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Effect of Heat Treatments and Carbon Content on the Damping Properties of Structural Steel

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ABSTRACT

Low- and medium-carbon structural steel components face random vibration and dynamic loads (like earthquakes) in many applications. Thus a modification to improve their mechanical properties, essentially damping properties, is required. The present study focuses on improving and developing these properties, significantly dampening properties, without losing the other mechanical properties. The specimens used in the present study are structural steel ribbed bar ISO 6935 subjected to heating temperatures of (850, 950, and 1050) ˚C, and cooling schemes of annealing, normalizing, sand, and quenching was selected. The damping properties of the specimens were measured experimentally with the area under the curve for the loading and unloading paths experienced from the tensile test. Considering the effect of different parameters on the damping properties, such as heat treatment temperatures, cooling rates, and carbon content, the results show that the damping properties in the annealing process at different temperatures have interesting damping properties, among other processes. Also, the highest damping energy for the annealing cooling scheme was attained at a heating temperature of 1050 ˚C, irrespective of the carbon content. Finally, better damping properties for the medium carbon content of (0.299%C) is achieved for all types of heat treatment process compared with a low carbon content of (0.188% C); and, in general, with increasing carbon content from medium to low, steel response to heat treatment increases and better damping properties are obtained.

Keywords: Damping properties, Heat treatment, Carbon content, Tensile test.

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تاثير المعاملات الحرارية والمحتوى الكاربوني على خواص الاخماد لفولاذ الهياكل

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الخلاصة

ان الاجزاء الميكانيكة المصنوعة من فولاذ الهياكل واطئ ومتوسط المحتوى الكاربوني تواجه احمال اهتزازية وديناميكية (مثل الهزات الارضية) في مختلف التطبيقات ولذلك تحتاج هذه الاجزاء الى تطوير خواصها الميكانيكية وبالذات خواص الاخماد. الدراسه الحالية تركز على تحسين وتطوير بعض من هذه الخواص وخصوصا خواص الاخماد مع عدم انقاص في الخواص الميكانيكيه الاخرى. العينات المستخدمة في الدراسه الحالية هي عينات من فولاذ الهياكل محزز و حسب معيار ISO (6935) وقد تم تعريض هذه العينات لمعاملات حرارية عند درجات تسخين (1050, 950, 850) درجه مئؤيه وطرق تبريد مختلفة مثل التلدين,التخمير,التغطية بالرمل والتقسيه. خواص الاخماد قيست بشكل تجريبي باستخدام المساحه تحت المنحني لحالة التحميل و الارجاع في اختبار الشد. مع الاخذ بنظر الاعتبار كل العوامل الموثره على خواص الاخماد بينت النتائج بان عمليه التلدين في جمع الاحوال تعطي افضل خواص الاخماد, وان افضل خواص اخماد في عملية التبريد بالتلدين تم الحصول عليها عند درجة حرارة تسخين 1050 درجه مئويه وبغض النظر عن المحتوى الكاربوني. واخيرا ولجميع انواع المعاملات الحرارية فقد تم الحصول على افضل خواص اخماد لمحتوى كاربوني عند (0.299%C) مقارنة بالمحتوى الكاربوني عند (0.188%C) وبصورة عامة مع ازدياد نسبه الكاربون في الفولاذ من نسبة واطئة الى نسبة متوسطة تزداد استجابة الفولاذ للمعاملات الحراريه و بالتالي يمكن تحسين وتطوير خواص الاخماد لفولاذ الهياكل.

الكلمات الرئيسية: خواص الاخماد, المعاملات الحرارية, المحتوى الكاربوني, اختبار الشد.

1. INTRODUCTION

Huge damages occur in automobiles, architectural industries, machines, housing, bridges, concert constructions, and aerospace due to mechanical vibration and dynamic loads. So light metallic materials with good mechanical properties and high damping capacity must be found. Several studies have been carried out on altering the molecular structure of materials to improve internal damping without any negative influences, such as durability and mechanical properties. The vibration damping of any structure can be gained by active damping that feels or repress vibrations in real-time or passive damping materials or structure that absorb the energy of the vibration. **(Tanaka et al., 2015).** The most common system to increase stiffness is called (outrigger); this system works by inserting viscous dampers between the outrigger and external columns. So this system is considered the best structural system to reduce the vibration due to forces such as earthquakes **(Hamid and Mukhtar, 2016)**. The vibration-damping structure components are chosen from many materials with high damping capacity, including many high-damping metallic materials **(Tanaka et al., 2015).**

Applying and improving damping properties of materials with greater damping capacity in engineering is an effective method to reduce vibration. Theoretically, decreasing the performance of vibration found out by internal friction of the material and the amount of damping capacity is always used to assess it. The ability of a material to convert mechanical vibration energy into thermal energy is referred to as its damping capacity. Heat treatment processes and alloying are used to increase the damping properties or damping capacity of the steel structure components with the balancing of some mechanical properties such as tensile strength or ductility, and also without changing the chemical composition of the materials **(Aaltio et al., 2008; Wu et al., 2010).**

In the development of the industry, the damage caused by vibration is increased. Steel structures and rotating machinery are the roots of many of these challenges. Several high-damping materials have been designed but are usually expensive, have restricted formability, are difficult to weld, and have low damping properties in applications. So to overcome the vibration problems, it is necessary to improve the damping capacity of the materials. Material or Hysteretic or Solid Damping may be defined such that when a material is deformed, energy is absorbed and dissipated by the material. The effect is due to friction between the inner planes, which slip or slide as deformations occur. When a body having material damping is subjected to vibration, the stress-strain diagram shows a hysteresis loop, as indicated in **Fig. 1.** The area of this loop denotes the energy lost per unit volume of the body per cycle due to damping (hysteric loop for elastic materials).

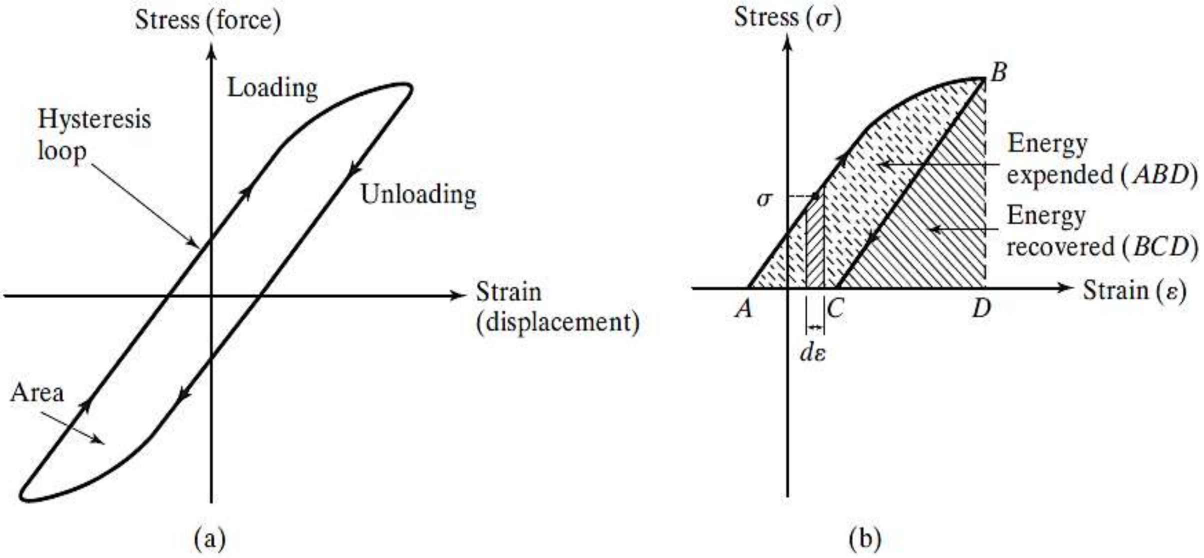


Figure 1. Hysteretic loop for elastic materials **(Rao, 2011),** a) force-displacement curve, b) Energy expended and recovered for stress-strain curve

The stress and strain increase when the load is applied to an elastic body. When the load on the body is decreased, energy will be recovered. When the unloading path is different from the loading path, the area ABC in **Fig.1b** is the area of the hysteresis loop **(Lalanne et al., 1984).**

Improving the damping characteristics of different materials by the heat treatment processes is considered an effective and more economical method to reduce the vibration amplitude and frequency in the structure, which results from a dynamic load. Thus, **(Alimanova et al., 2015)** experimentally examined the effect of the heating process on the improving damping capacity of low alloy steel. However, these types of steel have poor damping capacity. The forged bars were used to cut specimens to examine physical and mechanical properties. After two types of heat treatment, normalizing and carburizing with follow-up hardening and low-tempering damping properties of steels were analyzed.

Normalization was accomplished by heating the steel to Ac_3+50°C, waiting 1 hour, and then slowing the cooling rate. Gas carburizing was carried out at 935°C for 8.5 hours, cooling to 400-500°C in the furnace. Steel specimens were hardened by heating them to Ac_3+ 50°C, holding them for 0.5 hours, and then cooling them in oil. Low-temperature tempering was achieved by heating to 200°C, soaking for 0.5 hours then cooling. The damping capacity of the specimens is measured by the device called (sound and damping of the colliding plate and ball). The results of experiments have proved that carburizing and tempering do not reduce damping properties. At the same time, normalizing increases the steel's damping abilities due to producing a martensitic structure, which gives significant damping according to its high density of dislocations. Tempered steel has damping properties better than conventional steel because of the grain size of the tempered steel.

(Mouginot et al., 2020) studied the effect of different heat treatments on the damping properties of martensitic stainless steels (Eurofer97) using nano-indentation tests with continuous stiffness measurement technique. In this study, various heat treatments (varying tempering levels) were considered to change the flow stress significantly and assess its influence on the damping coefficient. The nanoindentation measurements are carried out with an instrumented MTS-G200 nano-indenter to evaluate the damping through the conventional expression of the loss factor. Also, dynamic tensile testing was used to establish a correlation between the loss factor in nanoindentation and tensile testing. The results showed that, for the different conditions of Eurofer97, the loss factor is increased with increasing the tempering level due to the associated softening in heat-treated samples. Also, the study shows a reasonable agreement between the loss factor results measured with continuous stiffness measurement nano-indentation and those obtained from tensile results.

Additionally, **(Xia et al., 2020)** investigated the influences of cold-rolling deformation and annealing on the damping property of Fe–19 Mn–8Cr alloy. The results show that, after 70% cold rolling deformation, the austenite grains grow with an increase in the annealing temperature, which resulted in a significant change in the content and morphology of martensite, which influenced the damping capacity of the experimental steel. Also, the damping capacity was optimum when the specimens were annealed at 800 °C for 30 min, showing that the grains' size influences the experimental alloy's damping ability.

Furthermore, **(He et al., 2020**) investigated the influences of cold-rolling deformation and annealing on the damping property of Fe–19 Mn–8Cr alloy. The results show that, after 70% cold rolling deformation, the austenite grains grow with an increase in the annealing temperature, which resulted in a significant change in the content and morphology of martensite, which influenced the damping capacity of the experimental steel. Also, the damping capacity was optimum when the specimens were annealed at 800 °C for 30 min, showing that the grains' size influences the experimental alloy's damping ability.

(Wang et al., 2006) presented the improvement of damping properties or damping behavior of shape memory alloy (SMA) by heat treatment processes experimentally. The specimens are cut to the same size (70X3X0.8) mm and heated to nearly 900 ˚C for 3 hours in a vacuum induction furnace. The cooling schemes included water, saltwater baths, air, and furnace cooling .The microstructure examination was performed using (SEM) microscopy after the grinding, polishing, and etching process. The experiment results show that when the specimens are rapidly quenched in water and formed of martensite, the damping property will increase, especially when increasing the quenching temperature, then air cooling has perfect results after the quenching process.

Similarly, Gray cast iron has excellent damping properties, but due to its poor tensile strength, it has limited application. So it is necessary to enhance the damping properties without any side effects. Accordingly **(Jang et al., 2003)** investigated experimentally the best combination of damping capacity and tensile strength properties by the austempering process. The temperature ranged from 320˚C to 380˚C, then held for 1 hr. This process showed that with increasing in austempering temperature hardness value decreased, but the damping and tensile strength increased. Austempering at 350˚C produces a mixture of upper and lower austenite and Bainite, which results in the best combination of damping capacity and tensile strength. While (**Zhang and Guo et al., 2019**) studied the effect of heat treatment on the damping properties of ductile iron or modified cast iron, which is widely used in engineering applications due to its excellent corrosion and wear resistance and high strength and toughness. The results indicated that the structure of the ductile iron is modified or changed by heat treatment. Thus, the enhancement of the damping and mechanical properties can be achieved. At the same time, the phenomenon of dislocation or slipping was studied, and it was found that interactions between the atom and grain boundary with the dislocation line and different damping mechanisms can be developed.

Likewise, a study was carried out by **(He et al., 2020)** to investigate the effect of long annealing on the damping capacity for the Fe Mg alloy (0.022C, 10.5Cr, 0.012P). This type of alloy was selected due to its high tensile, relatively low cost, and excellent corrosion resistance. The damping capacity was investigated with long annealing of up to 10 hours. A measurement of damping capacity is carried out experimentally by the dynamic mechanical analyzer. The results concluded that the damping ability of the alloy increases with increasing annealing time from a quarter to one hour, but the ideal annealing time was two hours. This decreases the amount of α′-martensite, which is the major factor for getting the higher damping.

On the other hand **(Zhang and Kou et al., 2019)** studied the optimization of the heat treatment procedure to improve the mechanical damping performance of a unique high-strength of Mg-13Gd-4Y-2Zn-0.5Zr magnesium alloy. The experimental work is based on the Box-Behnken technique, an effective practical design tool, to optimize the aging treatment and solid solution process. The results showed that the best technique is heating to 520°C for 10 hours and aging at 239°C for 22 hours. Accordingly, the damping coefficient jumps to 73.1 % from before the heat treatment with 346.78 MPa tensile strength. SEM and EDS were used to analyze the second phase's morphology, microstructure, and composition after heat treatment. It was determined that the area fraction of the second phase significantly impacts the damping capacity of heat-treated Mg-0.5Zr alloy and substantially increases the damping capacity. The statistical analysis data achieved using image software is compatible with the damping capacity of experimental results.

The present work investigates the effect of different heating temperatures and cooling schemes on the structural steel damping properties for two other carbon contents. The damping energy was evaluated using the loading and unloading conditions using the tensile test. The damping improvement is achieved without changing the chemical compositions of the specimens and by balancing other mechanical properties such as yield and tensile strength. Also, microstructural tests are carried out to explain the modifications in damping properties.

2. EXPERIMENTAL WORK

The experimental data is paramount to getting accurate and reliable results. Jig and fixture required to perform the experiments for vibration test for the specimens were designed and manufactured. Also, the heat treatment equipment’s prepared. Generally, the research methodology is divided into three subsections: material and specimen preparation, tensile test, and vibration test.

2.1 Material and specimen preparation

The specimens were divided into two groups according to low carbon content of (0.188% C) and medium carbon content of (0.299% C). The specimens are of structural steel of a rounded shape (ribbed rebar) according to standard ISO 6935, selected with a length of 40 cm and diameter of 12 mm for both groups. The chemical compositions of these specimens are given in **Table 1.**

Table 1. Chemical compositions of the specimen.

Chemical Compositions (wt %)	Low carbon steel	Medium carbon steel
C	0.188	0.299
Si	0.0.302	0.282
Mn	0.0894	1.03
P	0.0062	0.0103
S	0.0139	0.0203
Cr	0.108	0.157
Mo	0.0133	0.0175
Ni	0.0837	0.0963
Al	0.00050	0.00050
Co	0.011	0.0100
Cu	0.309	0.328
Nb	0.00036	0.00020
Ti	0.0014	0.0018
V	0.001	0.0018
Pb	0.00024	0.00098

To insert the specimens completely into the furnace, the specimen length was selected according to the furnace's maximum capacity, and all the specimens were coded according to a specific code, as shown in **Fig. 4.**

In the present work, the design of the experimental work procedure is carried out according to the following conditions or (parameters) groups shown in **Table 2.**

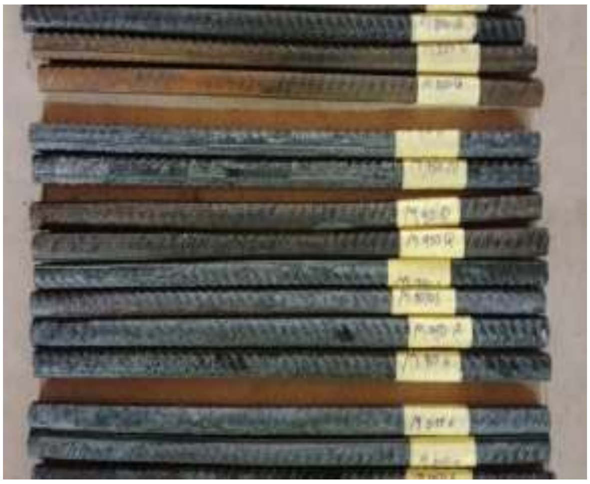


Figure 2. Coded specimens

Table 2. Design of the experiment work (Heat treatment) process.

Carbon Content	Heating Temperatures (˚C)	Cooling Schemes
Low carbon (L) Medium Carbon (M)	850	Normalizing (N) Annealing (A) Quenching (Q) Sand (S)
	950	Normalizing (N) Annealing (A) Quenching (Q) Sand (S)
	1050	Normalizing (N) Annealing (A) Quenching (Q) Sand (S)

2.2 Heat Treatment Processes

One of the most important factors in heat treatment is the holding or soaking time, which greatly affects heat treatment processes. The main reason is homogenous heat transformation in the specimen's outside and inside. So the most important factor determining the holding time is the thickness for models with rectangular shapes and the diameter for samples with round shapes. For 12 mm diameter specimens, 40 minutes is used as a holding time to guarantee that the transformation occurs completely in the specimens **(Wibisono et al., 2018).** The heat treatment heating and cooling processes, considering soaking time, are performed according to the Iron-carbon phase diagram for choosing the optimum temperature **(Lafta et al., 2019).**

The specimens are heated to different temperatures of 850 ˚C, 950 ˚C, and 1050 ˚C, then cooled with other cooling schemes such as annealing, normalizing, quenching, and in the sand; thus, various microstructures formed through heat treatment such as ferrite, cementite, pearlite, austenite, and martensite.

In short, the quenching process includes heating and maintaining the specimen inside the furnace with the required holding time and then rapidly cooling it in a water bath to room temperature. While in the normalizing process, the specimens were inserted into the furnace. The furnace was turned off after soaking time, and specimens were removed to reach room temperature. The annealing process involved slowly heating the metal and kept at this temperature as a holding time, then carefully cooled to room temperature inside the furnace **(Murmu et al., 2022).**

2.3 Tensile Test

The main purpose of performing a tensile test is to calculate the area under the curve during the loading and unloading conditions. All the tensile test runs were carried out using a hydraulic universal material tester type (UTEST 600). The machine capacity is ranged between (1 to 600 kN) as shown in **Fig. 5.**

Figure 3. Tensile test apparatus

The specimens were cut with 26 cm length according to international standard (15630-ISO) of reinforced rebar steel. The test is performed at room temperature, and the results are displayed through a digital computer connected to the machine. The tensile test result is presented graphically, showing the stress-strain diagram. According to the hysteresis damping energy definition, the area under the stress-strain diagram must be calculated according to predefined loading and unloading conditions, as shown in **Fig.6** (area ABCD). The loading and unloading of the tensile test can be carried out for metallic materials at any loading force beyond the yield stress state. Also, it was supposed that the loading and unloading paths are parallel for most metallic materials **(Hama et al., 2015; Shamass, 2020).** Accordingly, it isn't easy to accurately calculate the area under the curve without using any software. Thus, the (AUTOCAD) software was used for this purpose.

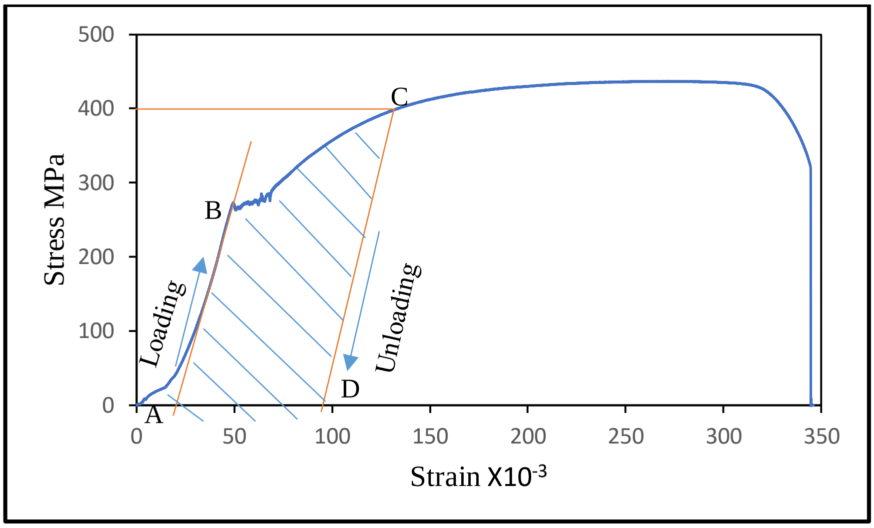


Figure 4. Determination of the area under the stress-strain curve

2.4 Microstructure Test

Different microstructures are produced at different stages due to heat treatment, and according to the time-temperature transformation (TTT) diagram, as shown in **Fig.7**, all the microstructure data can be interrupted. Microstructure alterations must be predicted to accurately determine the mechanical properties after the heat treatment processes.

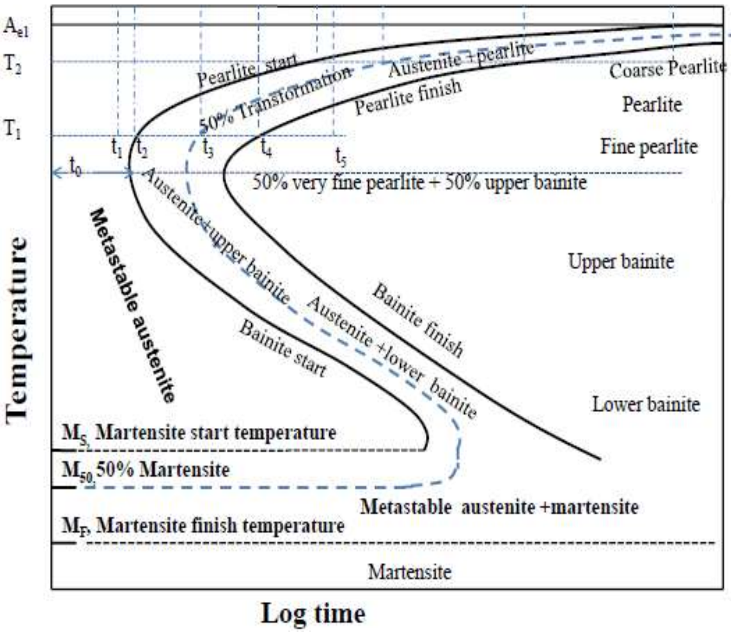


Figure 7. Time-temperature transformation curve (TTT) **(Manna, 2012)**

So, the microstructure test is conducted to show the differences in the microstructure of each heat treatment process (annealing, normalizing, quenching, and sand). The test started with specimen preparation by cutting the specimens carefully to 2 cm length using an electrical saw with coolant to prevent any deformation in the surface of the specimens. After that, the specimens were ground with five stages of emery papers (320, 400,600, 1000, and 1200) followed by a polishing process with a solution of Al_2O_3 (1 Micron); both processes are performed with special devices rotated at different speeds. Finally, a shiny surface like a mirror is obtained and ready to be examined under the microscope with specific magnification. Finally, the specimens sank in the etching solution (HNO_3) with a concentration of (3% HNO_3 and 97 % Ethanol) for 3 seconds.

3. RESULTS AND DISCUSSION

The effect of different parameters, including the heating temperatures, cooling schemes, and carbon contents, on the improvement of damping properties of structural steel was studied experimentally. The experimental work included conducting a tensile test for demining the damping energy. The energy absorbed is measured from the area under the curve of the stress-strain diagram obtained from the tensile test. Then, the damping properties of the structure, when subjected to permanent deformation, can be evaluated. To determine exactly if there is an improvement in damping properties, the evaluation is carried out by calculating the percentage ratio of the damping energy of the heat-treated specimens to as received specimen. The effect of the parameters mentioned above is presented graphically and discussed in subsequent sections.

3.1 Effect of Heating Temperature and Cooling Schemes

To achieve the desired influence, specimens are heated to a critical temperature of 700 ˚C (austenite range). This leads to a phenomenon in steel called phase transformation. A phase transformation is essential in treating materials, and it causes some modifications in microstructures. In the presented study, all the specimens are heated to above critical temperature to ensure that the phase transformation occurs or when the phase completely transforms to austenite, then cooled with a specific process.

Fig. 8 shows the effect of cooling schemes on the percentage damping energy at different heating temperatures for both low and medium carbon contents. Generally, it can be seen that the annealing process gives the best result among other processes at 850˚C, 950˚C, and 1050˚C for both the low and medium carbon steels, followed by sand and normalizing processes with approximately close values. Finally, the quenching process has the minimum values compared with other cooling schemes in low and medium carbon contends.

The interpretation of this effect is related to Time Temperature Transformation (TTT) diagram, as shown in **Fig. 7**. The diagram shows different microstructures produced during different cooling processes, such as in the annealing process when the specimens cooled to below 723 ˚C the microstructure changes from stable austenite to (Pearlite). Pearlite combines ferrite and cementite, forming bands or layers, as shown in **Fig. 9 (a),** of approximately 12% ferrite and 88% cementite. Annealing inside the furnace has a low cooling rate, allowing grain growth during the phase transformation. Pearlite has excellent ductility, leading to the increased area under the curve during the tensile test and getting a higher value than other cooling processes. Also, for both processes of normalizing and sanding, they have cooling rates faster than annealing. Thus, their microstructure shows a Bainite, a mixture of carbides and ferrite, as shown in **Fig. 9 (b).**

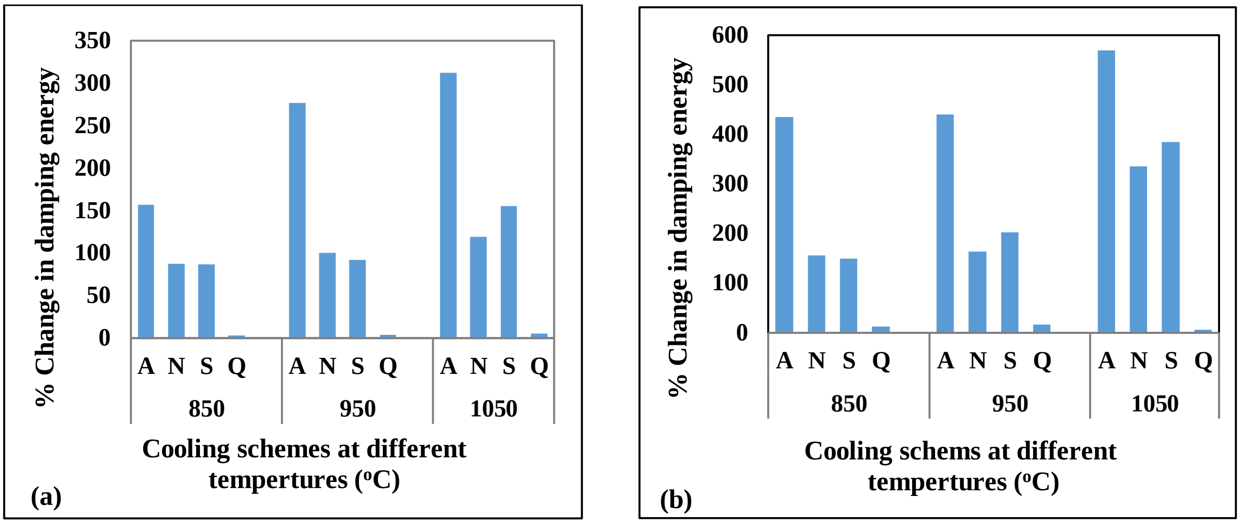
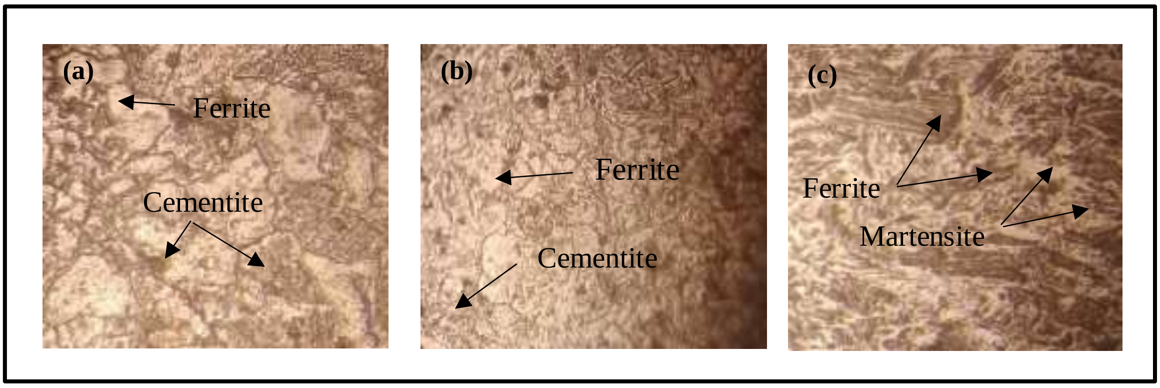


Figure 8. Effect of cooling schemes at different temperatures on damping energy of (a) Low carbon steel and (b) Medium carbon steel.



(a) **(b)** **(c)**

Figure 9. Different microstructures under an optical microscope (magnification power X500) Pearlite, (b) Bainite, and (c) Martensite

Consequently, the Bainite is harder and has less ductility than pearlite, resulting in less damping energy under the tensile test. The fourth cooling scheme is a quenching process characterized by a very fast cooling rate, and the microstructure formed during this process is (Martensite). In contrast to the disintegration of ferrite and pearlite, martensite transition involves a sudden diffusion less shear process rather than atom diffusion.

When unstable austenite transfers to martensite at starting temperature (M_s) in the (TTT) diagram, the martensitic begin forming. **Fig. 9 (c)** shows the microstructure of martensite, which appears as a (lath) called lath martensite under an optical microscope. As a specimen is quenched large percentage of unstable austenite turns to martensite until reaching to (M_f) line in the (TTT) diagram, at which point the transformation is completed. The martensite phase has properties different than pearlite or Bainite. It is very hard with little ductility. For that reason, the area under the curve of this process is very small, and its damping energy less than the other three cooling schemes.

3.2 Effect of Carbon Content on Damping Properties

Fig. 10 shows the effect of carbon content on the percentage change of damping energy for carbon content (low carbon 0.188 % C and medium carbon 0.299 % C) with respect to the different cooling schemes, namely (annealing, normalizing, quenching, and sand).

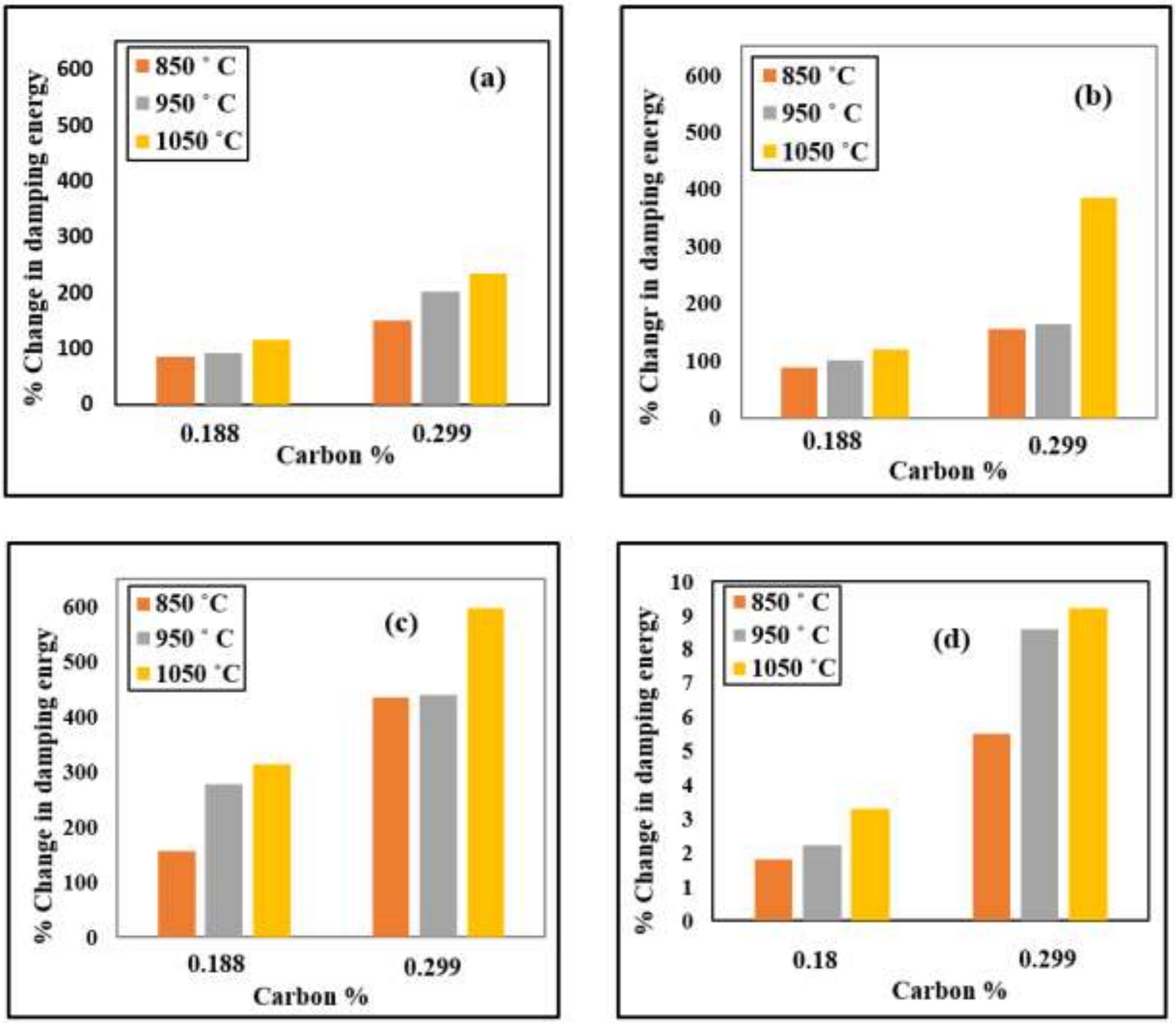


Figure 10. Effect of carbon content on damping properties for (a) annealing, (b) normalizing, (c) sand, and (d) quenching.

From these figures, it can see that medium-carbon steel has more damping energy than low-carbon steel, which means that by increasing the carbon percentage in steel, the value of damping energy in the structure will increase in all cooling processes because increasing carbon content increases steel responsivity to heat treatment.

Carbon tends to separate at the defects such as (dislocations and grain boundaries), and also the interaction between carbide forming elements and carbon form carbides alloy, and it is a response to enhance many mechanical properties such as strength. The influence of strengthening carbon in steel includes carbide dispersion strengthening and solid solution strengthening. The amount of cementite in steel increases along with its carbon content. Furthermore, cementite precipitation in steel microstructure acts as a barrier to moving dislocation, and the strength of steel increases, especially with medium carbon steel. In other words, the damping energy of medium-carbon steel is larger than that of low-carbon steel.

4. CONCLUSIONS

This study experimentally investigates the influence of parameter heating temperature, cooling schemes, and carbon content on improving the damping properties of both low and medium-carbon steel. Hence from the results, the conclusion is summarized as follows:
1- Temperatures greatly affect damping energy and are more pronounced at (1050 ˚C) than other low- and medium-carbon steel temperatures.
2- Improvement in damping depends on the cooling rate; it is responsible for forming many different microstructures which determine the properties of the metal.
3- The annealing process improves damping energy at 850˚C, 950˚C, and 1050˚C, followed by the sand and normalizing process while the quenching process has minimum improvement among other processes.
4- The damping energy increased by increasing carbon content from 0.188% C to 0.299% C.
5- Increasing carbon from low to medium carbon content increases steel response to heat treatment.

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