%	0.81%	1.8%	1.04%	0.68%	0.21%	-------

The samples were cut into the specifications and required dimensions using the lathe machine as shown in Figure 2. A cylindrical rod is used with the lathe machine and with a good surface finish.
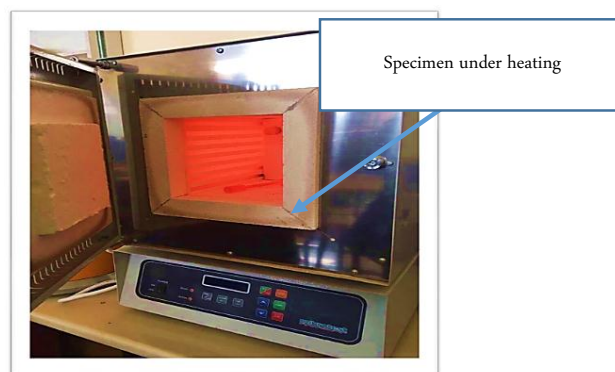
3.3. Heat treatment
The principle of full annealing includes heating to the austenite phase depending on the carbon percentage, removing all the residual stresses in steel, heating the samples above the upper critical temp (A3). The high temperature required in this work was approximately 850°C. The electric furnace was used to complete the
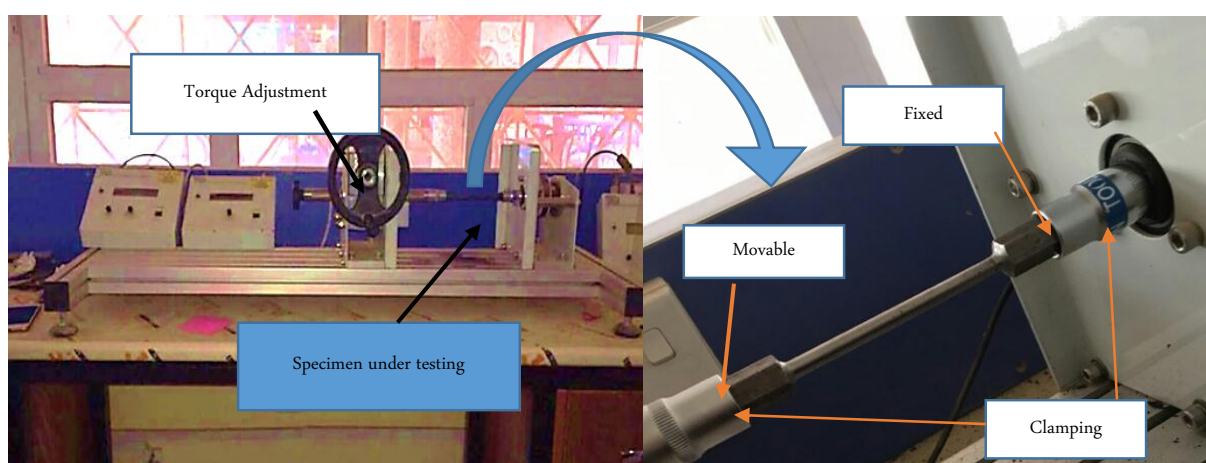
required heat treatments as shown in Figure 3. The specimen under testing by torsion and Brinell hardness device is shown in Figure 4 and Figure 5, respectively.

Figure 2. Specimen machining and finishing by turning device (lathe)

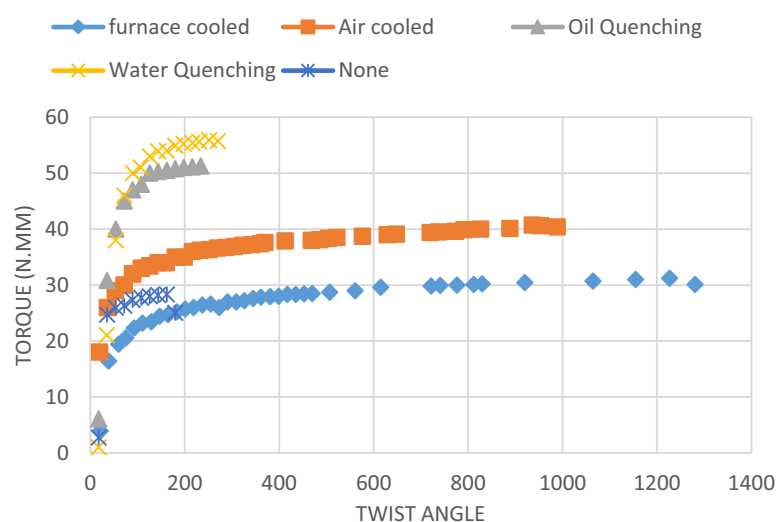**Figure 3.** The furnace used in the heat treatment process

Figure 4. The specimen under testing by torsion device
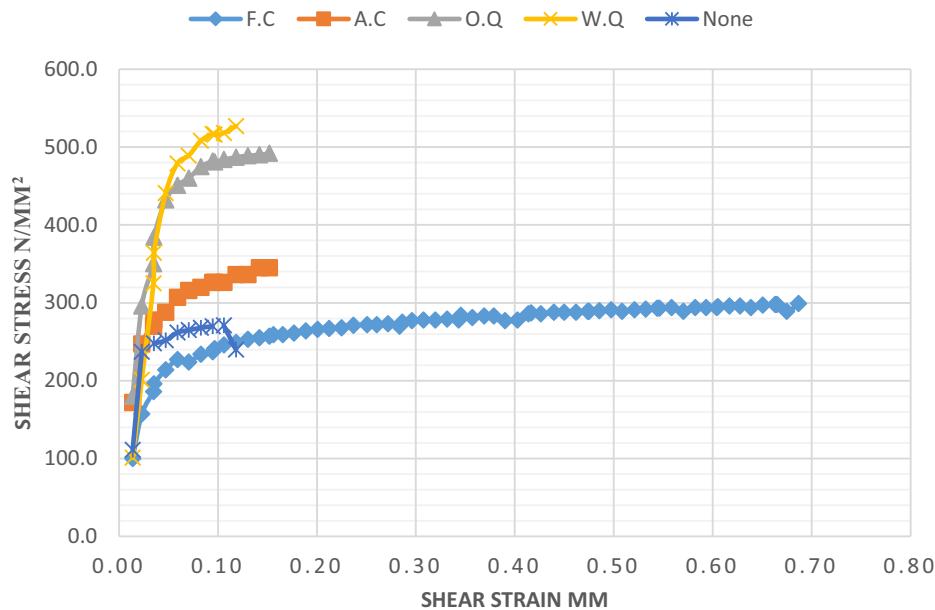
Figure 5. The Brinell hardness test

4. Results and Discussion

Through the results of the effect of torque with the twist angle (rotation angle) as well as the effect of the type of cooling medium, the following observations were made. As shown in Figure 6, the water-cooled sample has the highest torsion values compared to the other samples, reaching the highest value (55.9) with the angle of torsion. This is due to the ability of the alloy to withstand the rotational momentum due to the formation of the martensite phase, which is transformed from austenite and ferrite phases, which is formed by the high rate, which in turn prevents the rapid spread of atoms to form the fe3c cement. The oil-cooled sample will be the least thereafter because of the lower cooling rate if higher hardness can be obtained as the cooling is faster. The samples that have not been subjected to heat treatment are the lowest among the other samples and the heat treatment is up to (28.3). This in turn reflects the importance of our research in obtaining higher torsion resistance.

Figure 6. The relationship between torque and twist angle for different cooling mediums
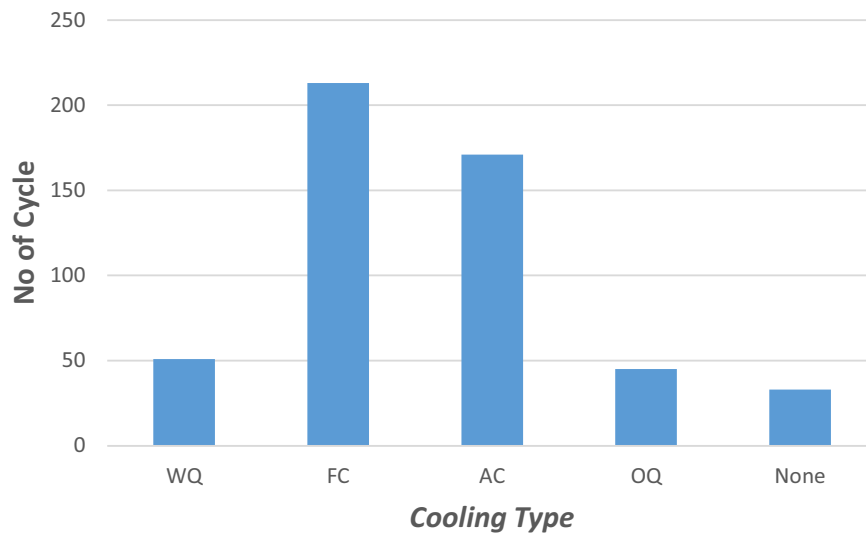
Furthermore, from Figure 7, the furnace cooling has maximum stress resistance proportional to the shear strength until failure due to the fine pearlite due to the slow cooling of the furnace. The sudden water cooling is of higher value for cut stress and early failure, with shear behavior and rapid failure is due to the fact that the behavior of the water-cooled sample is like that of fragile materials with the presence of the Martensite. The cooled samples of oil and air subsequently follow in terms of the least shear stress value, while the non-treated heat sample is the least of the rest.

Figure 7. Relation between shear stress and shear strain for different cooling mediums

Meanwhile, Figure 8 shows that the rotational torque resistance of the five samples is different since the chilled sample of the furnace has higher rotational torque resistance until the fracture occurs, thus increasing the number of cycles up to 213 cycles. This is due to the fact that slow cooling is successive phase of ferrite and cementite, combining the softness of the ferret and the hardness of the cementite and is in the form of a soft perlite phase. Air cooling is second best with the number of cycles 171 while the sample cooled with oil and non-heat treatment are the lowest. Table 2 shows the hardness of the samples with the water-cooled sample has a high hardness up to 1401 with the hardness of Brinell. The presence of the martensite phase, which is formed by rapid cooling gives the hardness and resistance to scratching.

Based on the readings of the device during the rotation of the lever, the reading of the torque and the torsion angle were taken during a complete cycle with the torque, which is equivalent to 1/6 cycles in the same sample. Table 3 tabulates the type of cooling methods used in the practical part after heating to the required crystallization temperature of 850°C, depending on "the carbon content of the sample which is approximately 0.55". The duration of the fixation (installation of the sample in temperature 850°C) is about half an hour depending on the thickness of the sample to ensure the occurrence of adequate crystallization process.

Figure 8. The relation between numbers of cycles and cooling type until specimens fail

Table 2. Tests results of some mechanical properties for tested samples

Conditions	HB (Kg. F/mm2)
Furnace cooled	205
Air cooled	456
Oil quenched	658
Water quenched	1401
As received	175

Table 3. Classification of samples

The samples symbol	Samples condition
FC	heated to (860ºC), for a 30 minutes and furnace cooled
AC	heated to (860ºC), for a 30 minutes and air cooled
WQ	heated to (860ºC), for a 30 minutes and water quenched
OQ	heated to (860ºC), for a 30 minutes and oil quenched
None	Samples without heat treatment (as received)

5. Conclusions and recommendations

The results from this research have demonstrated that the torsion resistance increases as the cooling rate increases, reaching its highest value when cooling with water. The test device used continues to measure the angle of torsion with a low cooling rate until the break occurs as with the cooling oven atmosphere. It is observed that the value of shear stress is the highest value with rapid cooling and the rate of hardness increases with increasing cooling rate.

For future study, it is recommended to use other methods of test such as fatigue and impact. In addition, other types of cooling mediums such as salty water and cold water can be used, as well as sand. Other types of heat treatments can also be used such as surface hardening.

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