International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2643-640X
Vol. 3 Issue 7, July – 2019, Pages: 41-46

Influence of Heat Treatment Temperature on the Strain Hardening Exponent and Strength Coefficient of AISI 4140 Alloy Steel

Meshref A. A., Mazen A. A., El-Giushi M. A. and Ashraf T.M.

Department of Production Engineering & Design, Faculty of Engineering, Minia University, EGYPT.

Abstract: *This study aims to discuss the effect of stress relief and full annealing temperatures on the strain hardening exponent and strength coefficient of AISI 4140 alloy steel. The material used is ultrahigh strength low alloy steel (AISI 4140 alloy steel). Two types of heat treatments were applied in this study. The first type was stress relief annealing, the second was full annealing. Effect of stress relief at temperature (500, 600 and 660 ^{0}C) on the strain hardening exponent and strength coefficient of AISI 4140 alloy steel was analyzed. It was found that the strain hardening exponent increased with increasing stress relief temperature, whereas the strength coefficient first increased and then decreased with increasing stress relief temperature. Also influence of full annealing at temperature (800, 860 and 900 ^{0}C) on the strain hardening exponent and strength coefficient of AISI 4140 alloy steel was analyzed. It was found that strain hardening exponent increased upon full annealing up to 860^{0}C, and then decreased as the full annealing temperature was increased. In contrast, the strength coefficient of AISI 4140 alloy steel decreased upon full annealing up to 860^{0}C, and then increased with increase in full annealing temperature.*

Keywords: Heat treatment, stress relief, full annealing, AISI 4140 alloy steel, strain hardening exponent and strength coefficient.

1. INTRODUCTION

For some metals and alloys the region of the true stress-strain curve from the onset of plastic deformation (yield strength) to the ultimate tensile strength (i.e., the point at which necking begins) may be approximated by Equation (1)

$$\sigma_T = K\epsilon_T^n \tag{1}$$

In this equation, σ_T is the true stress, ε_T is the true strain, K is the strength coefficient, and n is the strain hardening exponent and has a value less than unity. Also known as the strain-hardening
coefficient. The strength coefficient K, can be found by extrapolating to $\varepsilon_T = 1.0$. The strength coefficient K indicates the strength level of the material, and the strain hardening exponent n indicates the ability of a sheet of material to be stretched in metalworking operations. In other words, n evaluates the strain-hardening capability of the material. Typical values of n tend to be in the range of 0.15–0.18 for high-strength low-alloy (HSLA) steels and in the range of 0.20–0.23 for low-carbon steels [1-3].

The strain hardening exponent n and strength coefficient K are constants, which vary from alloy to alloy, and also depend on the condition of the material (i.e., whether it has been plastically deformed, heat treated, etc.) [1]. Heat treatment is the technique of heating and cooling of metals to attain the desired physical and mechanical characteristics through modification of their crystalline structure. The temperature, time duration, and cooling rate after heat treatment will have their dramatical impact on characteristics. The most important and also common reason to heat treat includes increasing strength or hardness, increasing toughness, improving ductility and maximizing corrosion resistance [4].
Heat treatment of steel includes; full annealing, stress relief, normalizing, hardening and tempering. Full annealing Consists of heating the steel above the A_{c3} temperature in the case of hypoeutectoid steels and the A_{c1} temperature in the case of hypereutectoid steels. The steel is then cooled in the furnace (very slowly) at the rate of a few tens of degrees per hour [5]. Stress relief heat treating is the uniform heating of the steel, or portion thereof, to a suitable temperature below the eutectoid temperature range (Ac_1 for ferritic steels), holding at this temperature for a predetermined period of time, followed by uniform cooling [6].

AISI 4140 is medium carbon low alloy steel made with chromium and molybdenum alloy additives. Chromium is added from 0.8 to 1.10 % with a small amount of molybdenum from 0.15 to 0.25%. These small amounts of these two elements increase the strength, hardenability and wear resistance of the 41xx series of alloy steels [7]. AISI 4140 widely used in different applications such as automotive driving elements (steering components, crankshafts), bolted assemblies, forged parts, welded components , armour materials, and among other applications. It is characterised with a high strength, an interesting fatigue behavior and good machinability, but as a metallic material it is mostly exposed to oxidation [8].

The goal of the present study is to discuss the effects of heat treatment temperatures on the strain hardening exponent n and strength coefficient K of AISI 4140 alloy steel.

2. EXPERIMENTAL

The material used in this study is ultrahigh strength low alloy steel (AISI 4140 alloy steel). The chemical composition of the AISI 4140 alloy steel is given in Table 1.

Table 1: Chemical composition of AISI 4140 steel, wt. %

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

3. HEAT TREATMENT

Two types of heat treatments were applied in this study, namely stress relief annealing and full annealing. Choose heating temperatures depends on A_{C1}, A_{C3} and M_s temperatures of AISI 4140 alloy steel used in this study. These temperatures are shown in Table 2. Heat treatment specimens were positioned in electrical furnace. The heating temperature, the soaking time at the heating temperature and cooling medium depends on the type of heat treatment process used which will be described in the heat treatment schedule in Table 3.

Table 2: Approximate critical temperatures for AISI 4140 steel [9]

A_{C1}	A_{C3}	M_s	M_f
730 ^{0}C	**805 ^{0}C**	**338 ^{0}C**	**118 ^{0}C**

Table 3: Heat treatment schedule

Type	Details of Heat treatment
Stress relief	Stress relief at 500, 600 and 660 ^{0}C, 0.5h, air cooling.
Full annealing	Full annealing at 800, 860 and 900 ^{0}C, 0.5h, furnace cooling.

4. TENSILE TEST

Strain hardening exponent and strength coefficient of the AISI 4140 alloy steel in the as heat treated conditions were determined using cylindrical tensile short specimens of 40 mm gauge length and 8 mm diameter. Tensile testing was carried out at room temperature on (type ZDN 10 t 191 VEB) at a cross-head speed of 5 mm/min. For each tensile specimen, the true stress versus true strain was determined using the relationship:

$$\sigma_T = \sigma(1 + \epsilon) \quad (2)$$

$$\epsilon_T = \ln(1 + \epsilon) \quad (3)$$

Where σ_T is the true stress, ε_T is the true strain, σ is the engineering stress, and ε is the engineering strain. The strain hardening exponent n and the strength coefficient K were determined for each specimen from the true stress versus true strain diagram by using equation (1).

5. RESULTS AND DISCUSSION

The strain hardening exponent of AISI 4140 alloy steel is plotted as a function of stress relief temperatures as shown in Fig. 1. The obtained results as shown in Fig. 1 revealed that stress relief temperatures showed pronounced effects on the strain hardening exponent at all used temperatures. The strain hardening exponent of AISI 4140 alloy steel increased from 0.06 to 0.1 at stress relief temperature of 500 - 660 ^{0}C. As can be seen in Fig. 1, the highest strain hardening exponent was obtained in the AISI 4140 alloy steel heat-treated at stress relief temperature of 660 ^{0}C, then the AISI 4140 alloy steel heat-treated at stress relief temperature of 600 ^{0}C and lastly the AISI 4140 alloy steel heat-treated at stress relief temperature of 500 ^{0}C. In other words, the formability of the AISI 4140 alloy steel heat-treated at stress relief temperature of 660 ^{0}C is higher than the AISI 4140 alloy steel heat-treated at stress relief temperature of 600 ^{0}C and AISI 4140 alloy steel heat-treated at stress relief temperature of 500 ^{0}C.

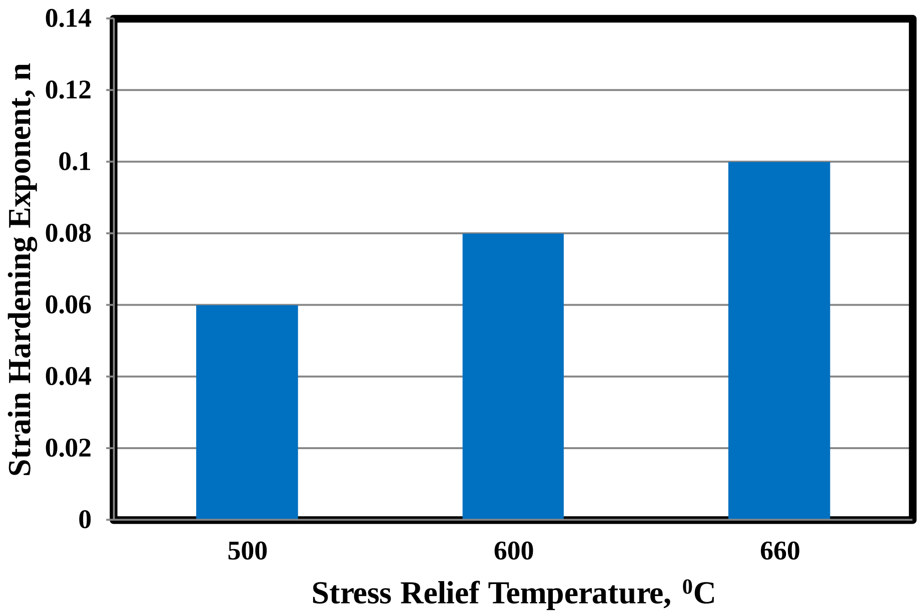

Fig. 1 Effect of stress relief temperature on the strain hardening exponent of AISI 4140 alloy steel.

Figure 2 appears the relationship between the stress relief temperatures and strength coefficient of AISI 4140 alloy steel. These data denoted that the strength coefficient of AISI 4140 alloy steel first increased from 1547 MPa to 1600 MPa at a stress relief temperature of 500 ^{0}C to 600 ^{0}C and then decreased from 1600 MPa to 1380 MPa at a stress relief temperature of 600 ^{0}C to 660 ^{0}C. These results demonstrated that the AISI 4140 alloy steel heat treated at stress relief temperature of 600 ^{0}C exhibited the highest strength coefficient followed by the AISI 4140 alloy steel heat treated at stress relief temperature of 500 ^{0}C and lastly the AISI 4140 alloy steel heat-treated at stress relief temperature of 660 ^{0}C. So, the order of the strength of the AISI 4140 alloy steel is as following: AISI 4140 alloy steel heat-treated at stress relief temperature of 600 ^{0}C > AISI 4140 alloy steel heat-treated at stress relief temperature of 500 ^{0}C > AISI 4140 alloy steel heat-treated at stress relief temperature of 660 ^{0}C.

International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2643-640X
Vol. 3 Issue 7, July – 2019, Pages: 41-46

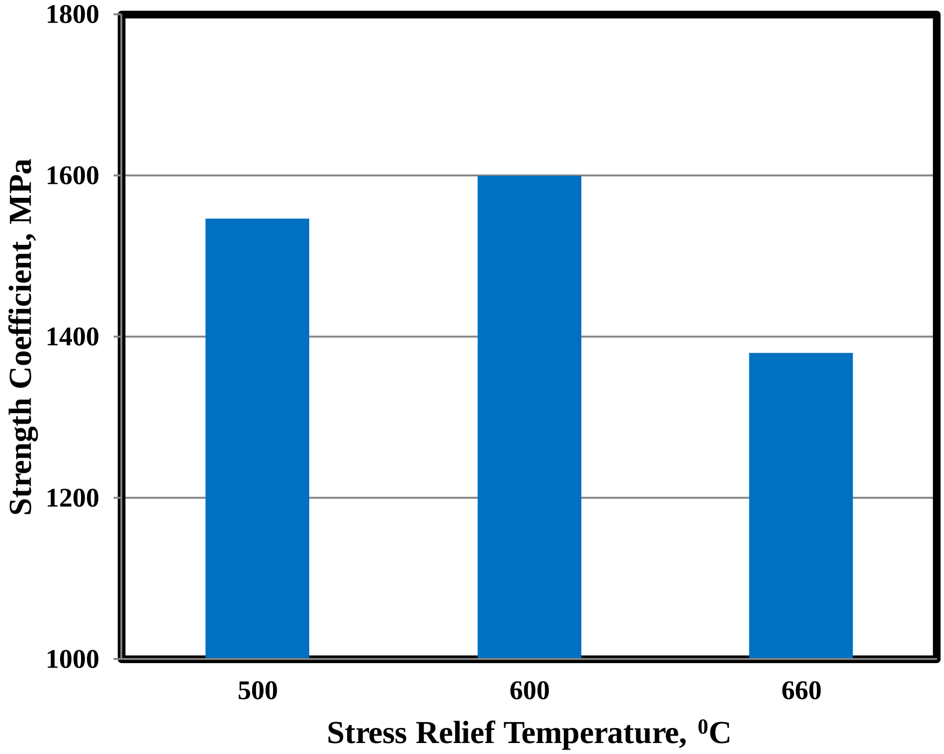

Fig. 2 Effect of stress relief temperature on the strength coefficient of AISI 4140 alloy steel.

The effect of full annealing temperatures on the strain hardening exponent of AISI 4140 alloy steel is shown in Fig. 3. These results revealed that the strain hardening exponent of AISI 4140 alloy steel first increased from 0.15 to 0.22 at a full annealing temperature of 800 ^{0}C to 860 ^{0}C and then decreased from 0.22 to 0.154 at a full annealing temperature of 860 ^{0}C to 900 ^{0}C. The reason for the decreasing in the strain hardening exponent of AISI 4140 alloy steel after a full annealing temperature of 860 ^{0}C may be attributed to the high thermal treatment temperature. Lakhteen, U. [10] reported that when the heating temperature increase more than it should above A_{c3}, the austenite grains growth and that lead to deterioration of the properties of steel. Based on Fig. 3, it may be concluded that the AISI 4140 alloy steel heat-treated at full annealing temperature of 860 ^{0}C exhibited the highest stretchability followed by the AISI 4140 alloy steel heat-treated at full annealing temperature of 900 ^{0}C and lastly the AISI 4140 alloy steel heat-treated at full annealing temperature of 800 ^{0}C.

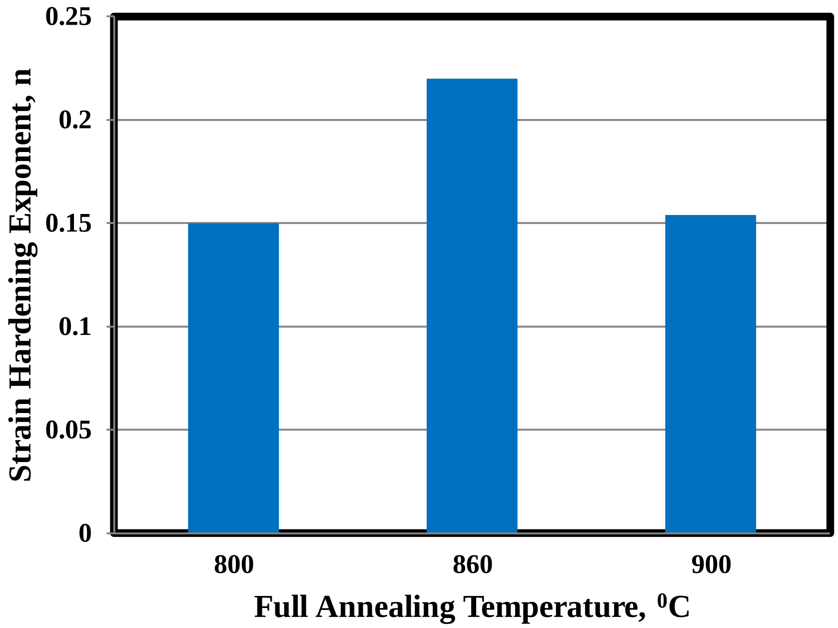

Fig. 3 Effect of full annealing temperature on the strain hardening exponent of AISI 4140 alloy steel.

The variation of the strength coefficient of AISI 4140 alloy steel against full annealing temperatures is displayed in Fig. 4. It is evident in Fig. 4 that when the full annealing temperature is above 800 ^{0}C, the strength coefficient decreased from 1380 MPa to 1200 MPa with increasing full annealing temperature up to 860 ^{0}C. Above this temperature up to about 900 ^{0}C, the strength coefficient increased from 1200 MPa to 1400 MPa. On comparing the strength of the AISI 4140 alloy steel according to full annealing temperatures, it was found that AISI 4140 alloy steel heat-treated at full annealing temperature of 900 ^{0}C give the higher value of the strength, followed by AISI 4140 alloy steel heat-treated at full annealing temperature of 800 ^{0}C, whereas AISI 4140 alloy steel heat-treated at full annealing temperature of 860 ^{0}C showed the minimum value of the strength.

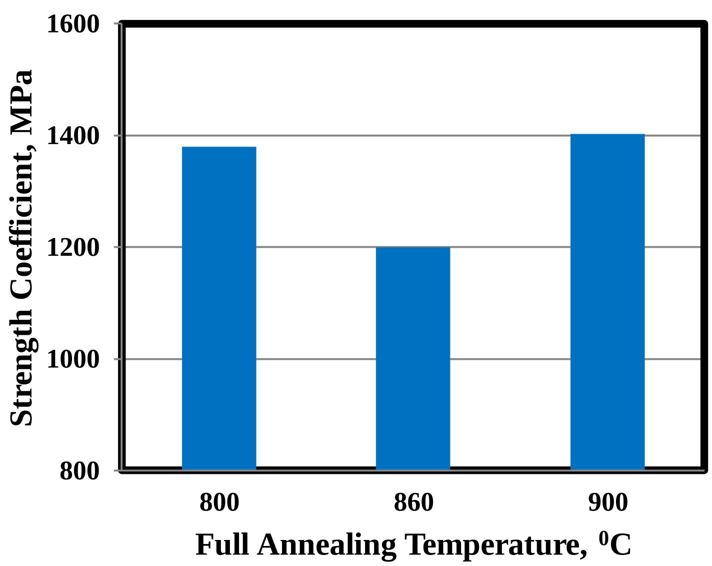

Fig. 4 Effect of full annealing temperature on the strength coefficient of AISI 4140 alloy steel.

6. CONCLUSIONS

Within the scope of the present study, the results showed that, the strain hardening exponent n and the strength coefficient K of the AISI 4140 alloy steel depended on the stress relief and full annealing temperatures, the following conclusions can be drawn:

1. The higher the stress relief temperature, the better the formability of the AISI 4140 alloy steel.
2. Stress relief at 600 ^{0}C produced 4140 alloy steel with high strength.
3. The AISI 4140 alloy steel heat-treated at full annealing temperature of 860 ^{0}C exhibited significantly high formability and low strength.

REFERENCES

1. Callister W. D, Materials Science and Engineering an Introduction ", Wiley,6th Edition, pp. 192 – 324, (2003).

2. ASM International, ASM Handbook Volume 8: Mechanical Testing and Evaluation, American Society for Metals, Metals Park, Ohio, p. 2229, (2000).

3. Rafael A. S., André L. P., Alexei K. and Ivani S. B., Precipitation and Grain Size Effects on the Tensile Strain-Hardening Exponents of an API X80 Steel Pipe after High-Frequency Hot-Induction Bending, Metals, 8, 168,pp. 1-13, (2018).

4. Tripathy I., Effect of Microstructure on Sliding Wear Behavior of Modified 9Cr-1Mo steel, M. Sc. Thesis, National Institute of Technology, Rourkela, pp.19 – 27, (2011).

5. Raghavan V., Physical Metallurgy principles and Practice, New Delhi, 2nd Edition, pp. 109 – 110, (2006).
6. Bailey N., The Metallurgical Effects of Residual Stresses, in Residual Stresses, The Welding Institute, pp. 28-33, (1981).
7. Smith, William F., Structure and Properties of Engineering Alloys, 2nd Edition, New York, McGraw Hill. p.156, (1993).
8. Meshref A. A., Comparative Study on Fracture Toughness of Steel after Different Thermal Treatments", M. Sc. Thesis, Minia University, Egypt, p.73, (2014).
9. ASM International, ASM Handbook Volume 4: Heat Treating, American Society for Metals, Metals Park, Ohio, pp. 18 – 325, (1991).
10. Lakhteen U., Metals Science and Heat Treatment for Metals, Mir, pp. 235- 243, (1983).