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Effect of heat treatment on the performance of 30MnB4 steel for being used as grade 10.9 bolt material

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Abstract: Due to technological advancements, alloy steels are now widely used in producing high-strength bolts through various heat treatments. One of the essential features desired in bolts is their strength, as they are subject to heavy loads. This strength is referred to as bolt quality, and interest in heat treatment methods applied to increase the strength of alloy steels is increasing. The mechanical properties achieved from different heat treatment methods and chemical compositions vary. This study aimed to impart the mechanical properties of grade 10.9 steel bolts onto 30MnB4 steel by applying different heat treatments. The effects of tempering temperature on tensile strength, yield strength, elongation at break, reduction in cross-sectional area at break, hardness, and notch impact values at -20 °C were examined by passing the prepared samples through five different tempering processes after preheating, annealing and quenching processes. The results revealed that the mechanical properties of grade 10.9 steel bolts were imparted to 30MnB4 steel at all tempering temperatures applied within the scope of the study. Yield strength, tensile strength, hardness, and -20 °C notch impact values increased as tempering temperature decreased, while elongation at break decreased. This study adds 30MnB4 steel to the literature as an alternative material that can be used to produce grade 10.9 steel bolts. In addition, mechanical properties obtained depending on tempering temperatures have also revealed the usability of 30MnB4 steel for different applications requiring high strength and toughness values.

Keywords: 30MnB4 steel, Grade 10.9 steel bolt, Heat treatment, Tempering, Mechanical properties.

1. Introduction

Many companies in the steel industry that are able to keep up with and effectively utilize advancing technology are able to select low-cost materials with desired mechanical properties among the increasing variety of products, providing a significant advantage over their competitors. Low cost in material selection can be achieved by incorporating newly developed low-cost materials or by developing existing materials to obtain the desired properties. The desired properties of a product vary depending on its use and purpose, and the desire to increase strength without increasing density or without decreasing ductility is a common goal in many products.

Methods such as strengthening by grain size reduction, solid state strengthening, strain hardening, precipitation hardening, and quenching can be used to increase strength. From the point of view of strength enhancement, which of these methods will be used in the product should be evaluated in terms of cost and feasibility. Strength, hardness and toughness can be increased by adding alloying elements to steel, and properties such as hardenability, corrosion resistance and high-temperature resistance can be imparted. For this purpose, elements such as Mn, Si, Cr, Ni, Mo, W, V and Ti can be added to steel at different rates. These steels also belong to the group of alloy steels [1]. As an example of the effects of the alloying elements, Mo can be added to alloy steels to increase hardenability and reduce susceptibility to temper embrittlement, Ni can be added for better corrosion resistance, P and S can be increased to improve machinability [2], Cr can be effective in forming carbides that contribute to the enhancement of matrix strength in alloy steels [3]. Although different properties can be imparted to steel by alloying, if it is done for the purpose of gaining strength, it may cause difficulties in shaping the material due to the gained strength. The advantage of using heat treatment to increase strength compared to other methods is that it can provide an advantage in situations where shape changes are required in previous stages of the process [4]. In addition, strength can be increased without changing the initial chemical composition.

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To provide extra properties to steels, both alloying and heat treatment can be used in some applications, as in the case of 30MnB4 steel. B alloy in 30MnB4 steel, which is a low-alloy steel, is used to increase strength and hardenability [5], while Mn is used to reduce brittleness and increase strength [6]. Low-alloy steels containing boron are widely used in many industrial applications such as gas and oil pipelines, construction and automotive, replacing high-carbon and low-alloy steels used in sheet and strip form due to their low cost [5]. Oruc et al. [7] mentioned in their study about low carbon steel 19MnB4 that, the addition of a relatively small amount of B to steel produces an equivalent improvement in hardenability as other more expensive elements that require significantly larger amounts to be added. Erdogan [8] compared the effects of heat treatment temperatures on the mechanical properties of 42CrMo4 and 30MnB4 steels.

There are limited studies in the literature regarding heat treatment applications of low-alloy steels containing boron. It was stated by Arman that boron steels are easily machinable and exhibit very good mechanical properties after applied heat treatments [9]. Çarboğa et al. [10] expressed that wear behavior and deformation properties were improved by heat treatment methods in boron steels. Haracic mentioned that the steel with and without B shows almost no variation in surface hardness but a significant difference in hardenability [11]. The inclusion of 30 ppm of B in steel with around 0.15 % C, 1 % Mn, and 0.9 % Cr results in a significant increase in hardness, by nearly 50 %, at a greater depth from the surface compared to steel with the identical composition but without B [11]. The fracture behavior of zinc-coated screws made of 30MnB4 steel was searched by Krawczyk et al. [12]. The samples made of 30MnB4 steel were compared after proper and improper heat treatment followed by baking performed as a means of dehydrogenation. They obtained significant differences between the sample quenched but not tempered (process no.2) and the other sample quenched and tempered (Process no.1): The microstructure of the sample deal with process no.2 has a high number of carbides as compared to the sample deal with process no.1.

Bozca and Kinit [13], studied on effect of the heat treatments on the mechanical properties of 30MnB4. They revealed that the values of yield strength and tensile strength assured the required yield strength values RP0, 2 and tensile strength values Rm presented in the literature. An other study deal with the effect of heat treatment was conducted by Zhu et al. [14]. The effects of quenching temperature on tempering microstructure, mechanical properties and wear resistance of 30MnB steel were evaluated. the tensile strength of 30MnB was about 1350 MPa after quenching at 840 °C - 900 °C and then tempering at 200 °C. The wear morphology was defined as fine wear mark, shallow furrow and ridge augmentation. Khoma et al. [15] investigated the effect of the heat treatment of 30MnB5 steel on its micromechanical properties and resistance to abrasion wear. They stated that the highest wear resistance of 30MnB5 steel is achieved when the steel is quenched and tempered at 200 °C, resulting in a hardness of 54 and 49 HRC.

This study evaluated whether 30MnB4 steel, a low-alloy boron steel, can be used as bolt material in high-strength bolts, such as grade 10.9 steel bolts. In this context, preheating, annealing, oil quenching and tempering were applied, and 5 different tempering temperatures were performed to determine the effect of tempering on the mechanical properties of heat-treated 30MnB4. The obtained results were evaluated taking into account the mechanical properties and chemical composition data that the bolts made of alloyed steels should have according to their quality (property class) specified in the standard ISO 898-1 [16], and the appropriate tempering temperature was determined

2. Materials and Methods

2.1. Material Preparation

The purpose of this study is to impart the quality characteristic of grade 10.9 carbon steel to 30MnB4 (DIN 1.5526) steel. In this context, 5 different tempering temperatures were studied to determine the effect of tempering to be performed after the quenching process.

The initial material, 30MnB4 steel, used in the study was supplied by Kroman Çelik company as Ø20 coil (casting number: 10037827, and coil number: 1003782702). After the straightening process was performed in the coil straightening machine, samples with dimensions of 250 mm were cut in a band saw.

2.2. Heat Treatment

Heat treatment was applied to samples with a diameter of 20 mm and a length of 250 mm obtained from 30MnB4 steel material, as illustrated in the flow chart in Figure 1. The samples were heated to 450 °C at a heating rate of 600 °C /h and kept at this temperature for 60 minutes. Then, the samples were heated to 860 °C at a heating rate of 600 °C /h and kept at this temperature for 90 minutes. After the annealing process was performed by waiting 90 minutes at 860 °C, the samples were quenched by cooling

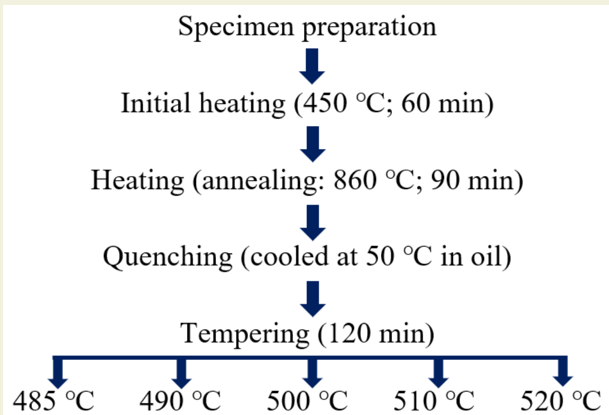

Figure 1. Flowchart diagram to present the heat treatment process performed on 30MnB4

them in oil at 50 °C. To determine the effect of the tempering process on the mechanical properties, tempering was performed at 5 different temperatures in the range of 485 - 520 °C for 2 hours.

2.3. Characterization

2.3.1. Chemical Composition

The chemical composition of the commercially obtained 30MnB4 steel was determined using an optical emission spectrometer for metals (Solaris S5).

2.3.2. Microstructure

Microstructure analysis was performed on both the commercially obtained initial material and the sample obtained after the oil quenching process to determine its microstructure and changes. For microstructure analysis, a 10 mm thick piece was cut and mounted in bakelite (Metkon, Ecopress 50), the surface was prepared for microstructure analysis on a grinding and polishing machine (Metkon Forcipol 2V) and then the obtained surface was etched with 5 % Nital. To facilitate comparison, images were captured at a consistent magnification of 400X during microstructural analysis using an optical microscope (Metkon, IMM 901).

2.3.3. Hardness

In order to determine the hardness values and changes in hardness, measurements were taken from both the starting material obtained commercially and the samples obtained before and after the tempering process in heat treatment. Vickers hardness was used as the hardness measurement method, and hardness measurements were taken on samples prepared for micro structural analysis.

2.3.4. Impact Test

The Charpy pendulum impact test was performed to determine the fracture toughness of both the commercially obtained 30MnB4 steel and the samples obtained after the tempering process in heat treatment. The Charpy pendulum impact test samples were prepared according to ISO 148-1 standard [17], and the test temperature was used as -20 °C as specified in ISO 898-1 standard. “Table 3 - Mechanical and physical properties of bolts, screws and studs”. V-notches were opened in accordance with ISO 148-1 standard. V-notched samples were completely immersed in an ethyl alcohol-carbon dioxide mixture and kept in a cooling cabinet at -25 °C to reach the experimental temperature. The samples that reached the desired temperature were quickly (within 5 seconds) placed in the Charpy pendulum impact test device (Alsa, Zbc 450J), and broken.

2.3.5. Tensile Test

The tensile test was performed to determine the mechanical properties of commercially available starting materials and samples obtained after the tempering process in heat treatment, both before and after the heat treatment. The tensile test was performed before heat treatment and after tempering to determine the mechanical properties of both the commercially obtained material and the samples obtained after the tempering process in heat treatment. The tensile test was performed in accordance with DIN EN ISO 6892-1 standard [18] using a 60 ton universal testing machine. The obtained yield strength, tensile strength, elongation at yield, elongation at break, and reduction in cross-sectional area at break values were compared and interpreted with each other and with the literature.

3. Results and Discussion

In this study, an investigation was carried out on the potential use of 30MnB4 steel as the grade 10.9 bolt material. The microstructure of the commercially obtained 30MnB4 steel is presented in Figure 2. The results of optical emission spectrometer analysis and data obtained from tensile, hardness, -20 °C impact tests are presented in Table 1 and Table 2, respectively. As seen in Table 1 and Table 2, the chemical composition and the mechanical properties of the commercially obtained material used in this study are consistent with the literature data of 30MnB4 steel. As presented in Figure 2, the microstructure composed of perlite and ferrite is also in agreement with the literature. From the chemical composition, mechanical data, and microstructure image, it was determined that the commercially obtained material is 30MnB4.

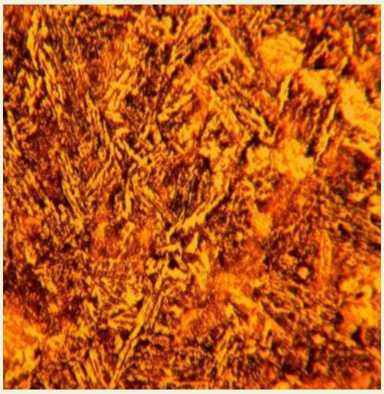

Figure 2. Microstructure of the commercially obtained material before heat treatment (magnification: 400x)

In Table 1, the chemical composition of grade 10.9 steel that is desired to be obtained within the scope of the study is presented, as well as 30MnB4 steel. It can be seen from Table 1 that the C, P, S and B ratios in 30MnB4 material match the C, P, S and B ratios that should be in “grade 10.9 alloy steel with additives, quenched and tempered” material according to ISO 898-1:2013 standard. As no other treatments will be applied to the 30MnB4 material during the study except for heat treatments such as annealing, water quenching, and tempering, the chemical composition of the 30MnB4 material will remain as shown in the middle column of Table 1 and will thus meet the chemical composition requirements of grade 10.9 alloy steel.

Table 1. Chemical compositions of the materials mentioned in this study.

	30MnB4[16]	The specimens used in this study	grade 10.9 alloy steel with additives, quenched and tempered [13]
C %	0.27 - 0.32	0.303	0.20 – 0.55
Si %	≤ 0.30	0.138	
Mn %	0.80 - 1.10	0.927	
P %	≤ 0.025	0.010	≤ 0.025
S %	≤ 0.025	0.012	≤ 0.025
Cr %	≤ 0.30	0.194	
Mo %	-	0.008	
Cu %	≤ 0.25		
B %	0.0008-0.005	0.003	≤ 0.003

Table 2. The mechanical properties of 30MnB4 steel

	30MnB4 steel from the standard [19]	Tensile test results of the material used in this study
Tensile strength, R_m (Mpa)	≤ 670	662.86
Yield strength $R_{p0.2}$ (MPa)		471.44
Percentage elongation after fracture, A (%)		23.78
Percentage reduction of area after fracture, Z (%)	≥ 58	59.63
Vickers hardness (HV)		180.33
Impact strength at -20 °C, K_V (J)		10.03

After being subjected to preheating, annealing, and oil quenching processes, as seen in Figure 1, commercially obtained 30MnB4 steel samples were examined for their microstructure and hardness values. The microstructure of the hardened 30MnB4 sample consists of perlite and ferrite, as seen in Figure 3. The hardness measurement conducted after oil quenching was measured as 51 HRC (Vickers: 528), which corresponds to a tensile strength of 1820 MPa according to the hardness conversion table in ASTM A370 standard [20]. The Vickers hardness value, which was approximately 180 before the heat treatment, increased to 528 after the oil quenching process performed within the scope of the study. As seen from the hardness conversion table in ASTM A370 standard, the tensile strength, which was approximately 605 MPa before the heat treatment, increased to 1820 MPa after the quenching process.

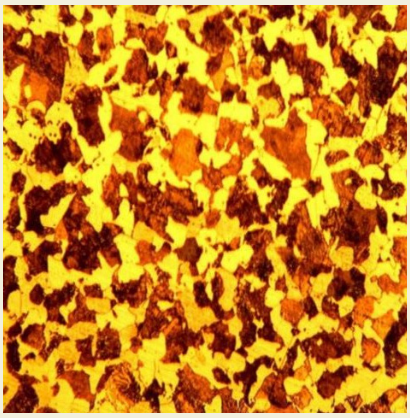

Figure 3. Microstructure of the 30MnB4 steel after oil quenching (magnification: 400X).

To determine the effect of the tempering process on the mechanical properties and microstructure of 30MnB4 material after quenching to obtain grade 10.9 steel bolt material, 5 different tempering temperatures were studied. The samples obtained after oil quenching were tempered at 485, 490, 500, 510 and 520 °C for 2 hours. The mechanical properties obtained according to the tempering temperature are presented in Table 3. Since no significant difference was observed in the microstructures obtained from the samples tempered at different temperatures, the microstructure image of one of the tempering temperatures is presented as Figure 4.

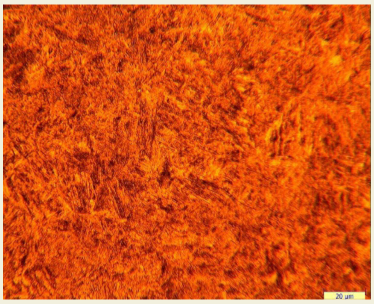

Figure 4. Microstructure of the 30MnB4 steel after tempering process at 500 °C for 2 hours (magnification: 400X)

The effects of different temperatures in the tempering process performed after preheating, annealing and oil quenching on tensile strength, yield strength, percentage elongation at break, percentage reduction in area at break, hardness and -20 °C impact values are presented in Table 3. The 528 Vickers hardness value measured after oil quenching decreased as expected after the tempering process and fell within the range of 323-371, depending on the tempering temperature used in the study. As expected, an increase in tempering temperature resulted in a decrease in yield and tensile strength, a decrease in hardness value, and an increase in percentage elongation at fracture. As shown in Table 3, tempering also has a significant effect on the results of charpy pendulum impact test performed at -20 °C. The Charpy impact value, which was 10.3 J after oil quenching, increased to the range of 33-96 J after the tempering process was applied at different temperatures. A decrease in tempering temperature increases the -20 °C Charpy impact result. The value obtained from the tempering process at 520 °C is approximately 33 J, rising to approximately 96 J when the tempering temperature is 485 °C.

In order to specify the desired mechanical properties, the mechanical properties of grade 10.9 steel bolts were given in Table 4 by utilizing the literature. When the mechan-

Table 3. The effect of tempering temperatures on the mechanical properties of annealed and oil quenched 30MnB4 steel

Tempering temperature	485 °C	490 °C	500 °C	510 °C	520 °C
Tensile strength, R_m (MPa)	1140.45	1131.85	1074.39	1066.58	1065.22
Yield strength, $R_{p0.2}$ (MPa)	1097.35	1082.86	1000.80	995.72	990.08
Percentage elongation after fracture, A (%).	11.21	11.59	13.20	17.58	18.60
Percentage reduction in area after fracture, Z (%)	58.91	61.58	59.89	61.42	63.85
Vickers hardness (HV)	371.50	360.50	354.50	323.00	323.00
Impact strength at -20 °C, K_v (J)	96.12	82.66	75.33	35.04	33.08

Table 4. The mechanical properties of class 10.9 bolts [16]

Tensile strength, R_m (MPa)	Stress at 0.2% non-proportional elongation, $R_{p0.2}$ (MPa)	Percentage elongation after fracture, A (%)	Percentage reduction of area after fracture, Z (%)	Vickers hardness (HV)	Impact strength at -20 °C, K_v (J)
≥ 1040	≥ 940	≥ 9	≥ 48	320 - 380	≥ 27

ical properties of 30MnB4 material that was tempered at different temperatures after preheating, annealing, and hardening processes (Table 3) were compared with the mechanical properties of grade 10.9 steel bolts, it was observed that grade 10.9 properties were obtained for all tempered temperatures studied. According to the effects of the tempered temperatures on the mechanical properties, it can be seen that the tempering temperature can be determined according to the extra demanded property in grade 10.9 steel material. As seen in Table 3, if relatively high strength, high hardness, and high Charpy impact value at -20 °C are desired in grade 10.9 steel bolt, 485 °C is advantageous as the tempering temperature; if relatively high ductility is desired, 520 °C provides an advantage.

4. Conclusion

In this study, it was aimed to obtain the mechanical properties of grade 10.9 steel bolts by applying different heat treatments to 30MnB4 steel. Preheating, annealing and quenching processes were applied to 30MnB4 steel material, and then the tempering process was used at five different temperatures (485, 490, 500, 510 and 520 °C). The effects of tempering temperatures on tensile strength, yield strength, elongation at break, reduction in cross-sectional area at break, hardness and notch impact values at -20 °C were examined. The results revealed that grade 10.9 steel bolt properties were obtained for all the tempering temperatures studied. When the obtained mechanical properties were compared with each other, it was determined that as the tempering temperature decreases, yield strength, tensile strength, hardness value, and impact value at -20 °C increase, and elongation at break decreases. Therefore, different tempering temperatures can be chosen to obtain specific mechanical properties required for different applications. It has been determined that when relatively high strength, high hardness and high impact values are required, it is appropriate to select the tempering temperature as 485 °C. On the other hand, choosing 520 °C as the tempering temperature is proper when high ductility is needed. Furthermore, the current study revealed the usability of heat-treated 30MnB4 steels for different applications requiring high strength and high toughness values.

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