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Heat treatment of AISI 1040 and AISI 4140 steels: microstructure-mechanical property relationships for normalization, spheroidization and quenching-tempering

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ABSTRACT

The mechanical properties of steels are enhanced through heat treatment according to their intended applications. In this study, normalization, pearlite spheroidization, quenching, and tempering at various temperatures were performed on AISI 1040 and AISI 4140 steels, which are widely used industrially. The effects of these heat treatments on microstructure and mechanical properties were examined. The impact of varying tempering temperatures on mechanical properties such as hardness, tensile strength, yield strength, impact toughness (at -30 °C, 0 °C, and room temperature), and elongation was analyzed and correlated with the microstructures. Additionally, examinations were conducted on AISI 4140 steel to assess the effect of alloying elements on the efficacy of heat treatment. The results revealed that increasing the tempering temperature caused morphological changes in the martensitic structure, leading to a significant decrease in hardness and strength up to 500 °C, with a notable increase in ductility beyond this point. AISI 4140 steel exhibited more pronounced changes in mechanical properties after tempering compared to AISI 1040 steel, highlighting the role of alloying elements in enhancing heat treatment efficiency. Impact tests indicated that the minimum tempering temperatures required to achieve an impact energy above 27 J were 500 °C for AISI 1040 steel and 450 °C for AISI 4140 steel. The study identified the appropriate heat treatment conditions to achieve the expected properties for AISI 1040 and AISI 4140 steels based on their application areas.

I. INTRODUCTION

Approximately 78% of metallic materials used in industrial applications are iron based. With the increasing demand in both the structural and logistics sectors, the need for production and heat treatments of these materials continues to grow daily. The steels utilized in this study, 1040 and 4140, contain 0.4% carbon [1, 2]. According to the iron-carbon phase diagram, this percentage represents the midpoint of hypo-eutectoid steels. Consequently, the microstructure comprises an equal proportion of ferrite and pearlite phases. This carbon content provides an opportunity to enhance mechanical properties through heat treatment [3, 4].

AISI 1040 steel is suitable for hardening processes that provide high strength and hardness, making it a preferred choice for applications such as machine components, tools, shafts, transmission gears, and bearing housings. While it is weldable, its high carbon content necessitates preheating. In addition to 0.4% C, its chemical composition contains 0.45% manganese. AISI 4140 steel is an alloyed steel known for its high strength and hardness properties. In addition to 0.4% C, it contains 1% chromium, 0.9% manganese, and 0.2% molybdenum. It is commonly used in parts requiring high strength, such as drill bits, crankshafts, piston rods, nuts, axles, and transmission bearings [5-8].

At room temperature, the crystal structure of these steels is body-centered cubic (BCC). When heated to the austenitic region, this structure transforms into face-centered cubic (FCC). If the material is cooled in a furnace

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or in air, the structure reverts to BCC. However, if cooling is accelerated (e.g., via quenching), the FCC lattice does not have enough time to revert to BCC, leading to the formation of internal stresses in the structure. These stresses distort the lattice, resulting in a body-centered tetragonal (BCT) martensitic structure, which is unstable, highly hard, and under high stress. Despite its high hardness, this martensitic structure is brittle. To reduce brittleness and improve toughness, a tempering process is required. Tempering is conducted at temperatures between 250 °C and 600 °C, following the standard steps of heating, holding, and cooling in heat treatment processes. Tempering can be performed in multiple stages or in a single stage. For instance, a multi-stage process might include heating and holding at 250 °C, followed by heating and holding at 350 °C, and then cooling. Alternatively, it can be completed in a single stage, such as heating and holding at 300 °C before cooling. Microstructural examinations reveal that tempering eliminates the notch-like structure in martensite responsible for brittleness [9-11].

During normalization, 1040 steel is heated to approximately 870-900 °C and then air-cooled. This process results in a fine-grained microstructure, improving both strength and ductility. During normalization, the steel transitions to the austenite phase, which undergoes homogeneous transformation during cooling, thereby enhancing the mechanical properties. Similarly, 4140 steel is heated to around 870-925 °C and air-cooled. This process provides a uniform microstructure and improves the steel’s high strength and toughness. Due to its chromium and molybdenum content, 4140 steels can be processed at higher temperatures, enhancing its durability. In both types of steel, normalization annealing is performed to reduce internal stresses, improve mechanical properties, and achieve a more uniform structure. Cooling is performed in air for both steels, but 4140 steel demonstrates greater temperature resistance due to its alloying elements [2, 12-14].

Spheroidizing annealing is a heat treatment process applied to transform the pearlite structure in steels from lamellar to a more spherical form. This process improves machinability and enhances specific mechanical properties. Given that 1040 steel is a medium-carbon steel, spheroidizing annealing is frequently applied. Initially, the steel is heated to approximately 700-750 °C. At this temperature, the lamellae within the pearlite structure begin to assume a spherical form. The heating process is maintained for a longer duration compared to other heat treatment methods, with the temperature held constant throughout. This ensures the transformation of pearlite into a spherical structure, after which the steel is slowly cooled in a furnace. As a result of this process, 1040 steel becomes less hard and more ductile, making it easier to machine during cutting and plastic deformation operations. While 1040 steel becomes softer and more ductile after this process, 4140 steel retains its strength while also achieving improved machinability. Therefore, spheroidizing annealing is commonly applied before processes such as machining, forging, or cold forming [5, 15, 16].

In this study, hardness and tensile tests were conducted after normalization, spheroidizing, quenching, and tempering heat treatments were applied to AISI 1040 steels. Additionally, the relationship between microstructure and mechanical properties was established. The effects of tempering temperature on the microstructure and mechanical properties of AISI 4140 steels after quenching were also examined, and the influence of alloying elements on heat treatment efficiency was investigated. The innovative aspects of this study include providing data for the literature and industrial research regarding the determination of optimal heat treatment conditions for these steels based on the desired mechanical properties. Furthermore, unlike previous studies, impact tests at different temperatures were conducted, highlighting another innovative aspect of the study.

II. EXPERIMENTAL METHOD

In the first part of the study, different heat treatment processes, as shown in Figure 1, were applied to AISI 1040 steel, of which chemical composition is given in Table 1. In the second part of the study, tempering at different temperatures following quenching was applied to AISI 4140 steels, which are also characterized by the chemical composition in Table 1. Cylindrical samples with a diameter of 20 mm were machined from steels produced by Asil Çelik A.Ş. using the Electric Arc Furnace / Ladle Furnace / Vacuum Degassing / Continuous Casting and Hot Rolling route. Heat treatment processes were then applied to these tensile and Charpy impact test specimens.

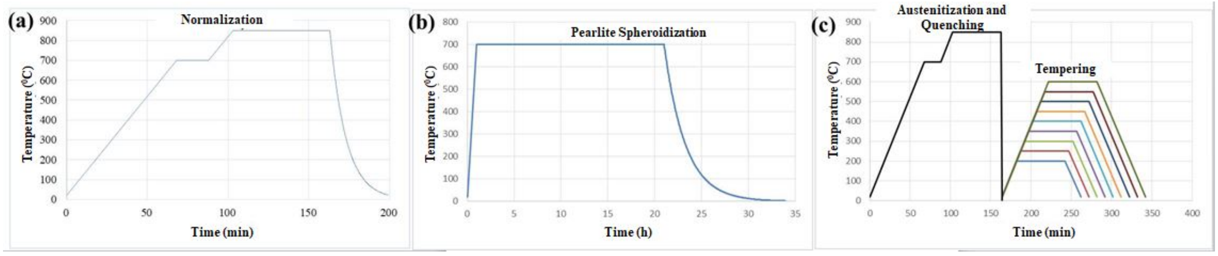

Figure 1. Time-temperature profiles for applied heat treatment processes (a) Normalization, (b) Pearlite spheroidization, (c) Quenching and tempering

Tablo 1. Chemical compositions of AISI 1040 and AISI 4140 steels (%, wt.)

Material	C	Mn	Si	P	S	Cr	Mo	Ni	Al
AISI 1040	0,430	0,730	0,230	0,009	0,007	0,170	0,090	0,110	0,023
AISI 4140	0,410	0,930	0,310	0,010	0,008	0,950	0,200	0,100	0,021

During normalization and quenching treatments, the samples were initially heated to 700 °C and held for 20 minutes, then further heated to 850 °C and austenitized for 1 hour. For spheroidization, the samples were heated to 700 °C, held for 20 hours, and then slowly cooled in the furnace. The heating rate for all processes was set at 10 °C/min. In the normalization process, cooling was performed in still air at a rate of 30 °C/min, while for quenching, the samples were immersed in stirred water at 5 °C, achieving a cooling rate of 85 °C/s.

Following heat treatment applications, metallographic examinations were conducted. Samples were sectioned using an abrasive cutting machine with a SiC disc, ground with SiC abrasive papers ranging from 120 to 1000 grit, and polished with a 3 µm diamond suspension. The samples were etched using Nital 3 (3% HNO_3 and 97% ethanol) and examined under a Leica DMi8 optical microscope for microstructural analysis. Hardness tests were conducted using the Brinell method, with measurements taken from three distinct points at the central region of the specimen cross-section. Charpy-V notch impact tests were carried out at room temperature, 0 °C, and -30 °C using a Zwick Roell RKP 300 device. In order to cool the samples, solid carbon dioxide (dry ice) was dissolved in acetone and when the solution temperature dropped to the desired temperature, the samples were placed into the solution container and hold for 5 minutes, then the tests were applied immediately. Additionally, tensile tests were performed at room temperature using a Zwick Roell tensile testing machine.

III. RESULTS AND DISCUSSIONS

3.1 Effects of Different Heat Treatment Processes

The effects of different heat treatments on the microstructure of AISI 1040 steel were investigated. Normalizing, pearlite spheroidizing, and quenching heat treatments were applied to hot-rolled AISI 1040 steel. The resulting microstructures are presented in Figure 2. In Figure 2a, the hot-rolled and untreated AISI 1040 steel showed no grain orientation due to the rolling process being carried out above the recrystallization temperature. The presence of elongated grains in the rolling direction indicates strain hardening in the material, leading to anisotropic mechanical properties [17]. The microstructures in Figures 2a and 2b consist of ferrite (white) at grain boundaries and pearlite (black) within grains. The pearlite phase exhibited a lamellar structure, with the dark phases being cementite (Fe_3C) and the white areas being alpha ferrite. The cooling rate affects the spacing between cementite lamellae, leading to the formation of fine or coarse pearlite, which significantly influences hardness and strength. Coarse pearlite was observed due to slow cooling in still air. After normalizing, a slight reduction in grain size was observed. According to ASTM E112-13 standard using the intercept method, the average grain sizes for hot-rolled and normalized AISI 1040 steel were determined to be 32 μm and 25 μm, respectively. This slight reduction in grain size is predicted to slightly increase both strength and toughness. As seen in Figure 2c, the pearlite phase (essentially cementite) in the lamellar structure transformed into a spherical morphology after spheroidizing annealing. This reduces hardness and strength while increasing ductility and toughness [5]. In Figure 2d, the microstructure obtained after quenching consisted of retained austenite, coarse martensite (M), and a small amount of Widmanstätten ferrite (WM), which extended from grain boundaries into the grains. Widmanstätten ferrite forms during the transformation of austenite to ferrite under rapid cooling rates. Initially, allotriomorphic ferrite nucleates at austenite grain boundaries with an irregular shape. As cooling continues, Widmanstätten ferrite grows into the austenite grains along specific crystallographic planes, forming needle-like or plate-like structures. It is well known that both coarse martensite and WF phases dramatically reduce impact toughness and cause extreme brittleness [18, 19].

The mechanical properties obtained from tensile testing after different heat treatments are presented in Table 2 and Figure 3. The yield strength and tensile strength of hot-rolled AISI 1040 steel were determined to be 670 MPa and 880 MPa, respectively. After normalization, these values decreased to 425 MPa and 681 MPa, respectively. Kazeem et al. [20] reported tensile strength and elongation values of 370 MPa and 26%, respectively, for normalized AISI 1040 steel at 900 °C. In the current study, both higher strength and ductility values were achieved. Aakarsh et al. [21] reported yield strength and tensile strength values of 378 MPa and 612 MPa, respectively, which are 12% and 11% lower, respectively, than those obtained in the present study. The elongation value was not reported in the related study. Gurumurthy et al. [22] normalized AISI 1040 steel at 850 °C and reported tensile strength and elongation values of 458 MPa and 30.4%, respectively. In the present study, the tensile strength value is 46% higher, while elongation is only 19% lower. S. Ekşi et al. [5] normalized AISI 1040 steel at 950 °C and reported tensile strength and elongation values of 600 MPa and 35%, respectively, which are 12% lower in strength and 40% higher in ductility compared to the present study. Despite a slight reduction in grain size after normalization, it was observed that strength values decreased while ductility increased significantly (elongation increased from 8% to 24.72%). This may be due to the increased spacing between cementite lamellae, resulting in coarse pearlite structure due to slow cooling in still air. During the hot rolling process, the movement of the steel may have caused a faster cooling effect resembling normalization.

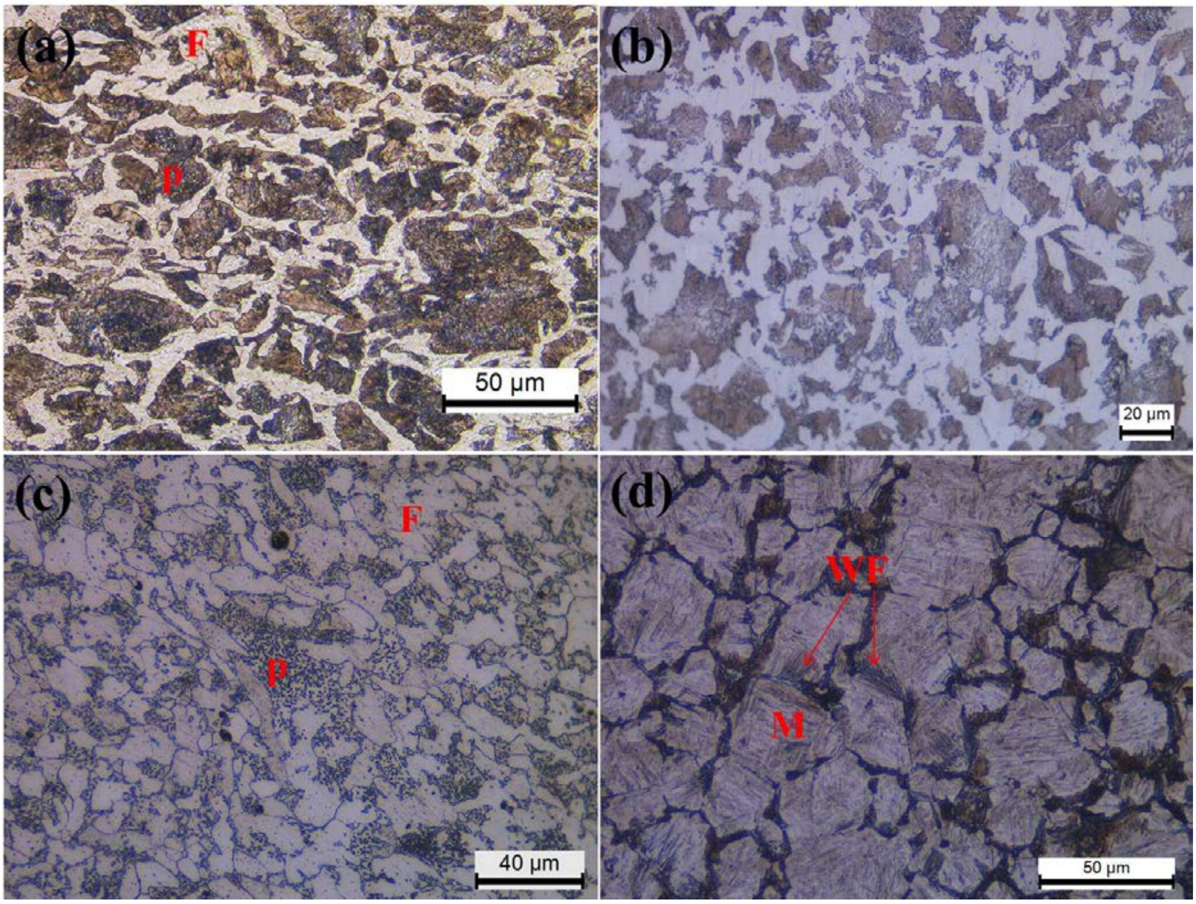

Figure 2. Microstructures of AISI 1040 steel subjected to different heat treatments, (a) Hot-rolled, (b) Normalized, (c) Spheroidized, (d) Quenched (500x magnification)

After spheroidization, due to the formation of spherical pearlite structure, the yield strength and tensile strength decreased to 250 MPa and 455 MPa, respectively. While strength decreased significantly, ductility increased considerably, with elongation measured as 29.77%. After quenching, excessive brittleness was observed due to the formation of coarse martensite and WF structure, with elongation measured as 0.35%. Failure occurred immediately after transitioning from elastic to plastic deformation. Therefore, the yield strength value for quenched sample hasn’t been provided in Table 2. The tensile test result is unsuitable for evaluation, and this material cannot be used in any engineering design. Therefore, tempering at 200-600 °C is applied after quenching. In this study, the effect of tempering temperature was also examined and detailed in a later section. However, for comparison, mechanical properties were evaluated here as well. Accordingly, significant improvements in both strength and ductility were achieved compared to hot-rolled AISI 1040 steel. Tensile strength increased by 20%, and elongation by 65%.

The hardness and Charpy impact test results of AISI 1040 steel subjected to different heat treatments are presented in Table 3 and Figure 4. After normalization, a hardness of 191 HB was obtained. Yanez et al. [12] normalized AISI 1045 steel and determined a hardness value of 203 HB. Aakarsh et al. [21] reported a hardness of 229 HB. Gurumurthy et al. [22] reported hardness and impact toughness values of 264 HB and 57 J, respectively. S. Ekşi et al. [5] normalized AISI 1040 steel at 950 °C and reported a hardness value of 191 HB, consistent with the present study. Compared to hot-rolled steel, normalization resulted in a 15% decrease in hardness and increas in impact toughness of 19% at room temperature and 75% at -30 °C. The importance of normalization for applications requiring high impact toughness at low temperatures is evident. After spheroidizing, the hardness decreased to 166 HB (25% reduction compared to untreated steel). S. Ekşi et al. [5] reported a hardness of 163 HB after spheroidizing at 700 °C, a value very close to that obtained in this study. Mohapatra et al. [15] conducted spheroidizing at 700 °C for 25 hours and reported a hardness of 162.5 HB. The highest toughness was achieved with this heat treatment, with an impact toughness of 78.5 J at room temperature, a 54% increase compared to untreated AISI 1040 steel. In the quenched sample, impact toughness values below 2 J were obtained due to coarse needle-like martensite and WF. However, after tempering at 500 °C, the impact toughness increased to 39.6 J at room temperature due to transformation of coarse needle-like martensite to fine tempered martensite.

Table 2. Tensile test results for heat treated AISI 1040 steel

Heat Treatment	**Yield Strength** *(MPa)*	**Tensile Strength** *(MPa)*	**Elongation** *(%)*
Hot Rolled	670	880	8,02
Normalized	425	681	24,72
Quenched	-	989	0,35
Spheroidized	250	455	29,77
Quenched + Tempered at 500 ^{0}C	718	1056	13,24

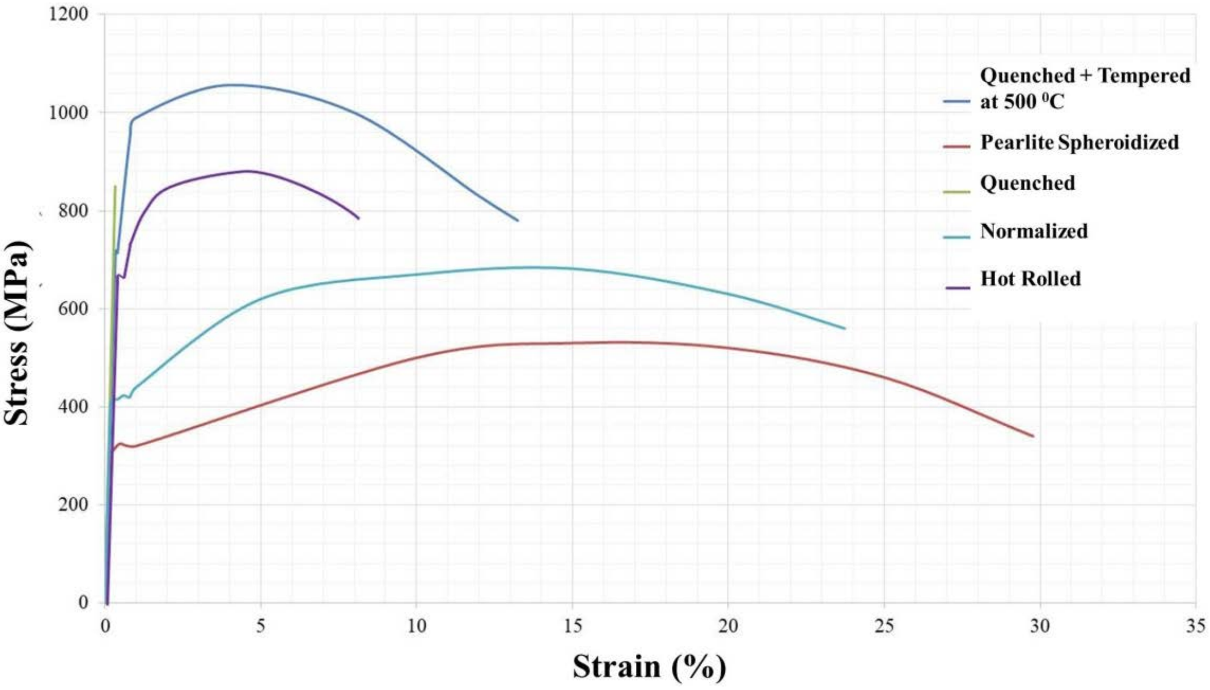

Figure 3. Stress-strain curves of heat treated AISI 1040 steel

Table 3. Hardness and impact test results for different heat-treated AISI 1040 steel

Heat Treatment	**Hardness** *(HB)*	**Impact Energy** *(J)*		
		-30 ^{0}C	**0 ^{0}C**	**25 ^{0}C**
Hot Rolled	221	16,6	33,2	51,1
Normalized	191	29,1	42,0	61,3
Quenched	572	1,05	1,05	2,05
Spheroidized	166	42,5	69,7	78,5
Quenched + Tempered at 500 ^{0}C	340	9,5	18,3	39,6

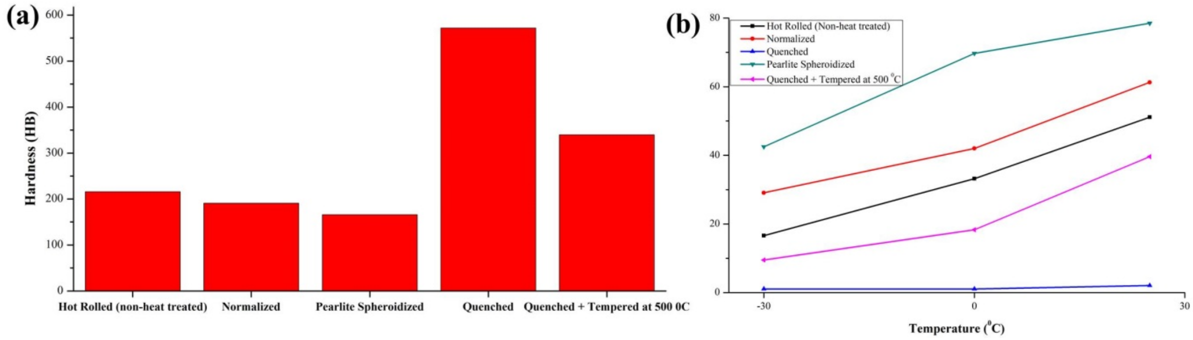

Figure 4. (a) Brinell hardness, (b) Charpy-V impact test results for heat treated AISI 1040 steel

3.2 Effect of Tempering Temperature

After the quenching process in steels, the formation of coarse tetragonal martensite structure increases hardness but drastically reduces ductility and impact toughness. Consequently, materials with such structures are rarely suitable for use in engineering designs. To transform coarse tetragonal martensite into fine tempered martensite, a tempering heat treatment is applied. Tempering temperature and duration are critical parameters. For AISI 1040 steel, analyzing the changes in mechanical properties according to tempering conditions is essential to achieve optimal mechanical properties suitable for its application.

The effects of tempering performed at temperatures ranging from 200 °C to 600 °C on tensile strength, yield strength, hardness, and elongation are presented in Figure 5. It was observed that tempering at 200 °C and 250 °C had no significant effect on mechanical properties, while dramatic decreases in strength and hardness occured beyond these temperatures. At 300 °C, a drop in ductility was also noted, which is attributed to a phenomenon known as tempering embrittlement, observed in non-alloy steels. Above this temperature, a significant increase in ductility was achieved. While yield strength remained constant beyond 500 °C, the decrease in tensile strength and hardness were observed. The sharp decrease in hardness at 350 °C could be due to the decomposition of retained martensite and the transition from ε-carbides to more stable cementite. This temperature range also promotes the recovery of dislocations, reducing internal stresses and contributing to a significant reduction in hardness [23, 24]. In summary, as the tempering temperature increased, strength and hardness decreased while ductility increased. It has been demonstrated that the desired mechanical properties can be achieved by controlling the tempering temperature according to the material's application area and design criteria.

S. Ekşi et al. [5] applied quenching at 900 °C followed by tempering at 400 °C, reporting hardness, tensile strength, and elongation values of 255 HB, 1100 MPa, and 21%, respectively. In the current study, these values were found to be 386 HB, 1262 MPa, and 10%, respectively. The higher hardness and strength but lower ductility in the present study may be due to the cooling medium. While quenching was performed in icy water at 5 °C in this study, room-temperature water was used in the referenced study. Özbek and Saraç [7] austenitized AISI 1040 steel at 880 °C, applied quenching, and then tempered it at 450 °C and 550 °C to evaluate its mechanical properties. For the sample tempered at 450 °C, they reported hardness, tensile strength, and elongation values of 373 HB, 1000 MPa, and 1.5%, respectively. In the current study, these values were determined as 354 HB, 1146 MPa, and 10%, respectively. These variations in mechanical properties stem from microstructural changes at different tempering temperatures. To establish the relationship between microstructure, heat treatment, and mechanical properties, the microstructure of AISI 1040 steel after quenching without tempering is shown in Figure 6a, while the microstructures tempered at 200 °C, 350 °C, and 500 °C are presented in Figures 6b, 6c, and 6d, respectively. In Figure 6a, the needle-like phases appearing dark brown are tetragonal martensite and represent a higher magnification of the structure shown in Figure 2d.

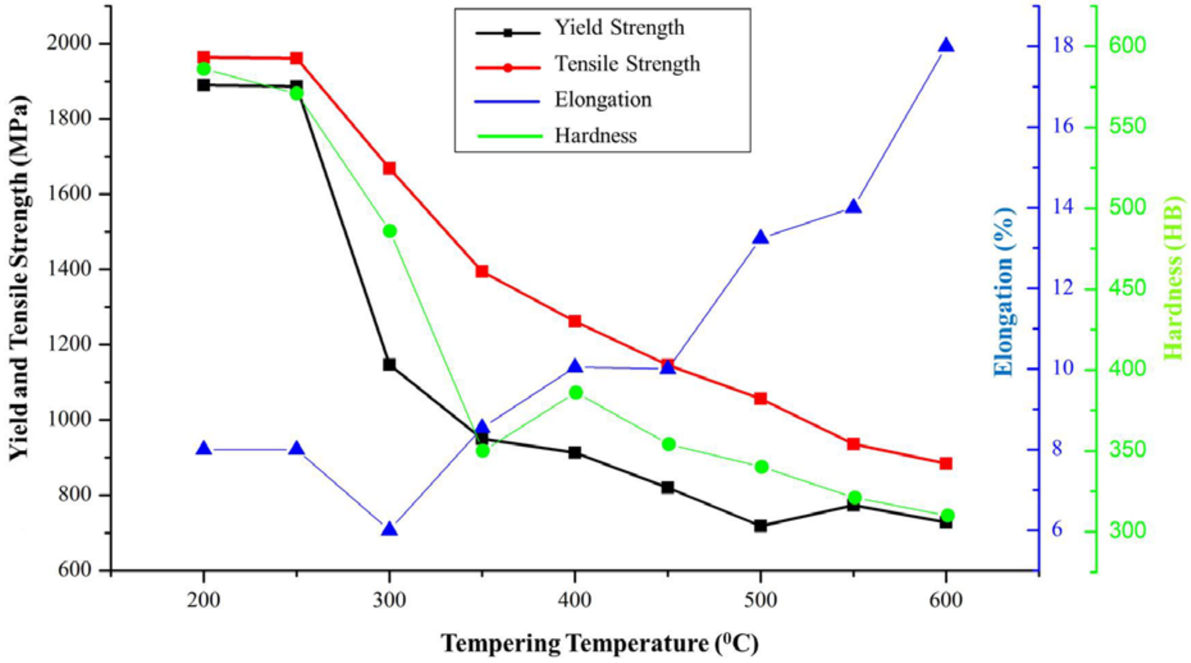

Figure 5. The variation of mechanical properties of quenched AISI 1040 steel with different tempering temperatures

It was observed that the very coarse tetragonal martensite transformed into fine tempered martensite after tempering at 200 °C (Figure 6b). The length of the martensite was reduced by approximately half. It should be noted that the tempered martensite appears white. With an increase in tempering temperature, the length of tempered martensite was significantly reduced when tempered at 350 °C (Figure 6c). This microstructural change corresponds with the significant decreases in tensile and yield strength and increases in ductility at this temperature. When the tempering temperature was raised to 500 °C, the width of the tempered martensite phases increased. The aspect ratio of the martensite phase influences mechanical properties, with an increasing aspect ratio leading to reduced strength and enhanced ductility [25].

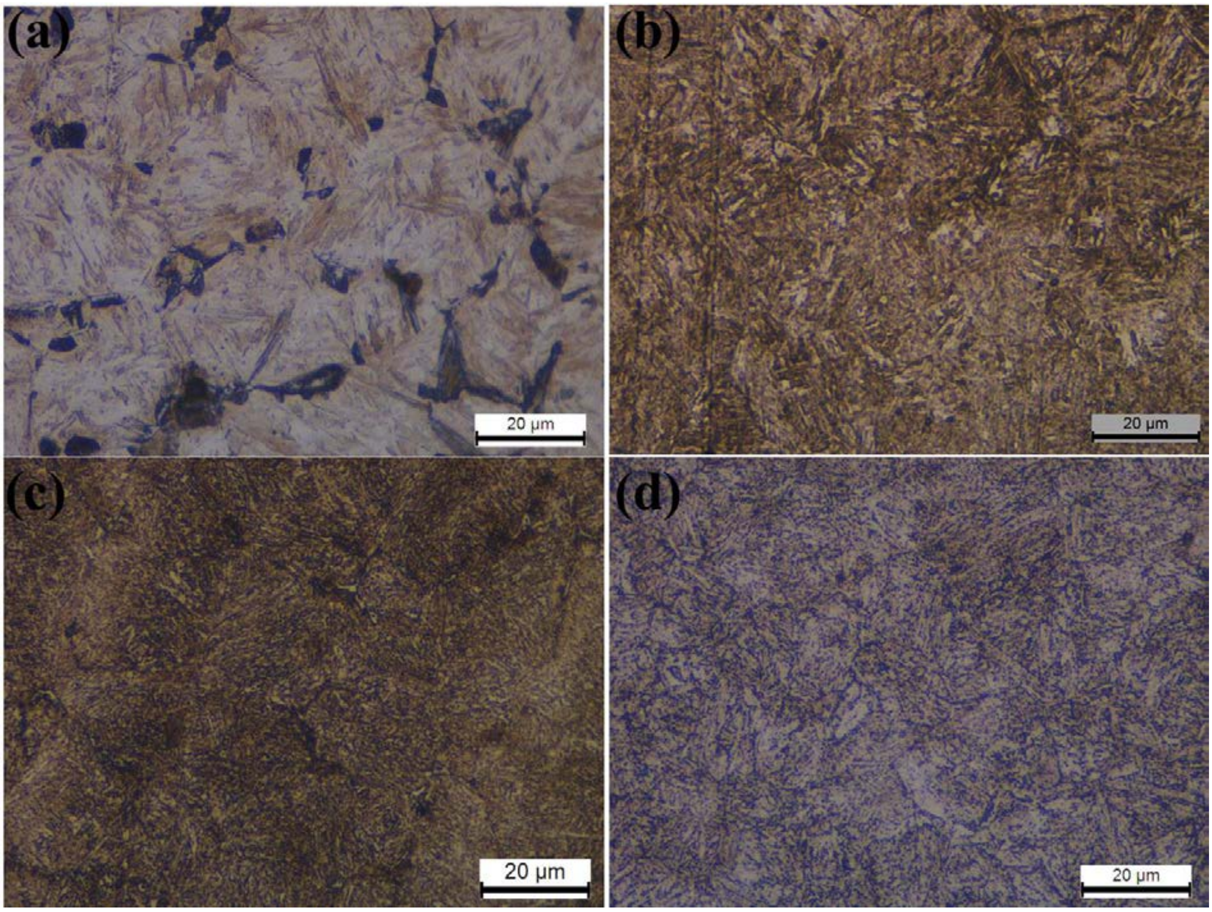

Figure 6. Microstructures of AISI 1040 steel tempered at different temperatures after quenching: (a) Untempered, (b) Tempered at 200 °C, (c) Tempered at 350 °C, (d) Tempered at 500 °C

3.3 Effect of Alloying Elements

Alloying elements in steels shift the transformation curves to the right in the Time-Temperature-Transformation diagram, increasing the critical cooling rate and enhancing hardenability. This allows not only the surface but also the core of the material to harden through martensitic transformation, significantly influencing the effectiveness of heat treatment. In this study, tempering processes were applied to AISI 4140 steel, in addition to AISI 1040 steel, at varying temperatures after quenching. The effect of alloying elements on tempering efficiency was examined, marking one of the innovative aspects of this research.

Figure 7a presents the strength values of AISI 1040 and AISI 4140 steels as a function of different tempering temperatures. While AISI 4140 exhibited higher tensile strength than AISI 1040 across all tempering temperatures, the yield strengths of both steels became nearly equal at higher tempering temperatures, indicating that alloying elements notably improved tempering efficiency, particularly in terms of yield strength. This was further evidenced in the impact toughness results provided in Figure 7b. At higher tempering temperatures (especially at 450 °C), the increase in impact toughness for AISI 4140 was significantly greater than for AISI

1040. For instance, at 400 °C, the impact toughness values for AISI 1040 and AISI 4140 were 10 J and 16 J, respectively (a 60% increase). At 450 °C, these values rised to 14 J and 29 J, respectively (a 107% increase).

Based on these findings, the use of alloyed medium-carbon steels and the optimization of tempering temperatures after quenching can ensure the desired mechanical properties for specific applications. The 27 J threshold is a critical design criterion in steels, typically referred to as the impact transition temperature, where behavior shifts from brittle to ductile. As shown in the graph, a minimum tempering temperature of 500 °C was required for AISI 1040 to achieve an impact toughness above 27 J at room temperature, while 450 °C sufficed for AISI 4140. Tempering AISI 4140 steel at 500 °C after quenching resulted in tensile strength and hardness values of 1318 MPa and 370 HB, respectively. Bhagyalaxmi et al. [13] reported these values as 1109 MPa and 271 HB, respectively, in their study, which did not investigate elongation, impact toughness, or the effects of different tempering temperatures. Hafeez et al. [14] quenched AISI 4140 from 900 °C and tempered it at 400 °C, reporting hardness, tensile strength, and elongation values of 348 HB, 1582 MPa, and 7%, respectively. In this study, these values were determined as 490 HB, 1426 MPa, and 8%, respectively. Hafeez et al. also reported an impact toughness of 22 J/cm² under these conditions, compared to 19.7 J (24.6 J/cm²) in the current study. Özbek and Saraç [7] tempered AISI 1040 steel at 450 °C and 550 °C after quenching, reporting room-temperature impact toughness values of 25 J and 35 J, respectively. The current study found these values to be 22.4 J and 39.6 J, respectively. Khani Sanij et al. [26] quenched AISI 4140 from 860 °C and tempered it at 600 °C, reporting tensile strength, elongation, and impact energy values of 1136 MPa, 12.8%, and 61 J, respectively. In this study, for tempering at 500 °C, these values were determined as 1318 MPa, 10.23%, and 47.3 J, respectively. Lower tempering temperatures resulted in higher strength but lower ductility and toughness. The study by Khani Sanij et al. [26] also investigated the effects of double quenching. In addition to quenching from 860 °C and tempering at 600 °C, they performed a prior quenching from 860 °C and tempering at 300 °C. This process increased tensile strength, elongation, and impact toughness by 4%, 33%, and 30%, respectively. Overall, the results are consistent with similar studies published in the literature.

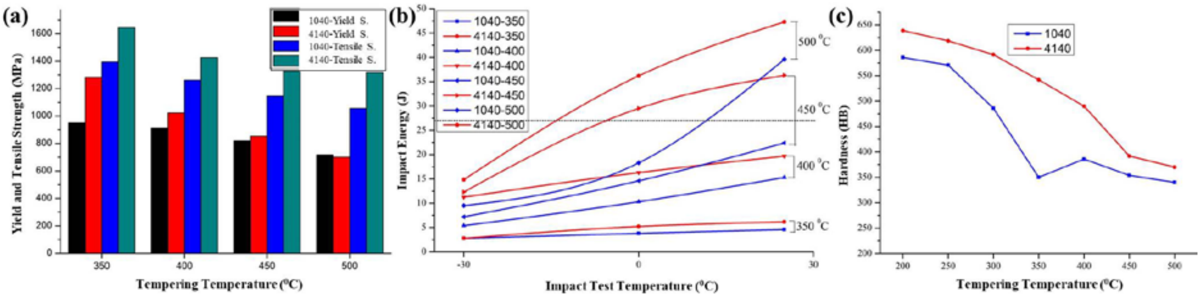

Figure 7. Comparative mechanical properties of heat treated AISI 1040 and AISI 4140 steels (a) Yield and tensile strength, (b) Impact toughness, (c) Hardness

IV. CONCLUSIONS

This study, which aims to optimize the mechanical properties of AISI 1040 and low-alloyed AISI 4140 medium carbon steels containing 0.4% C, produced by hot rolling, primarily examines the microstructural and mechanical property changes in AISI 1040 steel due to different heat treatment types. The following findings were obtained:

- After normalizing, the distance between cementite lamellae increased slightly (due to slower cooling compared to rolling), resulting in a small decrease in grain size, while strength values decreased and ductility values increased.
- After spheroidizing, the cementite phases almost completely spheroidized, leading to a 48% decrease in tensile strength to 455 MPa and a 372% increase in elongation to 29.07%.
- Due to the coarse needle-like martensite structure formed by quenching, hardness increased, but an excessively brittle structure was obtained. After tempering at 500 °C, AISI 1040 steel showed 20% higher tensile strength (1056 MPa) and 65% higher ductility (13.24% elongation) compared to the unheat-treated, directly supplied (hot-rolled) steel.

The effects of tempering applied at different temperatures after quenching, including for AISI 4140 steels, on microstructure and mechanical properties were also investigated. The following findings were obtained:

- During tempering, coarse martensites were transformed into fine tempered martensites, which resulted in a decrease in hardness and strength, while ductility and impact toughness increased. As tempering temperatures increased, morphological changes in the martensitic structure (with lengths decreasing and widths increasing) led to a significant decrease in hardness and strength, particularly up to 500 °C, and a significant increase in ductility after 500 °C.
- In AISI 4140 steels containing alloying elements, it was determined that the change in mechanical properties after tempering was higher than that of AISI 1040. This is considered an important indicator that alloying elements enhance the effectiveness of heat treatment.
- Impact tests conducted at three different temperatures showed that for AISI 1040 and AISI 4140 steels, with an expected impact energy of over 27 J, the minimum tempering temperatures were determined to be 500 °C and 450 °C, respectively.

When all the results are evaluated, it is indicator that the mechanical properties of medium carbon steels can be improved in the desired direction by optimizing heat treatment conditions. Heat treatment conditions have been determined according to the expected mechanical properties in the usage area, and a structure-process-mechanical property relationship has been established for industrial and academic studies.

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