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Abstract. AISI 4140 steel is widely used in various engine elements, such as connecting rods, crankshafts, axles, piston rods, and sprockets. The purpose of this study was to determine the hardness value and microstructure using temperature variations in the austempering process. The test results show that after the austempering process with temperature variations changed the hardness. The austempering process can increase the hardness value, but after the temperature is raised, the hardness value decreases. The greatest hardness value at 350°C was 264.4 BHN. After increasing the temperature to 400°C, the hardness decreased to 239.1 BHN. At a temperature of 450°C, the hardness was 226.7 BHN. Microstructure observations showed that the bainite is more uniform with increasing temperature. The test results show that the austempering temperature affects the hardness value and microstructure. When the austempering temperature is increased, the hardness value decreases.

Keywords: AISI 4140 steel, austempering, Brinell hardness, microstructure bainite

1. Introduction

AISI 4140 steel is widely applied in several engine components, such as connecting rods, crankshafts, axles, and gears [1]. Due to the application of AISI 4140 steel, it is required to be strong, tough, and able to withstand strong loads or moments [2]. One way to improve the mechanical properties of AISI 4140 steel is through the austempering process. According to research [3-6], the heat treatment process of austempering ductile iron can improve its mechanical properties. In this process, the resulting phase is bainite ferrite combined with high-carbon austenite [7,8].

A study was conducted by Long et al. [6] using 0.6CCrMn2Si steel. This steel is classified as high-carbon steel with 0.6% C and main alloying elements of 1.8% manganese, 1.24% chromium, and 2% silicon. The hardness of 0.6CCrMn2Si austempering steel tends to decrease more with the austempering temperature. Bilal et al. [9] studied medium-carbon steel with a chemical composition of 0.34 C, 1.52 Mn, 1.48 Si, 1.15 Cr, 0.71 Al, 0.93 Ni, and 0.40 Mo (wt.%). The temperature of Ms steel was 310°C. The research objective was to obtain steel with a bainite structure. The austempering temperatures used were 385°C, 350°C and 320°C. Jiang et al. [10] concluded that the bainite transformation at temperatures close to the Ms value has better mechanical properties. Based on several references, the effect of austempering temperature on hardness values and microstructure was the focus of the research.

In the present work, we have conducted austempering heat treatment on a low alloy steel, AISI 4140 steel, under different temperatures for austempering with constant holding time. The goal was to increase the surface hardness of the steel. The Brinell method was used to characterize the hardness property of austempered and non-austempered steel. Microstructural changes due to bainite structure formation in AISI 4140 steel after austempering heat-treated were characterized.

2. Experimental procedure

2.1 Sample preparation

We used a commercial, round, bar shape of AISI 4140 steel that was manufactured with hot forging in this experiment. The bar had a diameter of 16 mm. Raw steel was cut into a specimen with 20-mm length. A specimen surface area was ground using emery paper with 200 to1000 grade silica carbide until the specimen surface was mirror-like and smooth. Later, the specimen was ultrasonically cleaned by immersion into acetone solution for a few seconds.

2.2 Austempering process

Fifteen AISI 4140 specimens were heated in a box furnace at 850°C [1] under dry static air and atmospheric pressure (1 atm) for one hour of holding time. We used a Naberthem furnace with a maximum heating temperature of 1350°C. After the specimen of AISI 4140 steel had reached a uniform temperature of 850°C for one hour, the microstructure of the steel was in the austenite phase. All specimens were taken out from the furnace and directly immersed into a salt solution bath containing a composition of 50% $NaNO_3$ + 50 % KNO_3 (wt.%).

The austempering process was conducted by immersion into the salt solution bath with a holding time of a 1 hour at different temperatures: 350°C, 400°C, and 450°C [11]. After the austempering process, all specimens were taken out from the salt bath and cooled to room temperature. An ultrasonic cleaner was used for washing an austempered specimen by immersion into 500 mL of acetone in a glass beaker for five minutes. The cross-sectional area of each specimen of steel was polished using Autosol paste.

2.3 Sample characterization

RMU Hardness testing (made in Italia) was used to measure hardness specimen using Brinell method. A Brinell test was conducted using a 1-mm sphere-shaped hardened steel indenter (*D*) with 1.980 kN for loading indentation (*P*) for a constant time of 15 s. The diameter of indentation (*d*) formed on a specimen was measured using a profile projector Mitutoyo PJ-H30. Calibration was performed before measuring. Each specimen surface was measured for its hardness at five points in different areas. The hardness value was determined by Equation (1) [1], and the unit of the hardness value was BHN.

$$HB = \frac{2P}{\pi D\left[D-\sqrt{D^2-d^2}\right]} \tag{1}$$

The average hardness value for each specimen is displayed in Fig. 1. The microstructure of the austempered specimens and non-treated specimens were observed using an Olympus optical microscope. The preparation of the microstructure observation was similar to our previous research [2]. The microstructure of the steel was studied at the side of the cross-sectional area.

3. Results and discussion

3.1. Hardness test results

It can be seen in Fig. 1 that the temperature difference of the austempering heat treatment greatly affects the hardness value of the specimen. The hardness value for the raw steel is around 194.7 ± 7.13 BHN.

From the three temperature variations, it can be seen that the highest hardness value is 264.4 ± 6.07 BHN, which happens at 350°C. At a temperature of 400°C, the hardness decreased to 239.1 ± 8.33 BHN. Then, at a temperature of 450°C, the hardness value decreased to 226.7 ± 4.73 BHN.

This proves that in the austempering heat treatment, the higher the heating temperature, the smaller the hardness value is.

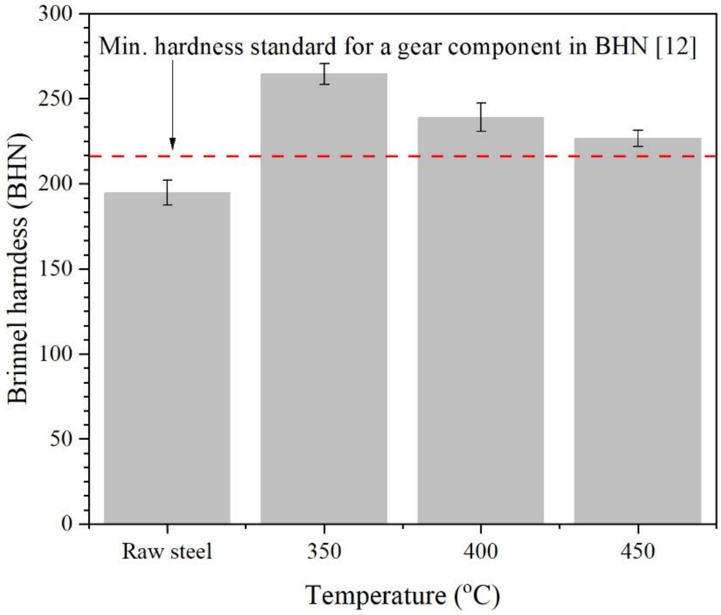

Figure 1. Variations of surface hardness of austempered AISI 4140 steel with different temperatures for austempering at one hour holding time

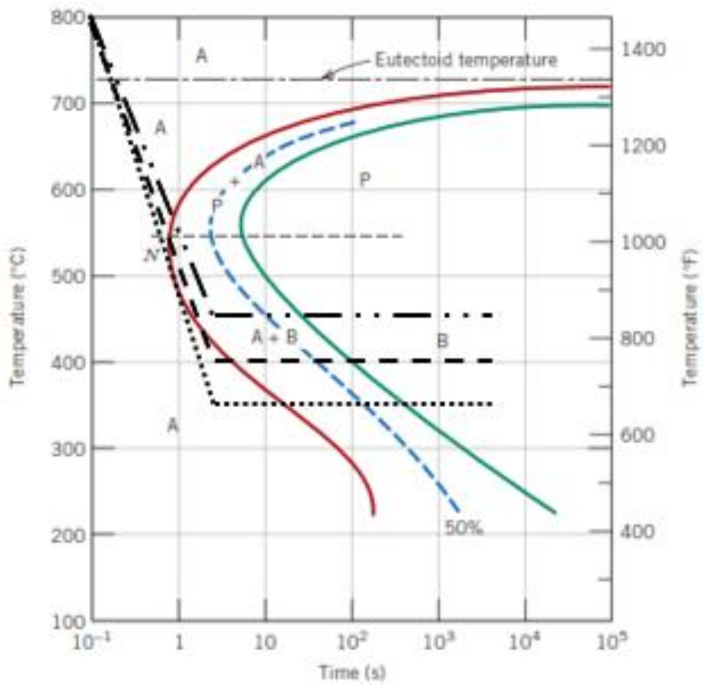

Figure 2. Transformation diagram of AISI 4140 steel austempering with temperature variations [1]

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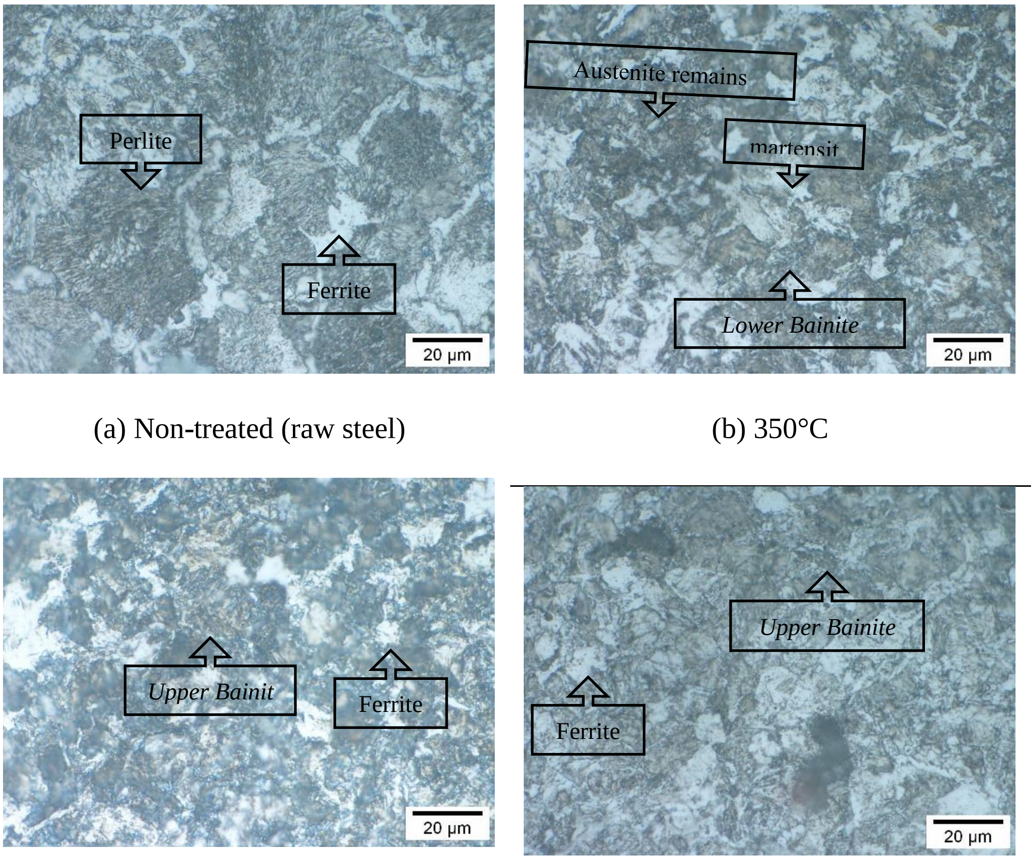
3.2. *Microstructural observation*

In a heat-treatment process, after the heating reaches a specified temperature and is given sufficient holding time, cooling is carried out at a certain rate. The austempering process is displayed in Fig. 2. The mechanical properties of the steel will depend on the microstructure that is determined by the rate of cooling during a heat-treatment. The microstructures of the steel before and after the austempering process are shown in Fig. 3.

The transformation of the austenite in cooling plays an important role in the properties of carbon steel, as demonstrated in phase diagram of Fe-Fe_3C [11]. When cooled slowly to the A3 temperature, austenite from hypoeutectoid steel begins to form a crystalline core of austenite. This transformation occurs due to a change from gamma iron (γ-austenite) to alpha (α-ferrite). Since ferrite can only dissolve very small amounts of carbon, the carbon content in the austenite will be even greater if there is much ferrite growth with decreasing temperature.



(a) Non-treated (raw steel) (b) 350°C

(c) 400°C (d) 450°C

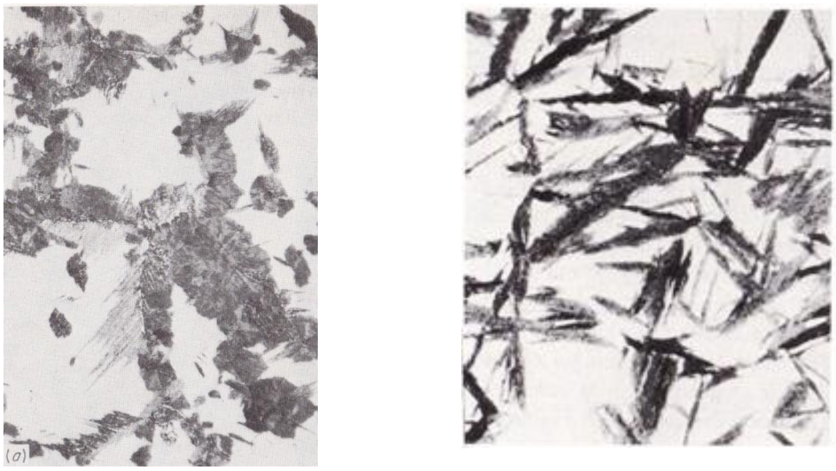
Figure 3. Microstructure of AISI 4140 steel subjected to austempering treatment

There is large carbon content at the critical temperature of A3, so when the temperature reaches the critical temperature of A1, the composition of the austenite is the same as the composition of the eutectoid composition, and at that time, the austenite deforms into pearlite. Pearlite is a special mixture of two phases and is formed when austenite with a eutectoid composition simultaneously transforms into ferrite and ferrous carbide [2,12]. The basic structure of pearlite is a lamellar structure composed of layers of ferrite and cementite [13].

The growth of pearlite begins with the growth of a cementite core at austenite grain boundaries. For cementite to grow, a large amount of carbon is required to be obtained from the surrounding austenite, so the austenite around cementite is poor in carbon and becomes ferrite. This atomic displacement takes place by diffusion, so it requires sufficient time.

In the tempering process, when the austenite is rapidly cooled, the transformed products of the austenite will change into new phases known as bainite and martensite. Bainite is formed when the austenite is subjected to a moderate cooling rate (slower than the rate required to form martensite but faster than the rate required to form pearlite) and the austemper temperature is kept constant. Bainite is a non-lamellar microstructure and is a mixed microstructure of ferrite and cementite phases [8]. This transformation of bainite is due partly to the diffusion process and partly to the non-diffusion process. The bainite structure obtained from the transformation at high temperatures has a feather-like shape, and at low temperatures, it has an accicular shape [14,15].

Martensite can occur when austenite is cooled very rapidly to a temperature below the temperature of bainite formation [1]. Martensite is a supersaturated solid solution of carbon in ferrite. It is very hard and brittle. With very fast cooling, there is not enough time for the carbon to diffuse out of the solid solution of the austenite, so the transformation occurs by shifting the atoms from face-centred cubic (FCC) structure to the body-centred tetragonal (BCT) structure.



(a) (b)

Figure 4. Microstructures for (a) upper bainite-feathery like shape and (b) lower bainite-like needle-like shape [16]

In the AISI 4140 steel, the initial condition was tested by the Brinell hardness test, which obtained an average hardness value of 194.7 BHN. This hardness value is lower than that of the hardness value AISI 4140 steel for a gear component [12]. The results of the microstructure analysis show that the microstructure of AISI 4140 steel has a pearlite phase and a ferrite phase (Fig. 3a). The ferrite phase has a light colour and is soft. Meanwhile, perlite is dark in colour and hard compared to ferrite. The results of the hardness test showed that AISI 4140 steel that was subjected to the austempering process with a temperature variation of 350°C had the highest hardness value among other temperature variations (264.4 BHN). The austempering process can change the microstructure. This structural change is caused by a heating process with a high-enough temperature and then cooling it with a fast cooling rate.

The residual austenite formed white and uniform spots, ferrite structure was also visible, and the lower bainite microstructure was also formed (Fig 3b). The combination of martensite and the formation of bainite causes the hardness value of the specimen to increase. In this condition, the austenite does not have time to remove carbon from its crystals, which results in the structure becoming body cubic tetragonal (BCT).

According to Speer et al. [12], the classification of bainite is generally based on the temperature area of its formation. Upper bainite is formed isothermally in the temperature range of 400–550°C, while lower bainite is formed isothermally in the temperature range of 250-400°C [13,14]. Upper bainite microstructures in AISI 4140 steel formed at 400°C and at 450°C are presented in Fig. 3c and Fig. 3d, respectively. Upper bainite is a structure that is formed at relatively high temperatures and looks like feathers (Fig. 4a) [16]. Lower bainite is a structure formed at relatively low temperatures (close to Ms) and looks like needles, as seen in Fig. 4b [16].

4. Conclusion

The following conclusions about the effect of austempering on the hardness value of AISI 4140 steel were obtained that the greatest hardness value was 264.4 BHN, which was achieved at the austempering temperature of 350°C. Hardness and microstructure values were affected by the austempering temperature. When the austempering temperature was decreased, the hardness value increased. Also, observation of the microstructure showed that bainite is more uniform with increasing temperature.

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