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EFFECT OF HEAT-TREATMENT TEMPERATURE ON THE MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF AISI 4140 STEEL

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ABSTRACT

Heat treatment is a metallurgical process for removing residual stresses in metals, improving their mechanical properties, reducing surface hardness, and preventing the formation of brittle fractures or cracks. The tempering (age hardening) process, which is a type of heat treatment in tempered steels, affects the mechanical and microstructural properties of the steel more than the other steel types. In this study, the base material test specimens with 13 HRC hardness and 12.5 mm diameter were heat-treated and tempered, and the effect of the heat treatment process on the mechanical and microstructural properties was investigated. AISI 4140 tempered steel was tempered at 600°C for 3 hours after 3 hours of heat treatment at 880°C, 850°C and 820°C and cooled in oil. While the base material has a tensile strength of 654.16 ± 12 MPa, the maximum tensile strengths were determined as 1022.44 ± 10 MPa, 1006.24 ± 9 MPa and 987.454 ± 11 MPa, respectively, after heat treatment at 880°C, 850°C and 820°C. The strength of the material increased by 56.29% by applying heat treatment at 880°C temperature. This increase in strength is associated with the transformation of the existing microstructure from ferritic to martensitic structure. The needle-like structure in the martensitic structure increased and lath martensite structure was formed with the combination of grain boundaries with increasing heat treatment temperature. Strength and hardness increased while the heat treatment temperature is increasing. It was observed that ductility decreased. Hereby, the temperature parameter in the heat treatment process is effective on the strength and the heat treatment has high advantages in terms of material saving in machine designs.

1. INTRODUCTION

Tempered steels are alloyed and non-alloyed machine-manufacturing steels that are suitable for hardening, especially in terms of carbon content, and show high tensile strength and high toughness at the end of the heat treatment process [1, 2]. Tempered steels can be used as non-alloy tool steel, alloyed cold work tool steel, high strength general construction steel, spring steel, heat resisting steel, nitriding steels and heavy forgings [3]. The number of steel applications can be expanded even more with the introduction of modern steel processing technologies [4, 5, 6]. In the manufacture of machine parts, the selection of appropriate materials and the heat treatments applied to these materials are of great importance. AISI 4140 (42CrMo4) steel, which is in the tempered steel class, is preferred where high strength and weldability are required [7, 8, 9]. The properties of a material can be changed by heat treatments and the addition of other alloying elements [10]. Martensite structure is one of the most common strengthening phases in steels. In addition, the carbon content of the metals affects the martensite structure hardness and hardening properties [3]. The surface properties, mechanical and microstructural properties of these steels can be improved by heat treatment processes [11, 12]. AISI 4140 steel, which is one of the tempered steels used in the manufacture of machine parts, is widely used in the automotive industry [13, 14, 15]. After the heat treatments applied to this steel, it has the desired mechanical properties. Heat treated 4140 steel is used in the manufacture of various machine elements such as crankshaft, axle shaft, splined shaft, bolts, nuts, studs, gear wheels, piston rods, cold drawn shaft and springs, and in the production of work machines [15]. The most important factors that determine the properties and conditions of use of materials are microstructure and mechanical properties. Mechanical properties are of great importance in material selection and can be improved by various methods such as increasing the carbon ratio, alloying, heat treatment, among the most common ways to increase the mechanical properties in steels [11, 16, 17]. Depending on the phase diagrams of metals and alloys, the desired mechanical properties and microstructures are obtained with different processes applied at temperatures below the melting temperature with the help of heat treatment procedure [18].

Heat treatment consists of three main stages. These are heating, holding at a certain temperature and cooling stages [19]. Heat treatment is a controlled process that increases the service life of parts by changing the microstructure of

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materials such as metals and alloys, improving properties such as surface hardness, temperature resistance, ductility and strength. Various heat treatments are applied to steels in order to increase material life and reduce processing costs [16, 20]. The fragility and hardness of the material decreases, its toughness increases, and the stresses in the structure are reduced by means of tempering process, which is a heat treatment process. Tempering or age hardening is the heat treatment carried out under transformation temperatures to remove brittleness and impart toughness to quenched steels. By keeping the metal at high temperature, the carbon atoms in it are stabilized. The metal, which is kept at high temperature for sufficient time, is suddenly cooled and can be applied to alloyed and non-alloyed steels.

There are many studies in the literature on the effects of heat treatment on the mechanical properties of steels [3]. Köksal et al. [16] applied the tempering process to steels with different carbon ratios at 100, 200, 400 and 600°C after quenching and investigated the change in the mechanical properties of the materials. They found that yield and tensile strength values increased depending on the increase in carbon content. Saraç et al. [1] investigated the effects of tempering heat treatment temperature applied after quenching of AISI 4140 tempered steel on the mechanical properties of the steel. The samples were quenched at 850 °C and then the samples were tempered at four different temperatures. They determined that the hardness value reached its maximum at 300°C, which is the lowest tempering temperature. Balan et al. [21] investigated the microstructural changes during the tempering of the steel to examine the structure-fracture-property relationship on 16Cr-2Ni steel. They found that tempered 16Cr-2 Ni caused the precipitation of fine austenite particles, which appears to be primarily responsible for the significant secondary hardening of the martensitic stainless steel. Gurumurthy et al. [22] investigated the mechanical characterization of medium carbon AISI 1040 and 4140 duplex steels and their mechanical characterization after heat treatment at temperatures of 750, 770 and 790°C. As a result, they found that the heat-treated samples showed better ductility and toughness. In addition, AISI 1040 steel showed higher ductility and toughness compared to AISI 4140 steel, while AISI 4140 steel had better mechanical properties in UTS (Ultimate Tensile Strength) and hardness. Laxmi et al. [5] investigated the mechanical properties of 42CrMo4 steel using different oil acids and also carried out tempering at different temperatures. They determined that the bainite tempered martensite formed during tempering showed excellent toughness and confirmed with the tensile test result. Nayak et al. [23] studied the effects of quenching in medium carbon and high carbon steel on the change of microstructure and consequent changes in hardness. As a result, they observed that in medium carbon steels, higher carbon cleavage and stabilization of austenite from martensite to retained austenite occur when martensite has a higher carbon supersaturation after treatment obtained at low heat treatment temperature.

In this study, the effect of temperature difference applied in the heat treatment procedure of AISI 4140 tempered steel on mechanical and microstructural properties was investigated. For the experimental research, hardness, tensile tests, and FESEM analysis were applied to the samples of AISI 4140 steel and heat treated at different temperatures. Thus, the mechanical effects of the heat treatment of AISI 4140 steel at different temperatures were determined in detail.

2. EXPOSITION

AISI 4140 steel, which is easily obtainable and widely used for industrial heat treatment applications, has been studied to determine its effects on heat treatment temperatures [24]. In this study, mechanical and microstructural tests were applied to AISI 4140 steel and AISI 4140 steel after heat treatment. The test sample dimensions used for the tensile test are presented in Fig. 1. The tensile test specimens for heat-treatment process are presented in Fig 2. The chemical composition of 4140 steel is presented in Table 1. Mechanical properties of AISI 4140 steel are presented in Table 2.

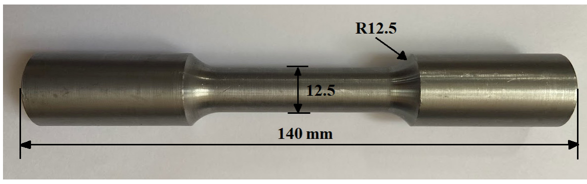

Fig. 1. AISI 4140 tensile test specimen dimensions

Fig. 2. AISI 4140 tensile test specimens

AISI 4140 test specimens are numbered from 1 to 12. The samples were preheated at 400°C for 2 hours in Ipsen brand DL (1200) model preheating/tempering furnaces. Then, in İpsen brand RTQF-XL (1200) model heat treatment furnace; Heat treatment process was applied to samples 1,2 and 3 at 820°C, samples 4.5 and 6 at 850°C, and samples 7,8 and 9 at 880°C. After being kept in the furnace atmosphere with a carbon content of 0.4% C for 3 hours, it was cooled in Petrofer brand ISORAPID 277 HM model heat treatment oil. No heat treatment was applied to samples 10, 11 and 12 (Fig. 3). The mixer speeds of the oil are 1500 rpm, the oil temperature is 60°, and the waiting time in the oil is 30 minutes. Then, tempering process was applied in İpsen brand DL(1200) model preheating/ tempering furnace. After heat treatment, all samples were tempered at 600° for 3 hours.

Steels with high carbon content are oil-hardened against the risk of cracking. Because the cooling rate of the oil in the oil quenching process is slower than the cooling rate of the water. The oil temperature at which the cooling rate is most efficient is between 50°C and 80°C. In this study, the temperature of the oil in the hardening process was taken as 60°C.

Three different heat-treated specimens were subjected to mechanical and microstructural tests such as Rockwell C hardness, tensile testing and, FESEM analysis.

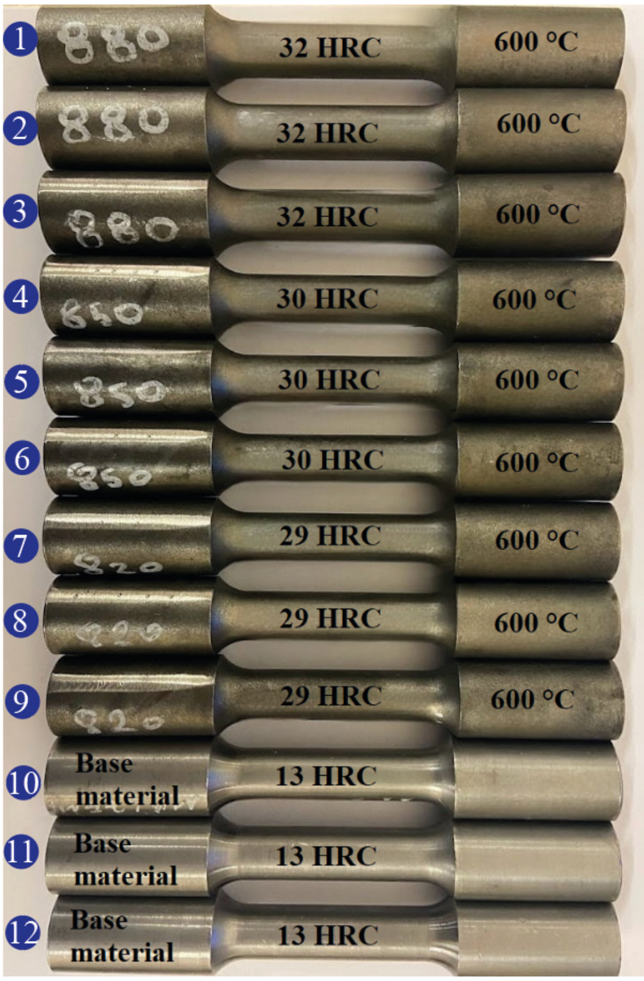

Fig. 3. AISI 4140 tensile test specimens after heat-treatment

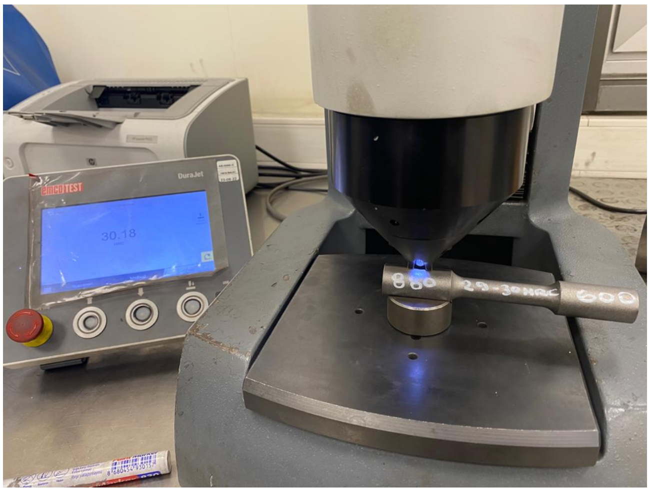

Fig. 4. Rockwell-C hardness measurement

For the microhardness test, a ball-shaped tip was dipped on the heat-treated samples and a main load of 150 kN was applied after a 10 kg (100 N) preload was applied. Rockwell C hardness values were obtained from the existing gauge by finding the depth increase in the permanent trace that occurred after the main load was removed. Hardness test was carried out with Struers Emco-test DuraScan G5 brand device according to ASTM E18-22 standard (Fig. 4).

Tensile test specimens were prepared with a length of 140 mm and a diameter of 12.5 mm, and the tensile test was performed according to the TS 138-A standard (Fig. 5). It was performed in three repetitions with the ALŞA AB-0066-K test device at a tensile speed of 5 mm/min at 22°C room temperature.

Standard metallographic sample preparation processes such as cutting, mounting, sanding, polishing, and etching were performed for microstructure investigations and AISI 4140 specimens were visualized at 1.00KX and 2.00KX and 3.00KX magnification with the help of FESEM (Carl Zeiss Gemini 500 FESEM).

Cutting process was done with Struer brand CitoPress-5 model device. Struer brand Tegramin 25 model abrasive grinding and polishing device was used for sanding and polishing processes. SiC abrasives with 120, 240, 400, 800, 1200 mesh sizes were used for sanding and sanding was carried out in the presence of water to prevent any deformation on the samples. 3% nital (97 ml Ethanol + 3 Nitric acid) solution was used for etching.

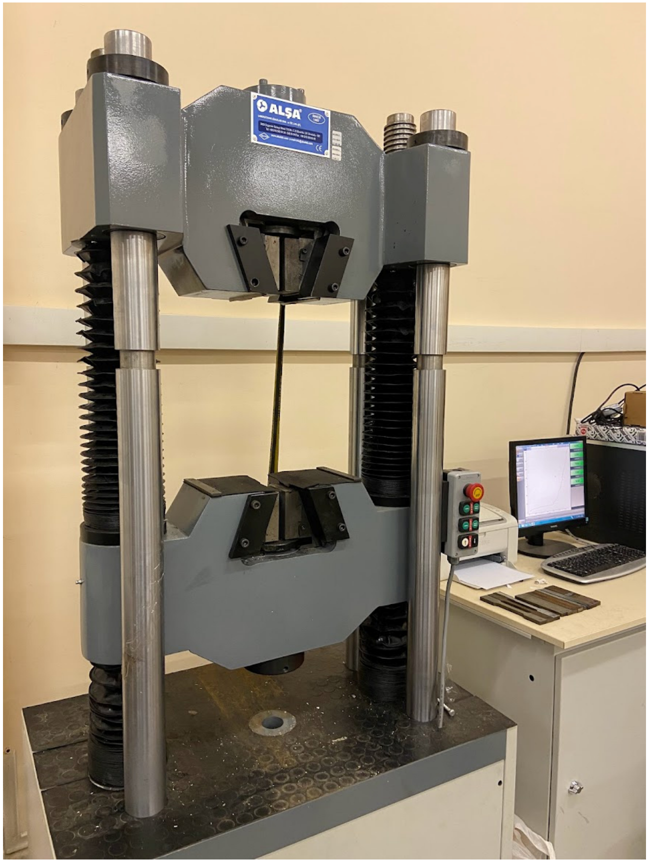

Fig. 5. Tensile testing device (ALŞA AB-0066-K)

Table 1 *Chemical composition of the AISI 4140 steel (wt%)*

C	**Cr**	**Mo**	**Mn**	**Si**	**S**	**P**	**Ni**	**Fe**
0.4	*1.12*	*0.18*	*0.93*	*0.33*	*0.031*	*0.025*	*0.17*	*balance*

Table 2 *Mechanical Properties of the AISI 4140 steel (wt%)*

Mechanical Properties	***4140 Steel***
Tensile Strength (MPa)	*655*
Yield Strength (MPa)	*415*
Bulk Modulus (GPa)	*140*
Shear Modulus (GPa)	*80*
Elastic Modulus (GPa)	*190-210*
Poisson's Ratio	*0.27-0.30*
Elongation at Break	*48.2%*
Rockwell Hardness	*11-13*

Result and Discussion

In this study, heat treatment was applied to AISI 4140 steel and its effect on mechanical and microstructural properties was investigated. It was determined that the heat treatment process temperature influenced strength and hardness and, microstructure.

Mechanical Investigation

As a result of the hardness tests performed for the numbered test (Fig. 3) specimens, the surface hardness of the samples was measured as 29 ± 3 HRC for samples 1,2 and 3, as 30 ± 3 HRC for samples 4,5,6, and as 32 ± 3 HRC for samples 7,8,9. The base material samples numbered 10,11,12 was measured as 13 ± 2 HRC (Fig. 6). The increase in hardness has been attributed to the formation (820°C) and development (850°C, 880°C) of the martensitic structure formed by increasing temperature in the structure [20].

In the tensile test, the maximum tensile strength was observed in the heat-treated sample at 880°C. The highest % elongation value was observed in untreated base metal as 45.345%. The lowest elongation value was observed as 27.088% in the sample that was heat treated at 880°C and tempered at 600°C. In the research carried out on tensile test specimens, it was determined that the tensile strength increased with increasing heat treatment process temperature, while the ductility decreased (Fig. 7). The stress-strain graph obtained from the tensile test is presented in Fig. 8.

As the heat treatment process temperature increased, the tensile strength increased. Gurumurthy et al. [22] applied heat treatment process to AISI 4140 and AISI 1040 steels at different temperatures (750, 770, and 790°C) and as a result, they observed that the yield and tensile strength values of both materials increased after the heat treatment process. Calik et al. [20] similarly determined that martensitic transformation occurred in the structure in the heat treatment process. The change in mechanical properties above 50% without weight change was attributed to the microstructural change occurring under the influence of the heat treatment process temperature (Fig. 9).

Microstructural Investigation

FESEM (Field Emission Scanning Electron Microscopy) microstructure examination of AISI 4140 steel was carried out. According to the results of the FE-SEM analysis, untreated 4140 steel has a ferritic microstructure like the general structural steel microstructure (Fig 9a). After the heat treatment, a martensitic structure was observed after the phase transformation in the microstructure in Fig. 9b-d. It was determined that the martensitic needle-like geometries increased from Fig 9b to Fig 9d as the heat treatment process temperature increased. Structures formed by the combination of grain boundaries are also observed in Fig 9c-d. Elongated lathes were formed at 850°C in Fig 9c. These structures were further developed at 880°C. The increase of these needle structures and formed lath martensite formed in the microstructure and observed in Fig 9 increased the strength while decreasing the ductility. Maximum strength was also obtained at 880°C, where the lathe size reached its maximum [5, 11]. Saraç et al. [1] performed a heat treatment process on 4140 steel and observed that the change in hardness, tensile and yield strength values is related to the phase transformation occurring in the microstructure of AISI 4140 steel.

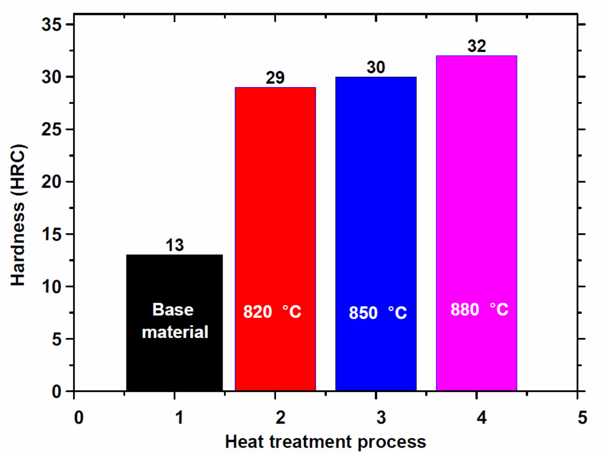

Fig. 6. Rockwell-C hardness graph

Fig. 7. Fractured tensile specimens after tensile testing

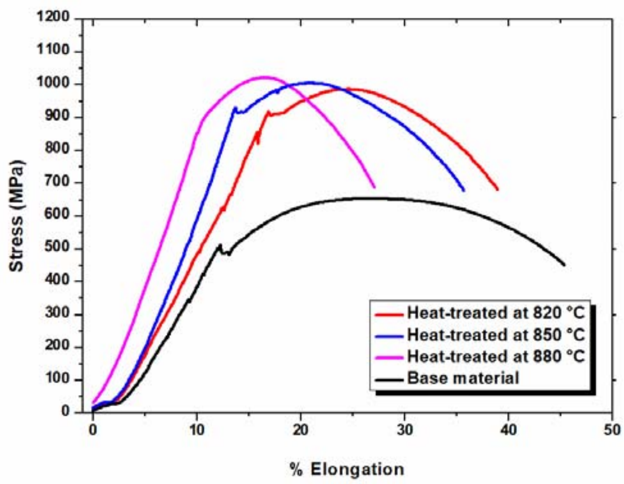

Fig. 8. Tensile test graph

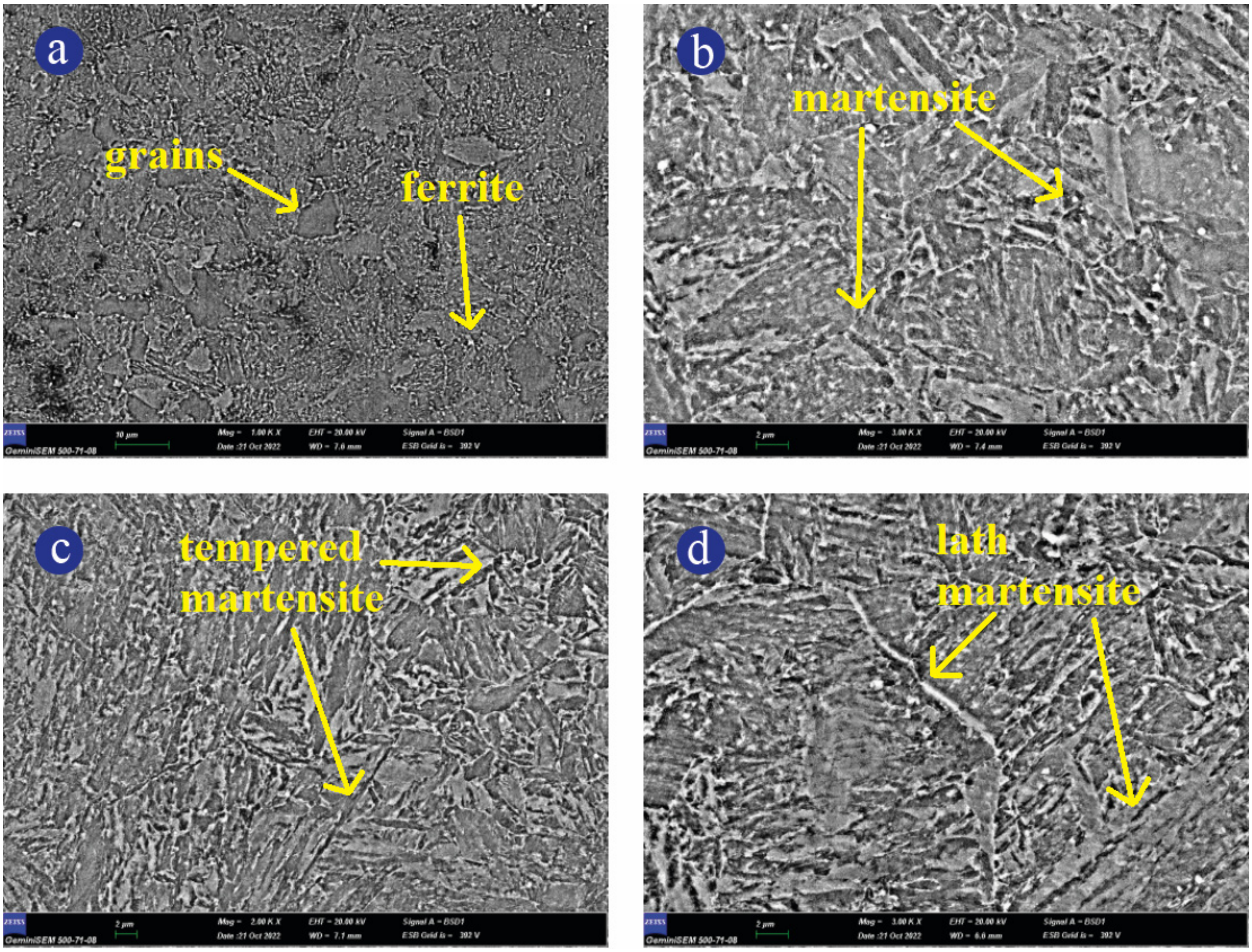

Fig. 9. FESEM microstructure of AISI 4140 a) Base material (1.00KX magnification) b) Heat-treated at 820 °C (3.00KX magnification) c) Heat-treated at 850 °C (2.00KX magnification) d) Heat-treated at 880 °C (3.00KX magnification)

3. CONCLUSION

In this study, the effect of different heat treatment process temperatures on mechanical and microstructural properties was investigated on tensile samples for AISI 4140 steel. It was determined that different process temperatures were effective on strength and microstructure. Obtained results are listed below.

1. The lowest hardness value was determined in the samples that were base material as 11 HRC. The highest hardness was determined as 32 HRC in the tempered samples. Strength and hardness increased with increasing heat treatment temperature.
2. The tensile strength of AISI 4140 base material without heat treatment was determined as 654.162 MPa. The maximum tensile strength was determined in the material that was heat-treated at 880°C and tempered at 600°C temperature. It was observed that the ductility decreased. It was concluded that the temperature parameter in the heat treatment process influences the strength.
3. According to the FESEM analysis microstructure results, it was observed that the microstructure changed from ferritic to martensitic after heat treatment process. In addition, it was determined that the hardness and tensile strength values of the martensitic structure increased.
4. Heat treatment at different temperatures revealed a difference of ~30 MPa in the tensile strength of the materials. An increase of ~56.29% was observed compared to the untreated condition.
5. The production of light-weight systems in industry and material saving can be achieved with the help of the heat treatment process.

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