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Study of the Influence of Heat Treating Temperatures on the Fracture Properties of the Ultrahigh-strength low-alloy Steel Type 4140

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Abstract: *The purpose of this work is to study the effect of heat treating temperatures on the fracture strength, fracture strain and fracture surface of the ultrahigh- strength low-alloy steel type 4140. In this work two types of heat treating are used. The first type is stress relieving at temperature 500 ^{0}C , 600 ^{0}C and 660 ^{0}C, the other type is full annealing at temperature 800 ^{0}C, 860 ^{0}C and 900 ^{0}C. Tensile testing is carried out at room temperature on type ZDN 10 t 191 VEB testing machine. The results obtained show that the fracture strength, fracture strain and fracture surface appear to depend on stress-relief and full annealing temperatures. It is found that the fracture strength decreases with increasing the stress-relief temperature. Fracture strain rises with rising stress-relief temperature. Before 860 ^{0}C, the fracture strength decreases with raising full annealing temperature. In contrast, the fracture strain increases upon full annealing up to 860^{0}C, and then decrease with increasing full annealing temperature. The appearance of the fracture surface of tested samples is found to change with increasing stress-relief and full annealing temperatures.*

Keywords: Fracture properties, heat treating, stress-relief, full annealing, fracture strength, fracture strain, fracture surface, ultrahigh- strength low-alloy steel type 4140.

1. INTRODUCTION

Fracture may be known as the mechanical segregation of a solid owing to the application of stress. Fracture of engineering materials is broadly categorized as ductile or brittle, and fracture toughness is related to the amount of energy required to create fracture surfaces [1]. For engineering materials, two types of fracture modes are possible: ductile and brittle**.** Sorting is based on the ability of a material to experience plastic deformation. Ductile materials typically display substantial plastic deformation with high energy absorption before fracture. On the other hand, there is usually little or no plastic deformation with low energy absorption accompanying a brittle fracture [2].
Heat treating operation is a means of controlled heating and cooling of materials in order to influence changes in their mechanical characteristics. Heat treating is also used to rise the strength of materials by altering some certain manufacturability objectives especially after the materials might have undergo major stresses like forging and welding [3].

Ultrahigh-strength steels are heat treated by use of equipment and techniques similar to those employed for heat treating constructional alloy steels [4]. 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 [5]. The steel 4140 is available as bar, rod, forgings, sheet, plate, strip, and castings [6].

The present work aims at studying the effect of stress-relief and full annealing temperatures on the fracture strength, fracture strain and fracture surface of the ultrahigh- strength low-alloy steel type 4140.

2. EXPERIMENTAL

In this work ultrahigh-strength low-alloy steel type 4140 with carbon content of 0.39 % carbon was used. Table 1reports the chemical composition of the ultrahigh- strength low-alloy steel type 4140. Ultrahigh-strength low-alloy steel type 4140 was received as round bars with a diameter of 19 mm and a length of 1000 mm.

Table 1: Chemical composition (wt. %) of the ultrahigh- strength low-alloy steel type 4140

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

In this work round bars with a length of 200 mm and a diameter of 19 mm were cut from the supplied bars and heat treated in an electrical furnace. Two types of heat treating were applied in this work, namely stress relieving and full annealing. The approximate critical temperatures for ultrahigh-strength low-alloy steel type 4140 are shown in Table 2. The heat treating temperature, the soaking time and cooling medium depends on the kind of heat treating process used which will be described in the heat treating schedule in Table 3.

Table 2: Approximate critical temperatures for ultrahigh-strength low-alloy steel type 4140 [4]

A_{C1}	A_{C3}
730 ^{0}C	805 ^{0}C

Table 3: Heat treating schedule

Process	Details of Heat treating
Stress relieving	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

4. TENSILE TEST

Cylindrical samples having a gauge length of 40 mm and a diameter of 8 mm were used to determine the fracture strength and fracture strain. The test was performed using the type ZDN 10 t 191 VEB testing machine at a cross-head speed of 5 mm/min at room temperature. Fig. 1 shows the shape of tensile sample used in this work.

Fig. 1 Shape of tensile sample used in this work.

Fracture Surface Examination

Fracture surfaces of the samples used in this work were examined by digital camera. The observation was focused on the fracture mode change from one heat treating condition to another.

5. RESULTS AND DISCUSSION

The fracture strength of the ultrahigh- strength low-alloy steel type 4140 is plotted as a function of stress relief temperature as shown in Figure (2). It is obvious that stress relief temperature shows important influence on the fracture strength of the ultrahigh- strength low-alloy steel type 4140 at all used temperatures. The fracture strength decreases from 881 MPa to 695 MPa with increasing the stress relief temperature from 500-660 ^{0}C. The increasing in stress-relief temperatures leads to the decreasing in the strength of AISI 4140 alloy steel [7]. This may be the reason for the drop in the fracture strength of the ultrahigh- strength low-alloy steel type 4140 from 881 MPa to 695 MPa. As can be seen in Figure (2), great fracture strength is obtained by stress relieving at 500 ^{0}C. This means that the ultrahigh- strength low-alloy steel type 4140 can be heat-treated by stress relieving at 500 ^{0}C to produce high fracture strength.

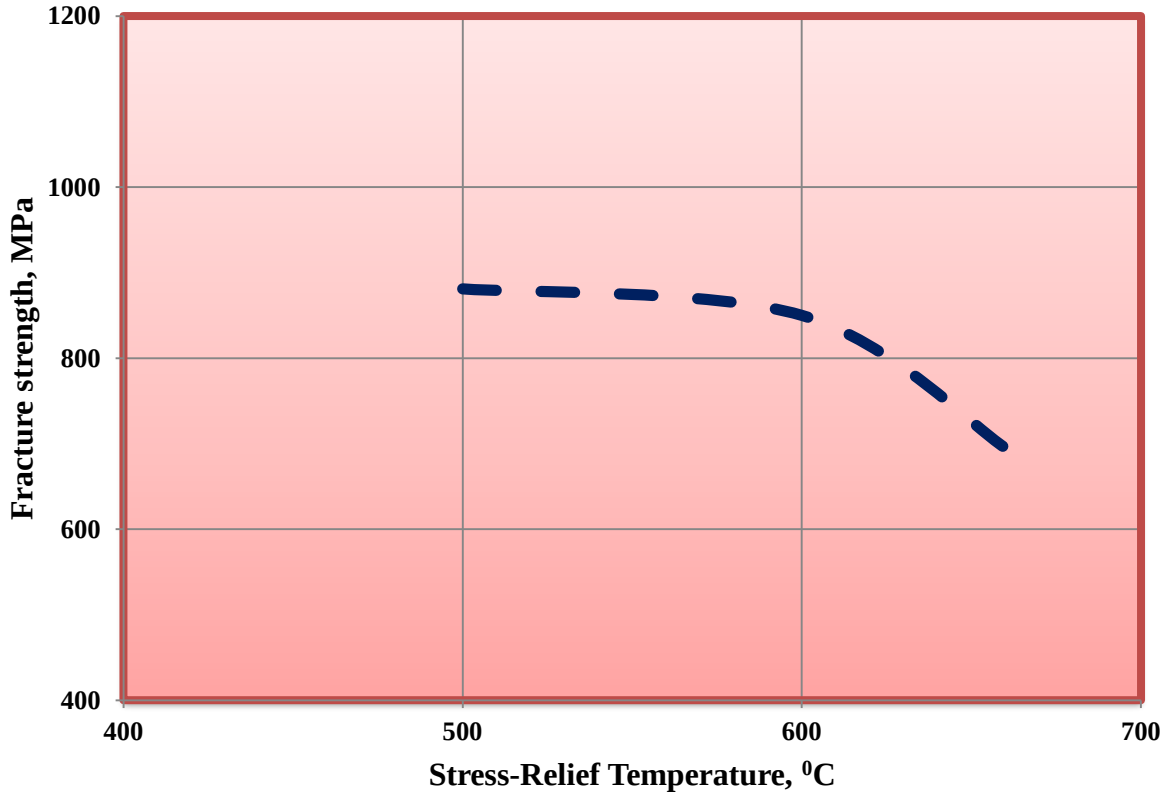

Figure (2) Dependence of fracture strength on stress relief temperature for the ultrahigh- strength low-alloy steel

The fracture strain of the ultrahigh- strength low-alloy steel type 4140 is influenced by stress relieving temperatures. This is shown in Figure (3), in which the fracture strain is plotted as a function of the stress-relief temperature for the ultrahigh- strength low-alloy steel type 4140. The fracture strain increases from 0.13 to 0.16 when stress-relief temperature increases from 500 to 660 ^{0}C. The increase in the fracture strain from 0.13 to 0.16 may be attributable to the increasing in the stress-relief temperature. Note that for fracture strain, the higher the value, the better the fracture strain for the ultrahigh- strength low-alloy steel type 4140. In summary, it is clear that the ultrahigh- strength low-alloy steel type 4140 stress relieved at 660 ^{0}C exhibits the highest fracture strain followed by the ultrahigh- strength low-alloy steel type 4140 stress relieved at 600 ^{0}C and lastly the ultrahigh- strength low-alloy steel type 4140 stress relieved at 500 ^{0}C.

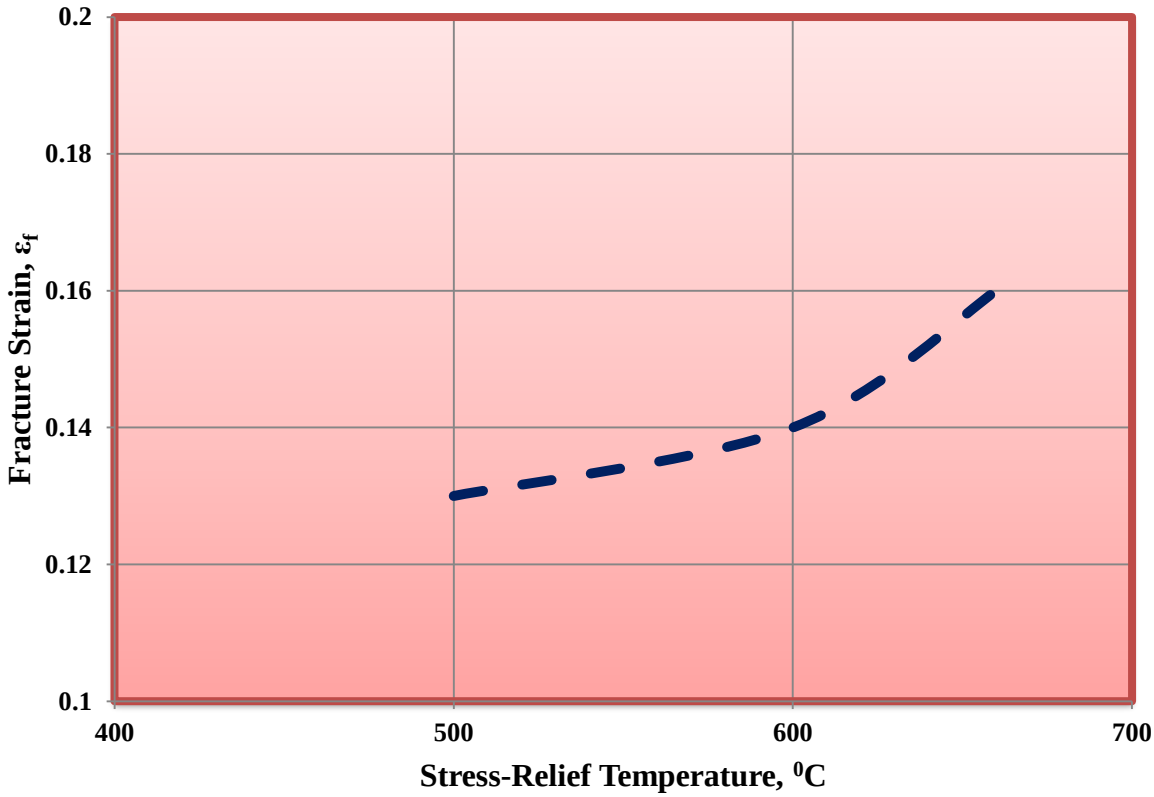

Figure (3) Dependence of fracture strain on stress relief temperature for the ultrahigh- strength low-alloy steel

The dependence of fracture strength on full annealing temperature for the ultrahigh- strength low-alloy steel type 4140 is presented in Figure (4). It is obvious that the fracture strength firstly decreases from 702 MPa to 482 MPa when full annealing temperature increases from 800 to 860 ^{0}C and then increases from 482 MPa to 923 MPa with rising full annealing temperature from 860 to 900 ^{0}C. The drop in the fracture strength before 860 ^{0}C may be attributable to the rising in the full annealing temperature from 800 to 860 ^{0}C. The reason for the increase in the fracture strength above 860 ^{0}C may be due to extra heat treatment temperature. It should be pointed out that the strength of the material is related to the temperature. From Figure (4) it is observed that the ultrahigh- strength low-alloy steel type 4140 fully annealed at 860 ^{0}C has the lowest fracture strength among the full annealing temperatures tested.

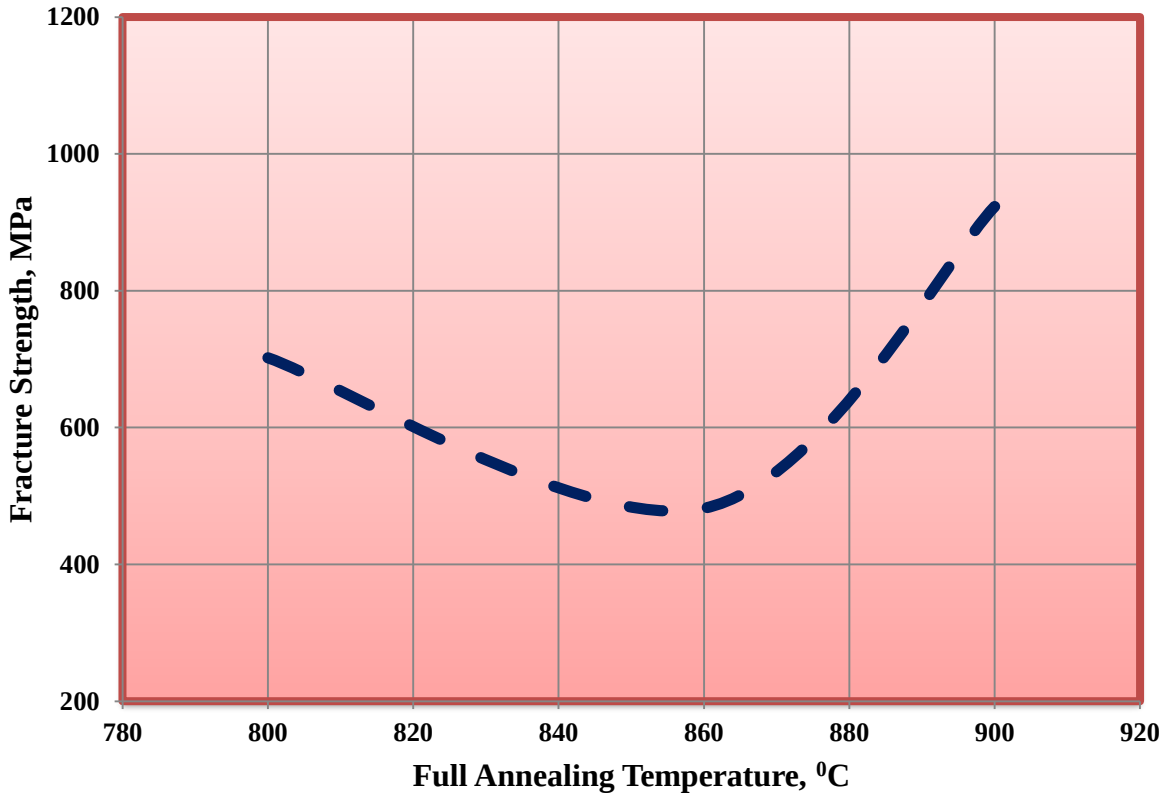

Figure (4) Dependence of fracture strength on full annealing temperature for the ultrahigh- strength low-alloy steel

Figure (5) illustrates the dependence of fracture strain on full annealing temperature for the ultrahigh- strength low-alloy steel type 4140. As it is evident in Figure (5), the fracture strain firstly excesses from 0.268 to 0.278 when full annealing temperature excesses from 800 to 860 ^{0}C and then reduces from 0.278 to 0.194 with rising full annealing temperature from 860 to 900 ^{0}C. The reason for the falling in the fracture strain above 860 °C may be a result of the high heat treatment temperature. Lakhteen, U. [8] 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 Figure (5) indicates, the ultrahigh- strength low-alloy steel type 4140 when fully annealed in the temperature range between 800 °C and 860 °C, the fracture strain exhibits a maximum value with 0.278 at about 860 °C. The lowest value of fracture strain for the ultrahigh- strength low-alloy steel type 4140 occurs at 900 °C.

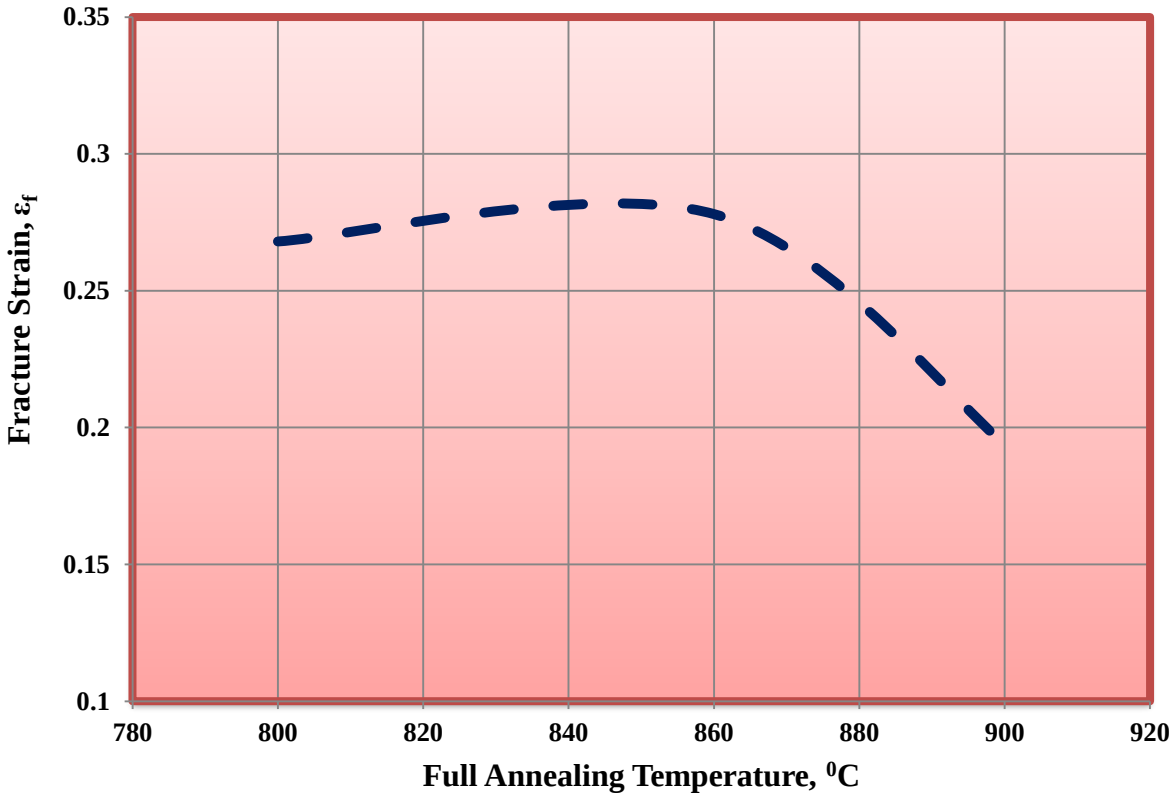

Figure (5) Dependence of fracture strain on full annealing temperature for the ultrahigh- strength low-alloy steel

6. Fracture Surface Examination

It is well known that fracture surface appears the mechanism involved in the process of fracture and gives worthy evidence concerning the cause of failure. Figure (6) shows the appearance of the fracture surface of tested tensile specimens for the ultrahigh- strength low-alloy steel type 4140 at stress-relief temperatures 500, 600 and 660 ^{0}C. From Figures (6) (a), (b) and (c) it can be seen that the fracture surface of specimens tested at stress-relief temperatures 500, 600 and 660 ^{0}C have cup-and-cone ductile fracture. In this type of fractured specimens, the central interior region of the surface has an irregular and fibrous appearance, which is indicative of plastic deformation [2]. The fracture surface of stress-relief specimen at 660 ^{0}C (Figure (6) (c)) has a fibrous appearance which is in good agreement with the stress- strain results which showed an increase in the fracture strain at 660 ^{0}C.

(a)

(b)

(c)

Figure (6) Fracture surface of tensile specimens for the ultrahigh- strength low-alloy steel type 4140, 2x; a) stress relief at 500 ^{0}C; b) stress relief at 600 ^{0}C; c) stress relief at 660 ^{0}C.

Figure (7) (a) and (b) illustrates the fracture surface of full annealing specimens at 800 and 860 ^{0}C for the ultrahigh- strength low-alloy steel type 4140. As it is evident the fracture surface of specimens tested at full annealing temperature at 800 and 860 ^{0}C have typical cup-and-cone ductile fracture with pronounced plastic deformation in the vicinity of an advancing crack. In addition, there will ordinarily be evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing) [2], while this type of fracture is not present at the specimen of full annealing at 900 ^{0}C. Figure (7) (c) reveals that the full annealing specimen at 900 ^{0}C has flat fracture surface (i.e. semi brittle fracture with very little accompanying plastic deformation). The fracture surface may have a grainy or faceted texture.

(a)

(b)

(c)

Figure (7) Fracture surface of tensile specimens for the ultrahigh- strength low-alloy steel type 4140, 2x; (a) full annealing at 800 ^{0}C; (b) full annealing at 860 ^{0}C; c) full annealing at 900 ^{0}C.

6. CONCLUSIONS

Within the scope of this work, the obtained results displayed that, the fracture strength, fracture strain and fracture surface of the ultrahigh- strength low-alloy steel type 4140 depended on the temperatures of the stress relief and full annealing, the following conclusions can be drawn:

1. Stress relieving at 500 ^{0}C produces steel alloy 4140 with high fracture strength.
2. As the stress-relief temperatures increases, the fracture strain increases, and the ultrahigh- strength low-alloy steel type 4140 becomes extra ductile.

3. The highest fracture strength value for the ultrahigh- strength low-alloy steel type 4140 used in this work is observed in full annealing at 900 ^{0}C.
4. Great fracture strain is obtained by full annealing at 860 ^{0}C.
5. Stress relief and full annealing temperatures are a powerful effect on the fracture surface of the ultrahigh- strength low-alloy steel type 4140.

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