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Improving the Microstructure, Mechanical and Magnetic Properties of AISI 4340 Steel Using the Heat Treatment Process

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Abstract

AISI 4340 steel is one of the super strong steels that can be selected for different applications. By designing the proper cycles of heat treatment, the optimum microstructure and properties of this steel can be achieved. In this study, different heat treatment cycles were introduced to achieve the optimum microstructure and improve the mechanical and magnetic properties of AISI 4340 steel. The results of tensile, impact, hardness, metallography and magnetic tests for various samples under different heat treatment cycles showed that parameters such as temperature and time of austenitizing and tempering were among the most important factors in achieving relatively a wide range of ultimate tensile strength (1467-933 MPa), impact energy (113-18 J), transport current density (1554-1347 mT), coercivity (1342-1240 A/M), diminished force (1165.6-947.5 mJ/kg) and microstructure (tempered martensite and bainite). This wide range of properties can lead to a large number of applications of this type of steel in various industries including manufacturing steel parts such as rotors.

Keywords: AISI 4340 Steel, Heat treatment, Strength, Microstructure, Mechanical properties, Magnetic properties

1. Introduction

One of the most rapidly growing fields of metallurgy is designing and developing super strong steels. The particular strength of the steel (strength-to-weight ratio) in many cases is higher than that of aluminum or titanium alloys. Therefore, in terms of the strength, super strong steels can be studied in the category of light alloys. Such super strong steels have been used for critical applications such as missile components, aircrafts, pumps, machineries, axles, dies, etc [1].

Due to rapid advances in technology and the growth of technical knowledge of strong steels in the last fifty years, there is no exact margin to define the properties of this material. The term 'super-strong steel' is somewhat arbitrary, so steels with the strength of 900- 2400MPa in annealed condition are located within the category of super strong steels. Recent reports in aerospace state that these steels are strong enough to be used in applications requiring a yield stress more than 1400 MPa [2].

The main advantage in the selection of super strong steels is their high strength to density ratio. These steels, due to their low inertia, which is because of weight reduction, are an appropriate choice for manufacturing rotating machines or reciprocating parts. These strong steels have the ability to gain strength and good toughness by heat treatment processes. By adjusting the heat treatment parameters, such as temperature and time of austenitizing, cooling rate, temperature and time of tempering, etc., a variety of changes in the microscopic structure of these steels can be obtained [3].

AISI 4340 steel is one of the steels that can be selected for different applications. By designing the proper cycles of heat treatment, the optimum microstructure and properties of this steel can be achieved. The aim of this study was to apply different heat treatment cycles on the steel and determine the appropriate cycles to achieve suitable properties for the use of centrifuge rotor shafts requiring the ultimate tensile strength of 1400 MPa or more. Also, the minimum requirements of magnetic properties of this part are listed in Table 1 [3-4].

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Table 1. The minimum required magnetic properties

Diminished force E, (mJ/kg)	Coercivity force (A/M)	The maximum applied magnetic field Hmax, (A/M)	Transition current density (mT)
925	1250	5000	1300

2. Materials and methods

AISI 4340 steel in hot forged condition with the diameter of 250 mm and the chemical composition brought in Table 2 was used to prepare the samples. Tensile and impact tests specimens were prepared according to ASTM E8-Sub Size and ASTM E23 standards, respectively, and the samples for the magnetic tests were prepared in block shape with the size of $15\times25\times25$ mm^3 based on the size of coils used in the magnetic measurement device. In order to eliminate the effects of oxidation and decarburization of the surface layers, the initial thickness of samples was designed to be 2mm more than that of standard dimensions.

Table 2. Chemical composition of AISI 4340 steel.

Ni	Mo	Cr	S	P	Mn	Si	C	Fe
1.4-1.7	0.2-0.3	0.9-1.4	0.035	0.035	0.5-0.7	0.15-0.35	0.35-0.45	Bal.

After the heat treatment cycle, the sample dimensions were modified by the turning process. According to the CCT diagram of the steel (Fig. 1), the thermal cycles, based on Table 3, were designed and applied to the samples.

Table 3. Designed thermal cycles and the final expected microstructure.

Sample Code	Austenitizing (°C/min)	Quenching environment.	Tempering operations (°C/min)	The final microstructure
A	1000/270	Oil	440/90	Been tempered martensite (rough)
B	860/30	Oil	450/60	Been tempered martensite (soft)
C	860/30	Oil	650/60	Been tempered martensite (soft)
D	845/40	Oil	600/90	Been tempered martensite (soft)
E	850/30	Salt Bath	320/40	Bainite
F	860/30	Oil	470/120	Been tempered martensite (soft)

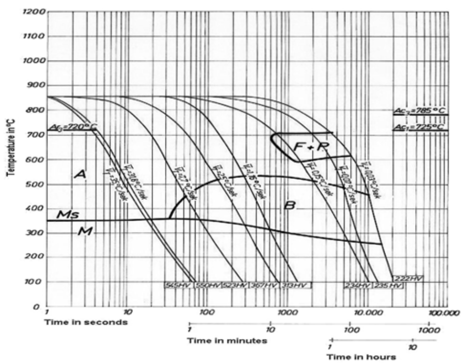

Fig. 1. CCT diagram of AISI 4340 steel

Although, during austenitizing in the electric furnace, the argon gas was used to prevent the oxidation of samples, thicker specimens were manufactured to remove the oxidized surface layer after heating and reach the standard size. The molten salt baths of sodium chloride-sodium carbonate for austenitizing and sodium nitrate-potassium nitrate for quenching were used. For each cycle, three tensile specimens, three impact specimens and a magnetic sample were prepared.

A tensile test with the speed of 5 mm/min was carried out for different samples obtained from different heat treatment cycles. Also, Charpy impact test and Rockwell C method hardness test at the ambient temperature were conducted for the specimens. Moreover, magnetic testing Histogram device, MBA, was used to measure the magnetic properties of the samples. To reveal the samples microstructure, after sandpapering and polishing with diamond paste, the samples were etched with a solution of 2% Nital and to determine the initial austenite grain size, etching solution of Picral was used.

3. Results and discussion

Magnetic and mechanical properties of the samples for different cycles are presented in Tables 4 and 5, respectively.

Table 4. Mechanical properties of the samples after different heat treatment cycles.

Sample Code	Hardness (HRC)	Elongation (%)	Yield strength (MPa)	Ultimate strength (MPa)	Impact energy (J)
A	46	10.5	1338	1467	36
B	42.3	7.7	1398	1466	20
C	24.5	16.2	816	933	113
D	34	18.3	988	1047	74
E	36	16.1	804	1054	18
F	43	11.4	1268	1333	34

Table 5. Magnetic properties of the samples after different heat treatment cycles.

Sample Code	Transition current density (mT)	Coercivity force (A/M)	Diminished force E, (mJ/kg)
A	-	-	-
B	1347	1240	947
C	1528	1276	1113
D	1551	1341	1165
E	1242	1348	957
F	1485	1159	965

Fig. 2 to 5 show the metallographic images of the samples. Also, the measured hysteresis loops (hysteresis cycles) for the samples are shown in Fig. 6 to 8. It can be seen that the results were quite dependent on the heat treatment cycles. In the following, these effects will be discussed.

In Cycle A, since the temperature and time of austenitizing were much higher compared to other cycles, it was expected that the primary austenite grains would grow well and thus, the final structure would consist of coarse tempered martensite grains (Fig. 2).

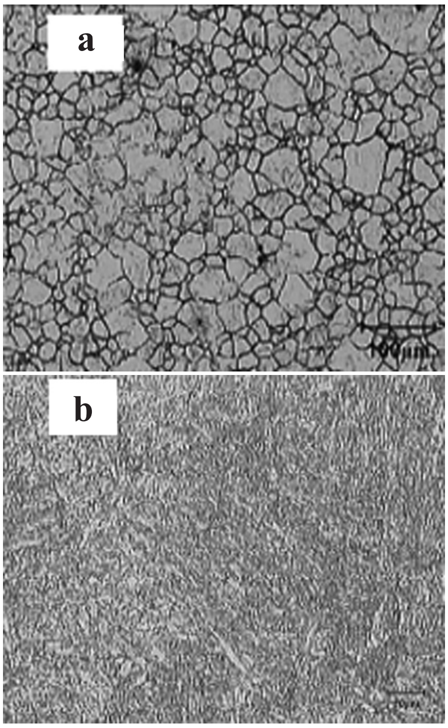

Fig. 2. a) Primary austenite structure and b) final structure after applying cycle A.

Although it was expected that this structure would lead to a decrease in strength and hardness, the strength was increased. This phenomenon can be explained by the increase in the solution of Carbide forming alloying elements presented in the composition at the high temperature of austenitizing process, which, in turn, increased the strength in the later stages of heat treatment.

According to Table 3, the only difference between cycles B and C was the tempering temperature. Therefore, the grain size of the initial and final structure of cycles B and C was almost similar. However, with increasing the tempering temperature to 650 ^{o}C in cycle C, the strength and hardness were decreased and impact energy was increased.

The initial grain size of cycle D microstructure and the final structure were almost the same as those of cycle B (Fig. 3).

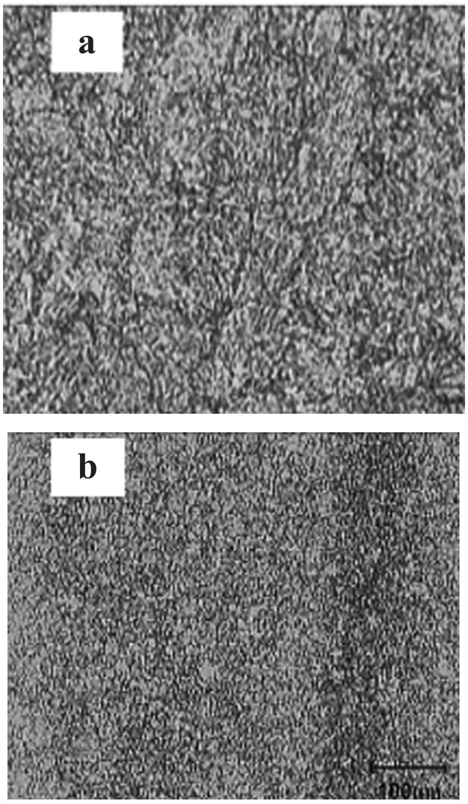

Fig. 3. a) Primary austenite structure and b) final structure after applying cycle D.

With decreasing the tempering temperature and holding time for cycle D, the hardness and ultimate tensile strength were decreased and the impact energy was increased.

Although it was expected that the initial austenite grain size obtained from cycle E would be similar to that of cycles B to D, the final structure was bainite (Fig. 4).

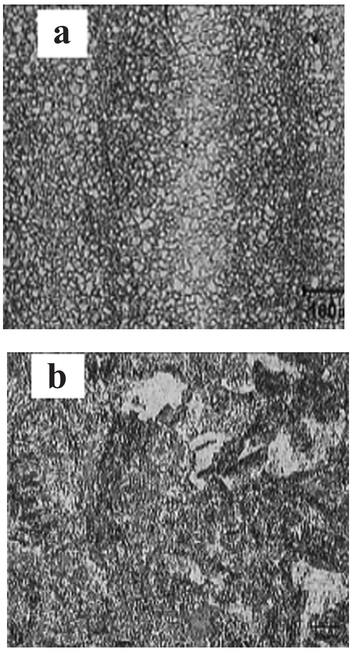

Fig. 4. a) Primary austenite structure and b) final structure after applying cycle E

Therefore, the structure was not unexpected given the design cycle. However, the impact energy of the samples obtained by this cycle was lower than that of other cycles and this result was not consistent with the structure of bainite. In this respect, improper tempering temperature can be raised as the reason. According to some reports, the tempering of this steel in the temperature range of 300-450 ^oC can lead to a kind of embrittlement just similar to the tempered martensite embrittlement due to the formation of Cr_3C_7 precipitates.

The only difference between cycle F and cycle C was the tempering temperature and holding time at this temperature. Hence, the grain size of the initial and final structure of cycle F (Fig. 5) was similar to that of cycle C. However, with increasing the tempering temperature to 470 ^oC for cycle F, the strength and hardness were decreased while the impact energy was increased.

Table 5 presents the results of the magnetic tests of the samples. As can be observed, the samples produced based on cycles C and D showed magnetic properties suitable for device fabrication. Tempering temperature and holding time for the sample produced based on cycle D were longer. This sample was considered to have the most homogeneous and delicate martensitic structure than the other cases based on the above-mentioned reasons, as obtained by the results of mechanical and metallographic tests and the initial grain size of austenitic .

Also, with decreasing the grain size, the coercivity coefficient (Hc) was increased, which was because of smaller particles that made the alignment of magnetic moments much easier.

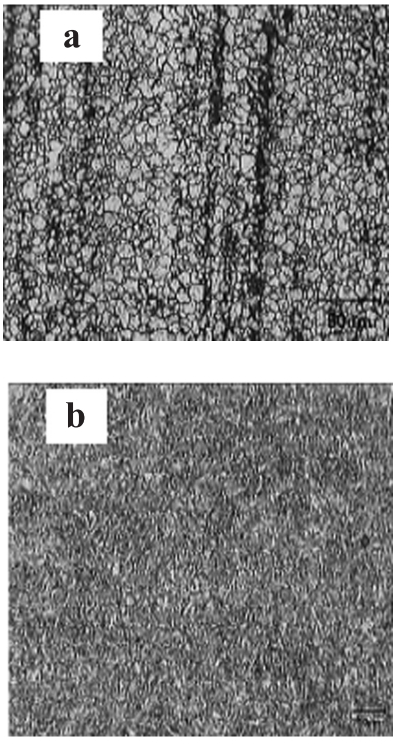

Fig. 5. a) Primary austenite structure and b) final structure after applying cycle F.

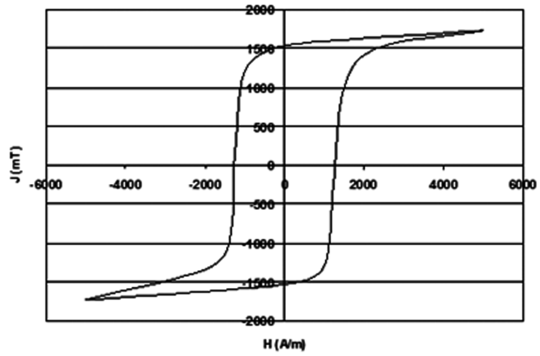

Fig. 6. Hysteresis graph of cycle C.

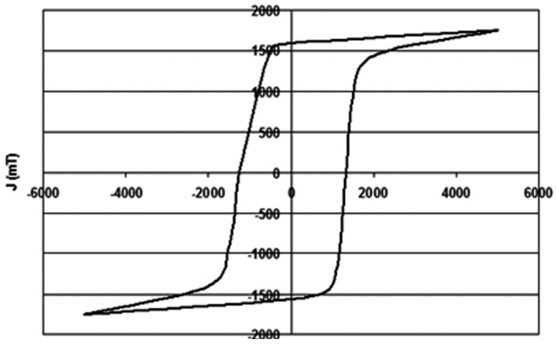

Fig. 7. Hysteresis graph of cycle D.

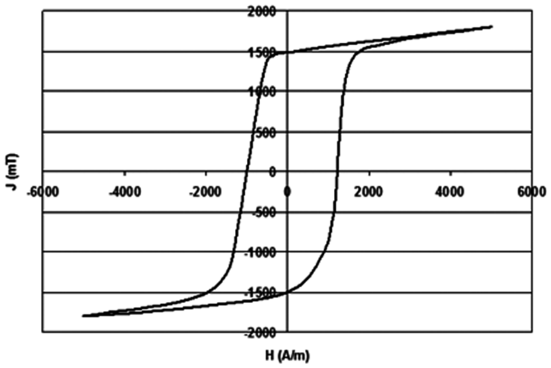

Fig. 8. Hysteresis graph of cycle F.

4. Conclusions

1- With the increase of tempering temperature in the cycles with similar austenitic time and temperature, better magnetic properties were obtained.

2- Since the rotating component of the rotor was mainly under radial stress, other than the magnetic properties, the impact energy and strength should also be noted. Among the designed cycles, samples obtained from cycle D showed the best mechanical and magnetic properties.

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