STUDY OF THE EFFECT OF HEAT TREATING TEMPERATURES ON THE CALCULATED FATIGUE LIMIT AND BRINELL HARDNESS NUMBER OF THE STEEL ALLOY AISI 4140

Meshref A. A., Mazen A. A., El-Giushi M. A.
Department of Production Engineering & Design, Faculty of Engineering, Minia University, 61111 Minia, EGYPT.
Corresponding author: alaa.moshref@mu.edu.eg

Abstract*: This work aims to discuss the effect of stress-relief and full annealing temperatures toward the Brinell hardness number (BHN) and fatigue limit of the steel alloy AISI 4140. The material used in this work is the steel alloy AISI 4140. Two kinds of heat treatments are applied in this work. The first one is stress-relief at temperature of 500, 600 and 660 ^{0}C; the second kind is full annealing at temperature of 800, 860 and 900 ^{0}C. It is found that the Brinell hardness number (BHN) and fatigue limit decreases with increasing stress-relief temperature from 500-660 ^{0}C. The Brinell hardness number (BHN) and fatigue limit decrease upon full annealing up to 860^{0}C, and then increase with increasing full annealing temperature from 860-900 ^{0}C. Also, the microstructure of the steel alloy AISI 4140 after the stress-relief and full annealing heat treatments has been studied. It is found that the fatigue limit and Brinell hardness number correlated well with microstructure produced by stress-relief and full annealing heat treatments in the steel alloy AISI 4140

Keywords: Heat treating, stress-relief, full annealing, steel alloy AISI 4140, Brinell hardness number and fatigue limit.

I. INTRODUCTION

Steel alloy AISI 4140 is medium carbon low-alloy steel made with chromium and molybdenum alloy additives. Chromium from 0.8 to 1.10 % is added with a small amount of molybdenum from 0.15 to 0.25 %. These small amounts of chromium and molybdenum excess the strength, hardenability and wear resistance of the 41xx series of alloy steels [1]. Steel alloy AISI 4140 steel widely used in different applications such as automotive driving elements (steering components, crankshafts), forged parts, bolted assemblies, welded components , armour materials, and among other applications. It is qualified with a high strength, an interesting fatigue behavior and good machinability, but as a metallic material it is mostly exposed to oxidation [2]. It is available as bar, rod, forgings, sheet, plate, strip, and castings [3].

Heat treating is the technique of heating and cooling of metals to get the desired physical and mechanical properties through modification of their crystalline structure. The temperature, holding time, and cooling rate after heat treating will have their dramatically impact on the properties. The most important reason to heat treat includes increasing strength or hardness, increasing toughness, improving ductility and maximizing corrosion resistance [4]. Heat treating of steel includes; full annealing, stress relief, normalizing, hardening and tempering. It is however known that mechanical properties of steels are hardly connected to their microstructure obtained after heat treating which are performed to achieve good hardened and tensile strength with sufficient ductility [5]. The phase transformations between BCC steel (ferrite) and FCC steel (austenite) during the heating and cooling process are that which define the microstructure and mechanic properties of steels [6]. In general, the procedure of heat-treating process consists of three stages. First stage is heating the metal; second stage is holding the temperature for a period of time and the third one, cool down the metal to room temperature [7].

Hardness is refers to the ability of material to resist permanent indentation, usually by indentation or known as penetration when in contact with an indenter under load. In addition, the hardness is the resistance to scratching, abrasion or cutting. Hardness is one of the mechanical characteristics of material 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 to deform [7].

Fatigue is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material [8]. Fatigue limit is the maximum stress that presumably leads to fatigue fracture in a specified number of stress cycles [9].

The goal of the present work is to discuss the effect of heat-treating temperatures toward the Brinell hardness number (BHN) and fatigue limit of the steel alloy AISI 4140.

II. MATERIALS AND METHODS

Material

In this work the steel alloy AISI 4140 with carbon concentration of 0.392 % is used. Table (1) reports the chemical composition of the steel alloy AISI 4140. Steel alloy AISI 4140 is received as round bars with a length of 1000 mm and a diameter of 19 mm.

Table (1): Chemical composition (wt. %) of the steel alloy AISI 4140

C	0.392
Si	0.194
Mn	0.738
S	0.021
P	0.0104
Cr	1.06
Mo	0.176
Ni	0.138
Cu	0.135
w	0.0116

Heat Treatment

Two kinds of heat-treating are employed in this work, namely stress-relief and full annealing. Heat-treating samples are positioned in electrical furnace. The heating temperature, the soaking time at the heating temperature and cooling medium depends on the type of heat-treating process used which will be described in the heat-treating schedule in Table (2).

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Table (2): Heat treatment schedule

Process	*Details of heat-treating*
Stress-relief	*Stress relieved at 500 ^{0}C, 600 ^{0}C and 660 ^{0}C, 0.5h, air cooling*
Full annealing	*Fully annealed at 800 ^{0}C, 860 ^{0}C and 900 ^{0}C, 0.5h, furnace cooling*

Tensile Test

Cylindrical tensile short samples of 40 mm gauge length and 8 mm diameter are used to determine the ultimate tensile strength. Tension test is carried out at room temperature on type ZDN 10 t 191 VEB testing machine at a cross-head speed of 5 mm/min. Fig. (1) shows the shape and dimensions of tensile samples used in this work.

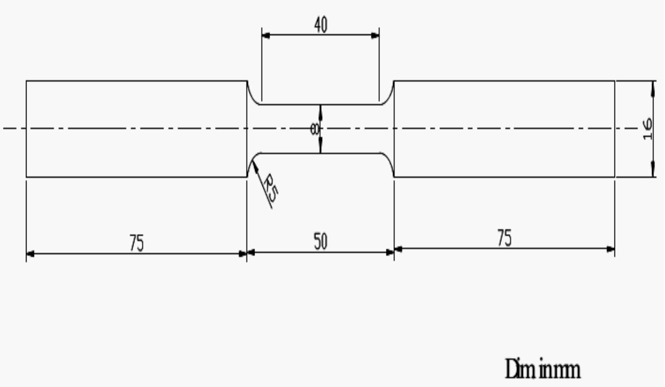


Fig. (1) Shape and dimensions of tensile samples.

Brinell Hardness Number Estimation

Both tensile strength and hardness are indicators of a metal's resistance to plastic deformation. Consequently, they are roughly proportional for cast iron, steel, and brass. As a rule of thumb for most steels [10], the Brinell hardness number (BHN) and the tensile strength are related according to

$$\mathbf{TS(MPa) = 3.45 \times BHN} \qquad (1)$$

Where TS is the tensile strength and BHN is the Brinell hardness number. The Brinell hardness number (BHN) is determined for each sample by using equation (1).

Fatigue Limit Estimation

The experimental determination of fatigue limit requires a large number of samples and takes a long time to perform. Therefore, any analytical method enabling prediction of this behavior from basic mechanical properties of the material (which would involve a reduced amount of experimental work) would be extremely appealing. It is very useful for the engineer to be able to estimate the fatigue limit of some materials using easy and quick tests. There is an empirical relationship between the fatigue limit under fatigue loads and the tensile strength for steel [11], namely

$$\boldsymbol{\sigma_e = 0.5\ \mathrm{TS}} \qquad (2)$$

Where $\boldsymbol{\sigma_e}$ is the fatigue limit and TS is the tensile strength. The fatigue limit is determined for each sample by using equation (2).

Optical Metallography

The samples for optical metallography are sectioned after the finishing of tension test. The sample surface must first be ground and polished to a smooth and mirrorlike finish. This is accomplished by using successively finer abrasive papers and powders. The microstructure is revealed by a surface treatment using an appropriate chemical reagent in a procedure termed etching. Microstructures are examined by optical microscopy.

III. RESULTS AND DISCUSSION

Table (3) shows the influence of increasing stress-relief temperature on the ultimate tensile strength of the steel alloy AISI 4140. It is clear that the ultimate tensile strength of the steel alloy AISI 4140 decreases with increasing stress-relief temperature.

Table (3): Ultimate tensile strength of the steel alloy AISI 4140 in case of stress-relief

Stress-relief temperature, ^{0}C	Ultimate tensile strength, MPa
500	1225
600	1213
660	963

Table (4) shows the influence of increasing full annealing temperature on the ultimate tensile strength of the steel alloy AISI 4140. It is clear that the ultimate tensile strength of the steel alloy AISI 4140 first decreases from 911 MPa to 680 MPa at a temperature of 800 ^{0}C to 860 ^{0}C and then increases from 680 MPa to 1029 MPa at a temperature of 860 ^{0}C to

900 ^{0}C.

Table (4): Ultimate tensile strength of the steel alloy AISI 4140 in case of full annealing

Full annealing temperature, ^{0}C	Ultimate tensile strength, MPa
800	911
860	680
900	1029

Figure (2) shows the effect of increasing stress-relief temperatures on the Brinell hardness number (BHN) of the steel alloy AISI 4140. As shown from Fig. (2), the Brinell hardness number decreases with increasing stress-relief temperatures from 500 to 660 ^{0}C. The reason for this behavior may be due to the increase in the amount of ferrite. The presence of the small amount of ferrite, since it is soft, causes the resulting steel to be slightly softer, and as a result there is a considerable drop in the hardness [12]. It may be observed from Fig. (2) that the stress-relief temperatures show pronounced effects on the Brinell hardness number at all used temperatures. However, the stress relieved steel alloy AISI 4140 at 500 ^{0}C shows the highest Brinell hardness number followed by the stress relieved steel alloy AISI 4140 at 600 ^{0}C, and lastly the stress relieved steel alloy AISI 4140 at 660 ^{0}C. In other words, the stress relieved steel alloy AISI 4140 at 500 ^{0}C has a surface with high resistance to indentation, while the stress relieved steel alloy AISI 4140 at 660 ^{0}C has a surface with low resistance to indentation. This means that the stress relieved steel alloy AISI 4140 at 500 ^{0}C has a surface with high resistance to plastic deformation, while the stress relieved steel alloy AISI 4140 at 660 ^{0}C has a surface with low resistance to plastic deformation.

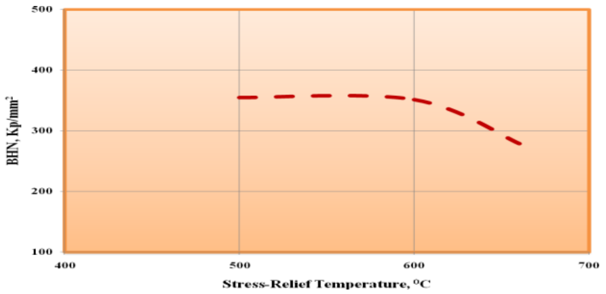


Fig. (2) Influence of increasing stress-relief temperature on the Brinell hardness number of the steel alloy AISI 4140

The variation in the Brinell hardness number (BHN) of the steel alloy AISI 4140 with full annealing temperatures is shown in Fig. (3). These results denote that the Brinell hardness number (BHN) first decreases from 264 Kp/mm^{2} to 197.1 Kp/mm^{2} at a temperature of 800 ^{0}C to 860 ^{0}C and then increases from 197.1 Kp/mm^{2} to 298.26 Kp/mm^{2} at a temperature of 860 ^{0}C to 900 ^{0}C. The decrease in the Brinell hardness number (BHN) may be due to the presence of ferrite and pearlite in the microstructure. The increase in the Brinell hardness number (BHN) above 860 °C are due to the high heat treating temperature. Lakhteen, U. [13] communicated that when the temperature of heating raise more than it should above A_{c3}, the grains of austenite grow and that lead to deterioration of the properties of steel. It is obvious that reductions in the Brinell hardness number (BHN) are observed in fully annealed steel alloy AISI 4140 at 860 ^{0}C. A maximum in the Brinell hardness number (BHN) of the steel alloy AISI 4140 is reached at 900 ^{0}C. The resistance of a material to plastic deformation is related to the hardness number of the material, that is, the higher the hardness number, the stronger the material. This means that the fully annealed steel alloy AISI 4140 at 900 ^{0}C has a surface with high resistance to plastic deformation compared to fully annealed steel alloy AISI 4140 at 800 ^{0}C and fully annealed steel alloy AISI 4140 at 860 ^{0}C.

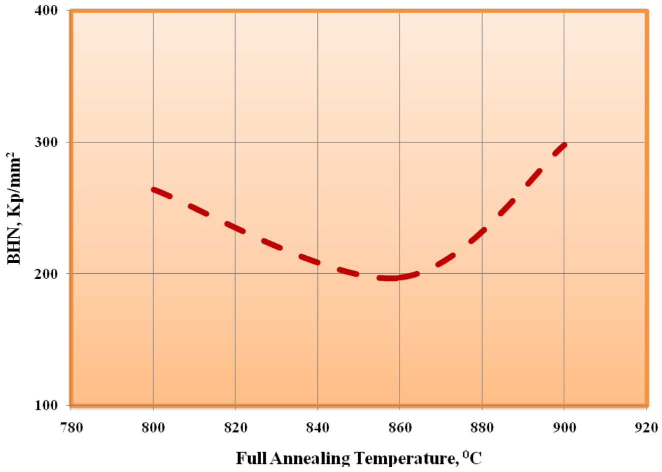


Fig. (3) Influence of increasing full annealing temperature on the Brinell hardness number of the steel alloy AISI 4140

The fatigue limit of the steel alloy AISI 4140 is plotted as a function of stress-relief temperatures as shown in Fig. (4). The obtained results as shown in Fig. (4) reveals that stress-relief temperatures show pronounced effects on the fatigue limit at all used temperatures. The fatigue limit of the steel alloy AISI 4140 decreased from 612.5 MPa to 481.5 MPa at stress-relief temperatures of 500 - 660 ^{0}C. The increasing in stress-relief temperatures leads to the decreasing in the strength of AISI 4140 alloy steel [14]. This may be the reason for the drop in the fatigue limit of the steel alloy AISI 4140 from 612.5 MPa to 481.5 MPa. As can be seen in Fig. (4), the highest fatigue limit is obtained in the steel alloy AISI 4140 heat-treated at stress- relief temperature of 500 ^{0}C, then the steel alloy AISI 4140 heat-treated at stress-relief temperature of 600 ^{0}C and lastly the steel alloy AISI 4140 heat-treated at stress relief temperature of 660 ^{0}C. In other words, the resistance to cyclic loads of the steel alloy AISI 4140 heat-treated at stress-relief temperature of 500 ^{0}C is higher than the steel alloy AISI 4140 heat-treated at stress-relief temperature of 600 ^{0}C and steel alloy AISI 4140 heat-treated at stress-relief temperature of 660 ^{0}C.

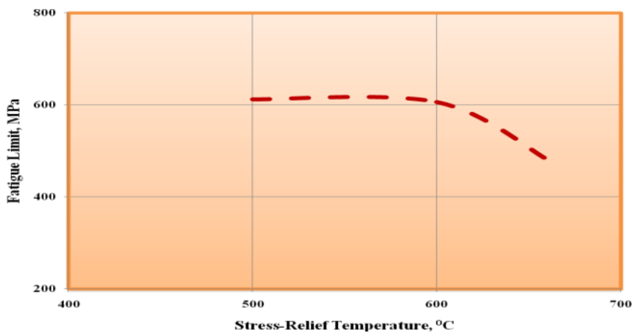


Fig. (4) Effect of increasing stress-relief temperatures on the fatigue limit of the steel alloy AISI 4140

Figure (5) illustrates the dependence of fatigue limit on full annealing temperature for the steel alloy AISI 4140. As it is evident in Fig. (5), the fatigue limit firstly reduces from 455.5 MPa to 340 MPa when full annealing temperature increases from 800 ^{0}Cto 860 ^{0}C and then excesses from 340 MPa to 514.5 MPa with increasing full annealing temperature from 860 ^{0}C to 900 ^{0}C. The decrease in the fatigue limit may be due to the presence of ferrite and pearlite in the microstructure. The reason for the increase in the fatigue limit above 860 °C may be a result of the high heat treating temperature. Lakhteen, U. [13] revealed that when the temperature of heating enhance more than it should above A_{c3}, the austenite grains increase and that leads to weakness of the properties of steel. As Fig. (5) indicates, the steel alloy AISI 4140 when fully annealed in the temperature range between 860 °C and 900 °C, the fatigue limit exhibits a maximum value with 514.5 MPa at about 900 °C. The lowest value of fatigue limit for the steel alloy AISI 4140 occurs at 860 °C.

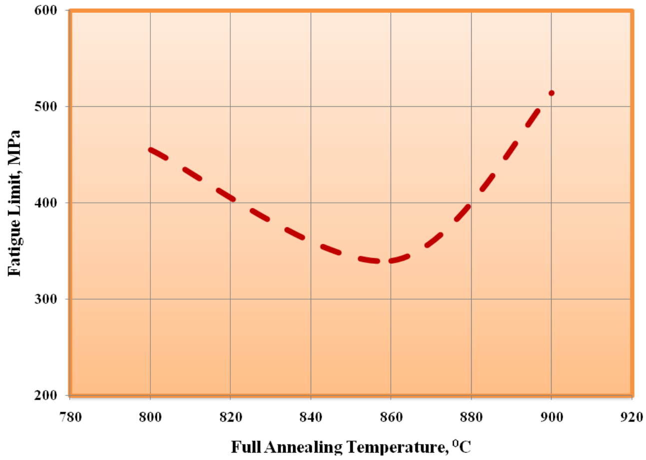
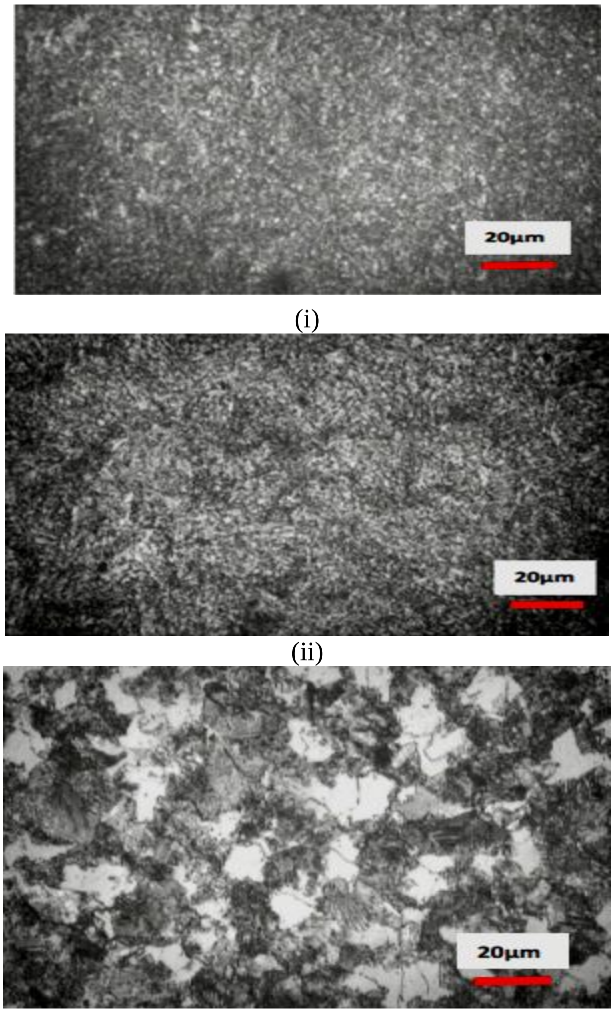


Fig. (5) Effect of increasing full annealing temperature on the fatigue limit of the steel alloy AISI 4140

Microstructures

Optical metallography shows the microstructures of as-received, stress-relief and full annealing samples of the steel alloy AISI 4140. Fig. (6) (i) shows that mixed structures of lath martensite (i.e. dark areas) and small amount of ferrite (i.e. light areas) are formed in the as-received samples. Fig. (6) (ii) shows that the stress relieved one also forms the same phases, i.e. lath martensite and small amounts of ferrite present in the microstructure of the sample. But in this case the amounts of ferrite (i.e. light areas) larger than the as-received one. This means that the small amount of the martensite changed to ferrite, the presence of the ferrite, since it is soft, causes the resulting alloy steel to be softer than in the as-received state. This increase in the amount of ferrite may be reducing the hardness and fatigue limit of the steel alloy AISI 4140. The optical micrograph of the fully annealed sample shows a typical ferrite and pearlite microstructures as shown in Fig. (6) (iii). It is obvious that most of the martensite has been changed to pearlite and this make the microstructure soft. This soft structure will reduce the hardness, strength and fatigue limit.



(i)

(ii)

(iii)

Fig. (6) Optical micrographs showing the microstructures of steel alloy AISI 4140: (i) as-received; (ii) stress relieved at 660 ^{0}C; (iii) fully annealed at 860 ^{0}C.

IV. CONCLUSIONS

The following conclusions can be drawn from the results of the present work:

1. As the stress-relief temperatures enhances, Brinell hardness number (BHN) and fatigue limit of the steel alloy AISI 4140 decrease,

2. The highest Brinell hardness number (BHN) of the steel alloy AISI 4140 used in this work is observed in stress-relief at 500 ^{0}C.
3. When the full annealing temperature is above 860 ^{0}C, the Brinell hardness number (BHN) and fatigue limit of the steel alloy AISI 4140 increases with increasing full annealing temperature up to 900 ^{0}C.
4. The highest fatigue limit of the steel alloy AISI 4140 used in this work is observed in stress-relief at 500 ^{0}C.
5. Fatigue limit and Brinell hardness number correlated well with microstructure produced by stress-relief and full annealing heat treatments in the steel alloy AISI 4140.

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