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Original Article

Microstructural features and mechanical properties of 22MnB5 hot stamping steel in different heat treatment conditions

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ABSTRACT

In this study, the microstructure and mechanical properties of the 22MnB5 steel sheet were investigated in different heat treatment conditions. The steel sheet heated to 700 °C, 800 °C, and 900 °C was subjected to air cooling, water quenching, and water quenching + tempering procedures. Microstructural properties post-heat treatment were analyzed under an optical microscope. To determine the mechanical properties, uniaxial tensile tests, and hardness measurements were performed. The highest mechanical properties were achieved with the water quenching from 800 °C and 900 °C. The elongation value was ranged of 2-4% with the water quenching. Also, the tempering process slightly increased the elongation value.

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1. Introduction

Today's automotive industry prioritizes lightness and durability to increase driving safety and reduce vehicle weights to reduce fuel consumption and carbon emissions [1–4]. For this reason, in recent years, the use of ultra-high-strengthened and heat treatment capability developed sheets has become widespread [5–7]. The 22MnB5 steel grade is the most used in the hot stamping process [8].

Hot-stamped parts are used for critical components such as A and B-pillars, roof rails, and crash management structures for safety performance due to high strength requirements in the automotive industry [9]. The hot stamping process can be described as heating the steel sheet in a furnace in the range of 850 °C–950 °C for austenitization and then transferring the hot blanks from the furnace to press, followed by simultaneously forming and cooling it in the die [10–14]. This process is a combination of heat treatment and plastic deformation of steel. In the heating process, the microstructure of the steel completely

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transforms the austenite phase and in a single step, forming and phase transformation are performed. The austenite phase transforms into a martensite phase with a cooling stage [10,15]. Thus, the tensile strength of 22MnB5 steel increases up to around 1500 MPa [13]. Also, the hot stamping process reduces the required force and enables easier forming applications.

In the literature, Güler reported that the tensile strength reached 1485 MPa and the hardness value was 492 HV after deformation and quenched process in the hot forming process of Usibor 1500 steel [16]. Güler et al. investigated the effects of quenching temperature (700 °C–950 °C) on the mechanical properties of 22MnB5 steel and the highest tensile strength (1506 MPa) was achieved by the water-quenching process at 950 °C for 15 min [17]. Mu et al. studied the mechanical properties of 22MnB5 and 30MnB5 steels after hot forming (800 °C–1000 °C) and quenching. The highest tensile strength and hardness value were achieved at 900 °C heat treatment temperature [18]. Andreiev et al. found that the mechanical properties of 22MnB5 steel were better after short austenitization with subsequent quenching than conventional heat treatment [19]. Naderi et al. investigated the effects of hot forming and tempering processes on mechanical properties of boron steel and reached optimum values with a 10–15 minutes tempering process to be applied at 250 °C [20]. Barcellona and Palmeri investigated the hot deformation on the hardness and continuous cooling transformations of 22MnB5 steel and determined that cooling rate and heat treatment were temperature effective parameters [21]. Wang et al. examined the microstructure of B1500HS boron steel at different austenitization temperatures (870 °C, 900 °C, 930 °C and 960 °C), and reported that the microstructure transformed completely austenite at 900 °C [22].

Considering the brief literature, it has been seen that the thermomechanical process parameters such as austenitization time, temperature, cooling rate, and method are effective on the microstructure and mechanical properties of the hot-stamped parts.

The purpose of this research is to determine the effects of heat treatment temperatures, cooling conditions, and tempering process on microstructure and mechanical properties of 22MnB5 steel in detail to improve quality hot stamping parts.

2. Material and experimental procedure

2.1. Material

In this study, the 22MnB5 steel sheet with 1.4 mm thickness, which is widely used in hot forming applications in the automotive industry, was used. It was supplied by ArcelorMittal. The commercial name of the steel is Üsibor 1500″. There is an aluminum-silicon coating called "Alusi" on both sides of the steel (Al 90%, Si 10%). The stress-strain curve of this steel can be seen in Fig. 1. The chemical composition of 22MnB5 steel is given in Table 1. The contents of carbon and boron elements that are an interstitial atom source are low in the chemical composition. These alloy elements are also sufficient to provide discontinuous yielding properties.

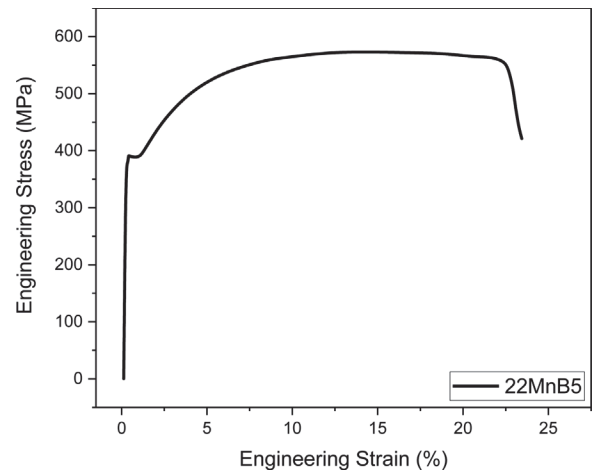

Fig. 1 – The stress-strain curve of 22MnB5 steel (as-received).

The yield strength, tensile strength, and elongation of as received 22MnB5 steel are about 387 MPa, 567 MPa, and 24.5%, respectively.

2.2. Experimental procedure

In this study, the effects of heat treatment on microstructure and mechanical properties of 22MnB5 steel were investigated. Five different heat treatment methods (air cooling, water quenching, water quenching + tempering at 200 °C, water quenching + tempering at 400 °C, water quenching + tempering at 600 °C) were subjected to samples that were held on at three different temperatures (700 °C, 800 °C, and 900 °C) for 30 min. Also, tempering processes were conducted during 30 min after air cooling and water quenched applications. The average cooling rate is 120 °C/min for air cooling, 500 °C/s for water quenching, respectively.

The heat treatments and tempering applications were done by using a conventional heating method in the Nabertherm brand industrial furnace. The transformation temperatures can be predicted by using some empirical formulas according to the chemical composition of the steel and so the heat treatment process can be planned. In this study, Ac3 and Ac1 temperatures were calculated according to Andrews' empirical formula [23–25]. The formula is given in Eq (1) and Eq (2).

$$\begin{aligned} Ac3 = {} & 910 - 203C - 15.2Ni + 44.7Si + 104V + 31.5Mo \\ & + 13.1W - (30Mn + 11Cr + 20Cu - 700P - 400Al \\ & - 120As - 400Ti) \end{aligned} \quad (1)$$

$$\begin{aligned} Ac1 = {} & 723 - 10.7Mn - 6.9Ni + 29.1Si + 16.9Cr \\ & + 290As + 6.38W \end{aligned} \quad (2)$$

The transformation temperatures of Ac3 and Ac1 for 22MnB5 steel were determined to be approximately 836 and 713 °C, respectively. Similar transformation temperatures Ac1

Table 1 – Chemical composition of 22MnB5 steel (wt, %).

22MnB5	C	Mn	Si	Cr	Cu	S	P	Al	Ti	B
	0.22	1.59	0.25	0.006	0.002	0.001	0.015	0.092	0.026	0.0027

and Ac3 were also used in Ximenes et al.'s study for this steel [4].

Tensile test specimens were cut by blanking die on the rolling direction and prepared according to EN ISO 6892-1 standard [26]. Tensile tests were carried out at 6.7×10^{-3} s^{-1} strain rate using a Zwick tensile testing machine with a capacity of 25 kN. The data obtained from the tensile test were processed and yield strength, tensile strength, and elongation were determined depending on the heat treatment conditions. The hardness measurements were carried out using the UHL VMHT hardness tester as a Vickers (HV). All the tests were repeated three times to reduce error margin and the average values of results were presented. Besides, a Leica DMI 8C optical microscope was used for the microstructural characterization of samples.

3. Results and discussion

3.1. *Mechanical properties*

The stress-strain curves of samples in different heat treatment conditions are given in Fig. 2. The highest tensile strength at all heat treatment temperatures was obtained by the water quenching method and the tempering process generally increased the ductility of the steel. When Fig. 2a is examined, the yield strength values of the quenched tempered samples are higher as expected than the air-cooled sample. At the same time, these stress values increased with increasing temperature of tempering, and the discontinuous yield property was seen more obvious. As the reason for the increase in yield strength with the increase of soaking temperatures after quenching, it is currently considered as more effective prevention of dislocations movement by allowing diffusion of interstitial atoms to longer distances. Subsequently, it may have led to the extension of the discontinuous yield gap by contributing to the formation of Lüders bands.

In Fig. 2b and 2c, the yield and ultimate tensile stress values of the water-quenched samples are higher as expected than the air-cooled sample. However, the continuous yielding property was observed in the only water quenched and water quenched + tempered samples at 200 °C. Discontinuous yielding properties were observed by increasing the tempering temperature. The martensitic phase is degraded by an excessive increase in tempering temperature. As a result of this, it is thought to cause discontinuous yielding due to the release of dislocations and interstitial carbon atoms.

Fig. 3 shows the effect of heat treatment conditions on the yield strength of the steel. It was observed that the yield strength of the 22MnB5 steel hold at 700 °C was not affected significantly according to the heat treatment and tempering conditions. However, there was a slight upward trend in yield strength with increasing the tempering temperature after water quenching. Higher yield strength values could be obtained at the holding temperatures at 800 °C and

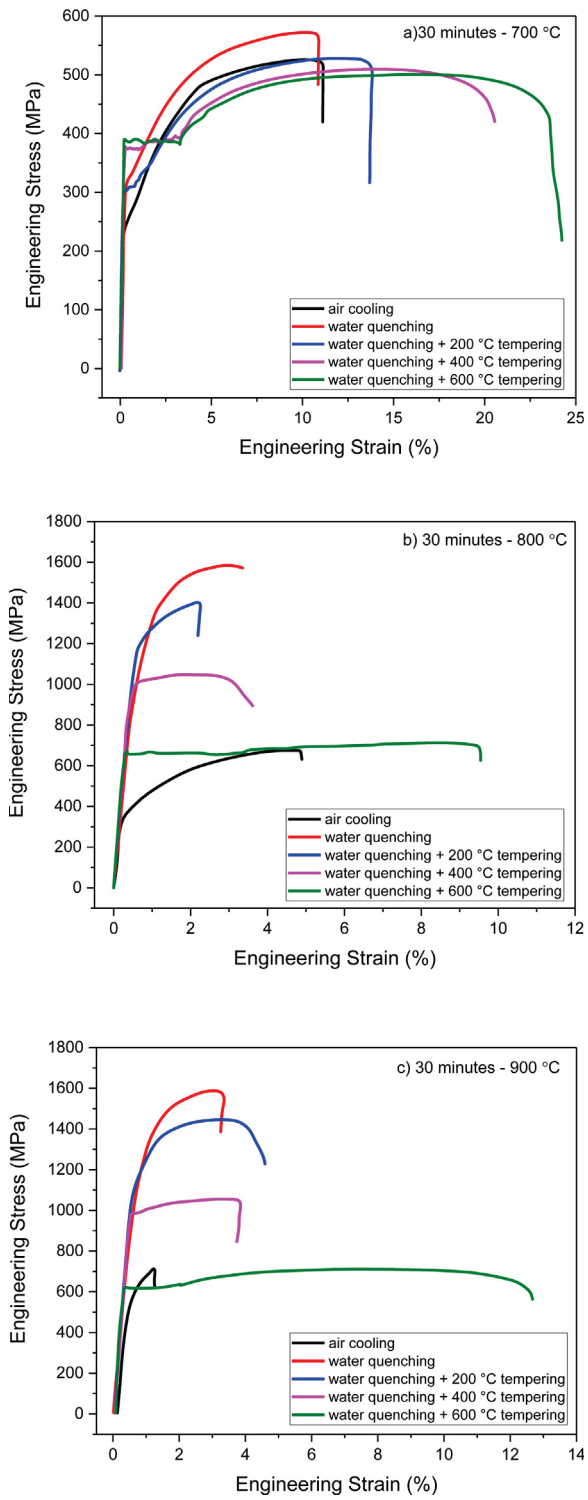

Fig. 2 – The stress-strain curves of 22MnB5 steel in different heat treatment conditions.

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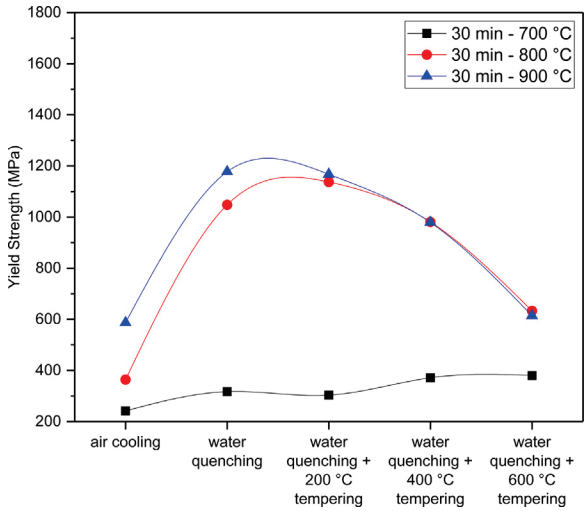

Fig. 3 – Yield strength versus heat treatment condition of the 22MnB5 steel.

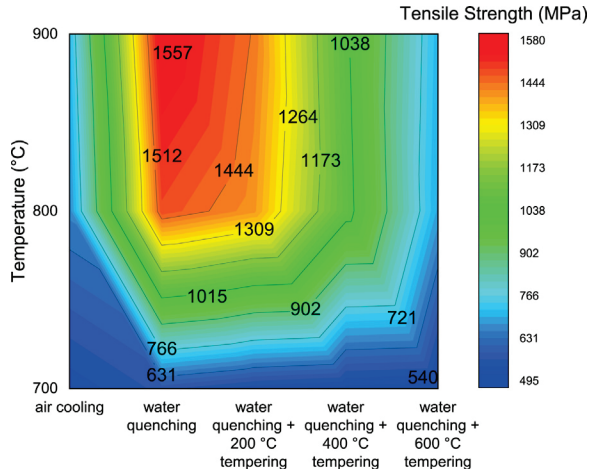

Fig. 5 – Tensile strength map dependent on the holding temperature and heat treatment method.

900 °C. The yield strength values obtained at 700 °C are quite low (241–380 MPa) compared to other holding temperatures. Especially, high yield strength values can be obtained in water quenching and water quenching + tempering process at 200 °C. The highest yield strength was determined as 1177 MPa at a holding temperature of 900 °C and then water quenching. At holding temperature of 900 °C, water quenching and water quenching + tempering process at 200 °C revealed yield strength is 1167 MPa. The yield strength decreased with the increase of tempering temperature after water quenching at a tempering temperature of over 200 °C. It is seen that similar results were obtained for 800 °C and 900 °C holding temperatures.

The tensile strength values in different heat treatment conditions are given in Fig. 4. Tensile strength was in the range of 498–570 MPa at holding temperature of 700 °C. These values are significantly lower than the tensile strengths of the steels at a holding temperature of 800 °C and 900 °C. The tensile strength values of samples at holding temperatures of 800 °C and 900 °C exhibited similar behavior to the yield strength values. The highest tensile strength at both holding temperatures was obtained by water quenching process (Fig. 5). At holding temperature of 800 °C, water quenching revealed tensile strength of 1484 MPa, and tensile strength of 1407 MPa was achieved by water quenching + tempering process at 200 °C. At holding temperature of 900 °C, water quenching revealed tensile strength of 1577 MPa, and tensile strength of 1440 MPa was achieved by water quenching + tempering process at 200 °C. At holding temperatures of 800 °C and 900 °C, an increase in the tempering temperature over 200 °C after water quenching caused a decrease in tensile strength. The lowest tensile strength was obtained in the air cooling process.

The relationship between elongation and heat treatment conditions is given in Fig. 6. Although the lowest yield and tensile strength were achieved at a holding temperature of 700 °C, the highest elongation was obtained at this holding temperature. This can be attributed to the high fraction of the

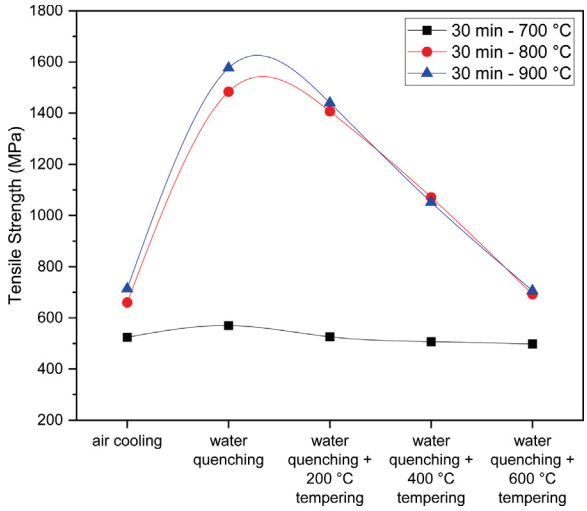

Fig. 4 – Tensile strength versus heat treatment condition of the 22MnB5 steel.

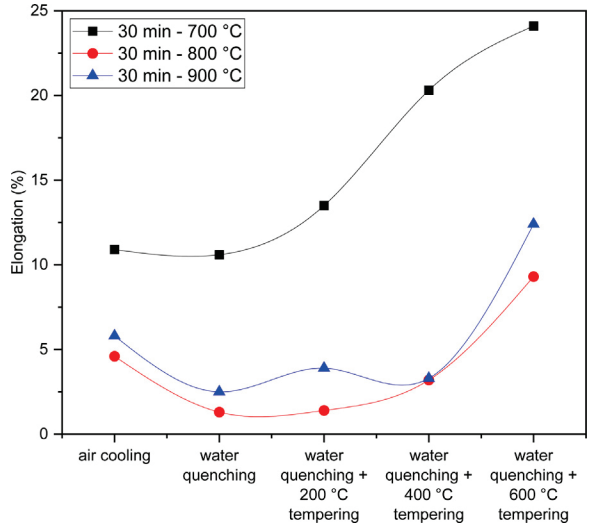

Fig. 6 – Elongation versus heat treatment condition of the 22MnB5 steel.

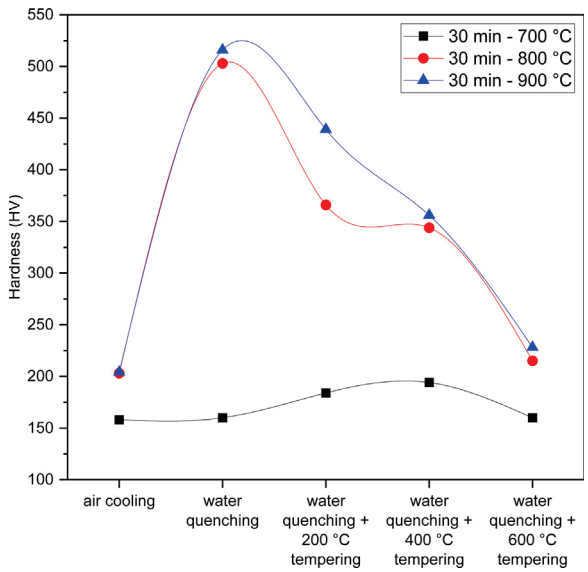

Fig. 7 – Hardness versus heat treatment condition of the 22MnB5 steel.

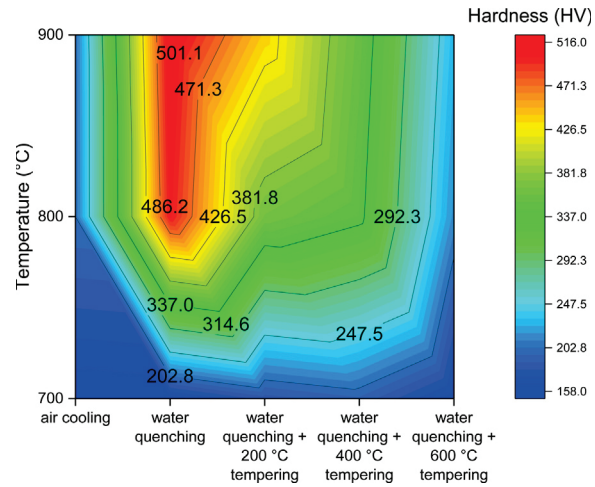

Fig. 8 – Hardness map dependent on the holding temperature and heat treatment method.

ferrite phase in the microstructure. The holding temperature of 700 °C was insufficient for austenite transformation. Additionally, the increase in tempering temperature after water quenching increased the elongation value. At holding temperature of 700 °C, the elongation, which is in the range of 10.6% - 10.9% with air cooling and water quenching processes, can be increased up to 24.1% with the tempering process at 600 °C. As a result of heat treatments carried out after holding temperatures of 800 °C and 900 °C, the elongation value ranged from 1.3% to 5.8%, excluding water quenching + tempering at 600 °C. In water quenching + tempering at 600 °C, the elongation of 9.3% was achieved at holding temperature of 800 °C and the elongation was 12.4% at holding temperature of 900 °C. The lowest elongation was obtained with the water quenching and water quenching + tempering at 200 °C, where high yield and tensile strength were achieved. It is possible to say that this is due to the highest fraction of martensite in these samples.

The hardness heat treatment condition relations are given in Fig. 7. The hardness of as-received 22MnB5 steel was 163 HV. The highest hardness values were obtained with the samples subjected to the water quenching process having holding temperatures of 800 °C and 900 °C (Fig. 8). The hardness values of samples at holding temperatures of 800 °C and 900 °C were 503 HV and 516 HV, respectively. The increase in tempering temperature after the water quenching process caused to softening of the steel. Similar results were observed by Ganapathy et al. [27]. At holding temperatures of 800 °C and 900 °C, the lowest hardness values (215–230 HV) were obtained in air cooling and water quenching + tempering at 600 °C processes. The hardness values obtained by heat treatments after holding temperature of 700 °C changed in the range of 158–194 HV due to the higher fraction of the soft ferrite phases. It is known that intercritically annealing temperature Ac1 is above 700 °C for 22MnB5 steel [4]. For that reason, primary ferrite plus partially austenite transformation does not occur at this temperature and since the transformation to partial martensite phase did not ensue after quenching from this temperature, the hardness values remained low [28]. Considering the hardness of as-received steel, the heat treatments performed after 700 °C holding temperature did not have a significant effect on the hardness.

3.2. *Microstructural evaluation*

The microstructure of this steel in the as-received condition is shown in Fig. 9. The microstructure images were taken after grinding, polishing, and etching with Nital 4% solution. This microstructure is mainly composed of a light-colored ferrite matrix with dark-colored pearlite [29]. The grains in this microstructure are elongated along the rolling direction.

The microstructural changes of 22MnB5 steel according to different holding temperatures and different heat treatment conditions are given in Fig. 10–14. Holding temperatures subjected to 22MnB5 steel were chosen as 700 °C, 800 °C, and 900 °C. 700 °C is below the calculated Ac1 (subcritical temperature), 800 °C temperature is in the intermediate critical region between the Ac1 and Ac3, and 900 °C is in the austenite region over the calculated Ac3 temperature. The microstruc-

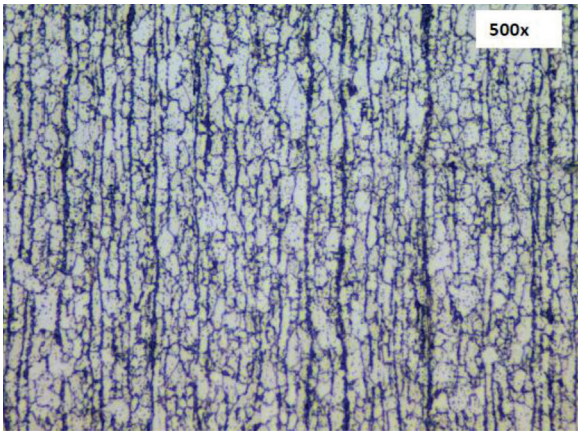

Fig. 9 – Microstructure image of 22MnB5 steel (as-received).

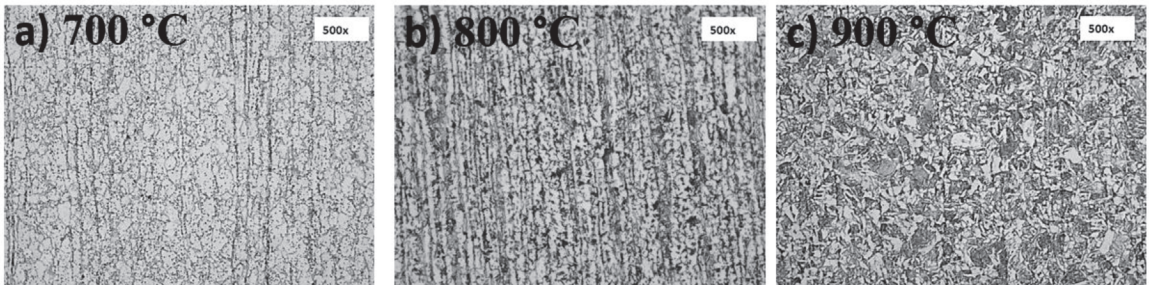

Fig. 10 – Microstructure images of 22MnB5 steel after air cooling.

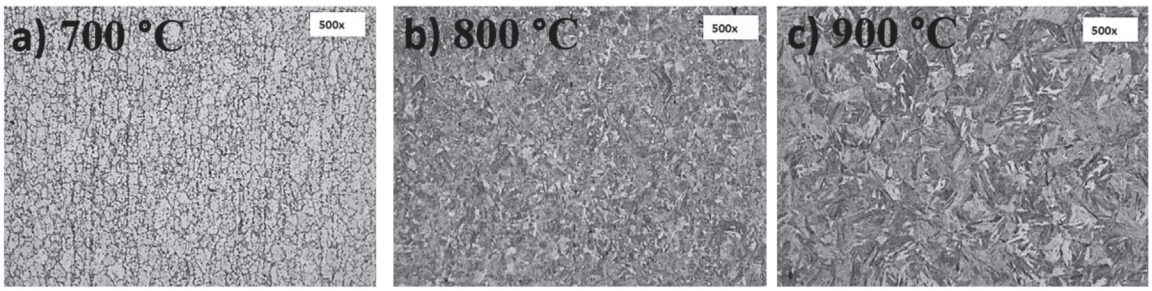

Fig. 11 – Microstructure images of 22MnB5 steel after water quenching.

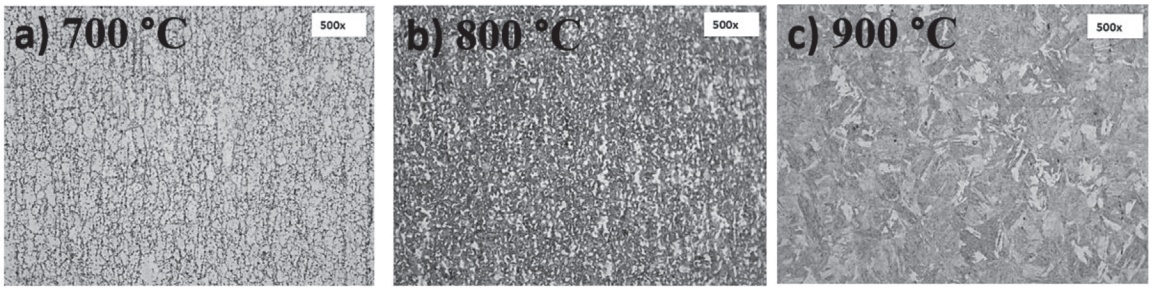

Fig. 12 – Microstructure images of 22MnB5 steel after water quenching+200 °C tempering.

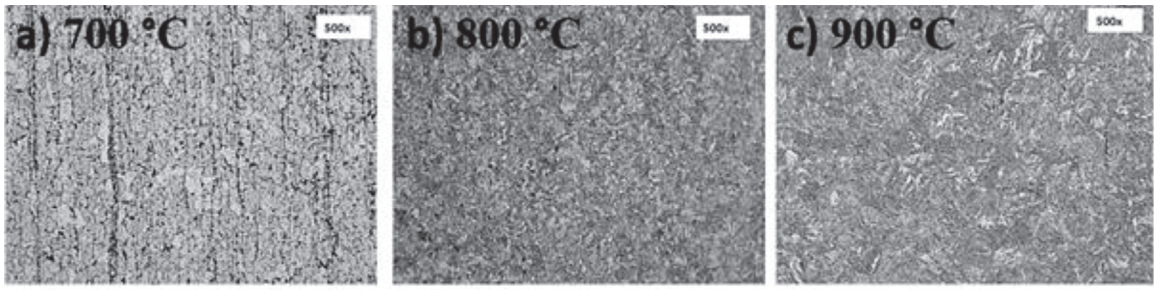

Fig. 13 – Microstructure images of 22MnB5 steel after water quenching+400 °C tempering.

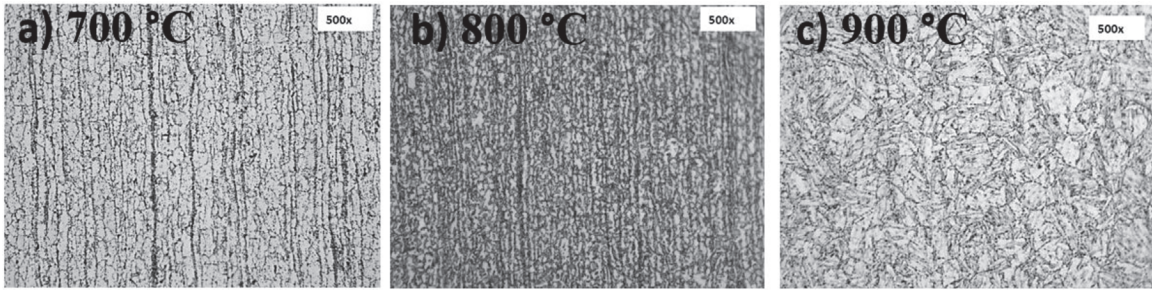

Fig. 14 – Microstructure images of 22MnB5 steel after water quenching+600 °C tempering.

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ture of the sample cooled in the air from 700 °C is similar to the microstructure of as received 22MnB5 steel as it is below the eutectoid transformation temperature (Fig. 1 and Fig. 10a). It can be clearly understood from the microstructure that there is no transformation in the microstructure at the end of air-cooling at 700 °C, which is below the Ac1 conversion temperature. Because slow cooling has preserved the lines of rolling in the original microstructure (Fig. 10a). However, air cooling is thought to cause stress relief. Thus, the yield stress is provided lower than the original material. When water is given at this temperature, the rolling lines of the microstructure have disappeared and it is seen that it has a more homogeneous and fine-grained microstructure (Fig. 11). Thus, while the harness does not change significantly. Some increase in yield stress has been achieved. At the end of holding at 200 °C after quenching from 700 °C, the equiaxial granular microstructure was preserved (Fig. 12a). By holding temperature at 400 °C and 600 °C, the textured grain microstructure appeared (Fig. 13a and 14a). Although this situation caused some increase in the hardness and the yield stress, it was very low compared to other heat treatment results. The microstructure of the sample cooled in the air from the intermediate critical temperature zone (800 °C) had slightly finer grains than the as-received microstructure (Fig. 10b) due to partial austenite transformation. A low fraction of martensite also occurred in the microstructure during air cooling. At the intermediate critical temperature, in addition to the ferrite phase, it is enriched by C following the balance rule of the partial austenite phase produced. Thus, the martensite phase can occur in this microstructure even in air cooling conditions. When the sample was cooled in the air from 900 °C (in the austenite phase region), equiaxed coarse grains and pearlitic colonies were roughened as expected in the microstructure (Fig. 10c). It is possible to form ferrite, perlite, and martensite phases and structures in the microstructure, respectively, when cooled at a cooling rate of 120 °C/min from 900 °C [13].

Microstructures of the images for water quenching with different temperatures are given in Fig. 11a-c respectively. Martensitic and partially ferritic phases are formed in the microstructure when water quenched from the intermediate critical annealing region at 800 °C (Fig. 11b). The high martensite phases in this microstructure are due to the 800 °C temperature which water quenched close to the Ac3 temperature. When water quenched at 900 °C, it has completely transformed from austenite to martensite (Fig. 11c).

In Fig. 12a-c, 22MnB5 steel microstructures are given that water quenched from different temperatures and tempered at 200 °C. In Fig. 12b, the presence of partial martensite phases remained as ferrite and tempered martensite when tempered at 800 °C in the intermediate critical annealing ($\alpha + \gamma$) region and when tempered at 200 °C. Fig. 12b shows the tempered microstructure of the martensite phase at 200 °C when water quenched from 900 °C and therefore from the austenitic region. This microstructure is similar to the non-tempered (Fig. 11c) microstructure and it can be said that the partial needle-like morphology is reduced.

In Fig. 13a-c are given the sample's tempered microstructures at 400 °C and quenched in different temperatures. It was observed that the morphology of partial martensite phases turned into equiaxed grains in the sample, which was given water at 800 °C, and after tempering at 400 °C (Fig. 13b). Fig. 13c shows that the needle-like martensite morphology is partially reduced by the tempering fully martensitic microstructure at 400 °C. This formation is compatible with the decrease of hardness. The hardness value decreased to 344 HV for 800 °C, 356 HV for 900 °C, respectively.

Finally, in Fig. 14a-c, the microstructures obtained at the end of excessive tempering of 22MnB5 steel after quenching are given. Similar to other conditions, a morphology similar to the original microstructure was provided since no serious phase transformation occurred in the microstructure at 700 °C (Fig. 14a). It is understood that in samples that have been given water at 800 °C and 900 °C and over tempered at 600 °C, both the martensitic (Fig. 14b) and the full martensitic (Fig. 14c) sample has lost the needle-like morphology of the martensite and precipitated to the spherical transition carbides and cementite phases. Thus, the hardness values decreased close to the cooling conditions in the air.

4. Conclusion

From the investigated heat treatment routes, mechanical properties, and microstructural analysis performed on a 22MnB5 hot stamping steel sheet, the following conclusions are summarized as:

The highest yield strength, tensile strength, and hardness values were obtained with the water quenching method and the lowest values were obtained under air-cooling conditions. There was no positive effect of the tempering process on improving strength and hardness. It is determined that the yield strength, tensile strength, hardness, and elongation values at 800 °C and 900 °C are close to each other. It has been observed that the elongation ability of the steel is extremely limited at 800 °C and 900 °C temperatures, but some increase in the amount of elongation can be achieved by tempering.

Conflicts of interest

The authors declare no conflicts of interest.

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