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Original Article

A feasibility study on warm forming of an as-quenched 22MnB5 boron steel

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ABSTRACT

In this paper, the feasibility of a newly proposed forming method, being the warm forming of as-quenched 22MnB5 boron steels, was studied through a series of proof of concept experiments. To assess the material thermo-mechanical behaviours under the proposed forming conditions, first, the as-received 22MnB5 boron steel was austenized and quenched to below the martensite transformation finish temperature to obtain a martensitic microstructure; second, uniaxial tensile tests of the as-quenched steel were conducted under proposed warm forming conditions on a Gleeble 3800 materials simulator. To evaluate the material post-form properties, first, tempering treatments on the as-quenched steel samples were performed to simulate the heat-treating conditions in the proposed warm forming process; second, the mechanical properties (hardness, strength, and ductility) of as-tempered samples were measured and a microstructure analysis was conducted. From the experimental results, it was found that, under the proposed warm-forming process conditions (420 °C–620 °C), the material showed significant strain softening, which would increase the tendency of necking during stamping and adversely affect its drawability. In addition, it was found that the heating of martensite in a 22MnB5 boron steel to higher temperatures (>400 °C) adversely affected its post-form strength and ductility due to the tempering effect. Therefore, according to the results obtained in this study, the warm forming of as-quenched 22MnB5 boron steel may reduce the strength of formed parts by more than 50% in comparison to the possible strength the material could achieve under the investigated process.

1. Introduction

Global requirements set by new environmental policies and health and safety legislation, combined with evolving consumer expectations, are imposing conflicting requirements on automotive design. To meet these expectations, the automotive industry is seeking increasingly innovative solutions to achieve the stringent targets assigned to them in the next ten years. As fuel economy improvements are directly linked to emission standards across the globe, a new fuel economy target of 65 miles per gallon equivalent (mpge) has been set for passenger cars by 2025, compared to the current 40mpge target [1]. In 2010, the European Union renewed its commitment to improve road safety by setting a target of reducing road deaths by 50% by 2020, compared to 2010 levels [3]. A number of further tests and regulations have been introduced with the aim of reducing injuries to both the passenger and the pedestrian [2]. In addition, consumers require cars which are affordable and fuel efficient, with attractive design. The European New Car Assessment Programme (NCAP) has increased consumer awareness for vehicle safety, which resulted in changes to the global auto market [5,6]. To meet these demands, car manufacturers are looking for innovative optimised design concepts, new materials and manufacturing processes. Whilst alternative materials like aluminium, magnesium and carbon fibre reinforced composites (CFRP) are also being considered for light-weighting and reducing fuel consumption [4], they also increase the cost of vehicle. Hence, among all other materials, steel is still playing a significant role in automotive manufacturing, and steel producers are also continuously working on the development of new automotive steel grades [7–9].

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The application of new automotive steel grades, combined with new manufacturing processes, can meet all the above requirements of weight reduction, good structural stiffness, strength and enhanced safety [1,2]. In the automotive industry, the advantages of ultra-high strength steel (UHSS) has been realized to meet the weight reduction targets; thus, the use of these steel grades has increased in recent years. UHSS is very high strength steel with a tensile strength of 1500 MPa and elongation of 8%, and consists of a fully martensitic microstructure. Therefore, it is very difficult to shape the material with existing press capacity, and poor formability is also a major drawback. To overcome these limitations in the processing of UHSS, the hot stamping process has been established for automotive applications [10].

Hot stamped UHSS are mostly 22MnB5 boron steels consisting of a martensitic microstructure. However, in a structural automotive part such as the B-Pillar, a fully martensitic phase might not be sufficient for high-energy absorption capacity. Hence, the concept of fine-tuning the microstructure of the hot stamped product with moderate strength and improved ductility was proposed. Accordingly, novel hot stamping methods have been developed to obtain a part consisting of both a high energy-absorption region and a high intrusion-resistance region through a single process [3,4]. For example, as shown in Fig. 1, the B-Pillar upper region needs to retain a martensitic microstructure for high intrusion resistance, but the lower region consists of softer phases (ferrite and perlite) to provide high-energy absorption capacity to improve side crash performance. To meet both these requirements in a single part, the solution is to tailor the material mechanical properties through innovative processing strategies such as selective heating, selective cooling and tailored tooling [5–7].

Lichler et al. investigated the application of tailored welded blanks (TWB) in hot stamping, and concluded that particular care needs to be taken on edge preparation for welding the initial material [9,10]. To obtain tailored properties in the final hot stamped part, Hartmann et al. proposed the concept of patchwork blanks [11]. The application of tailored rolled blanks for producing hot stamped automotive parts was proposed by Benteler Automotive [12]. In hot stamping, a tailored microstructure can also be obtained by a selective annealing process. Annealing of the martensitic microstructure could decompose the material into phases such as ferrite and carbides, which reduce the strength and provide a softer region [13]. A tailored die quenching process was also developed by using grooved tools. These tools could create both contact and non-contact regions between the tool surfaces and the steel sheet, tailoring the material with both hard and soft mechanical properties [14].

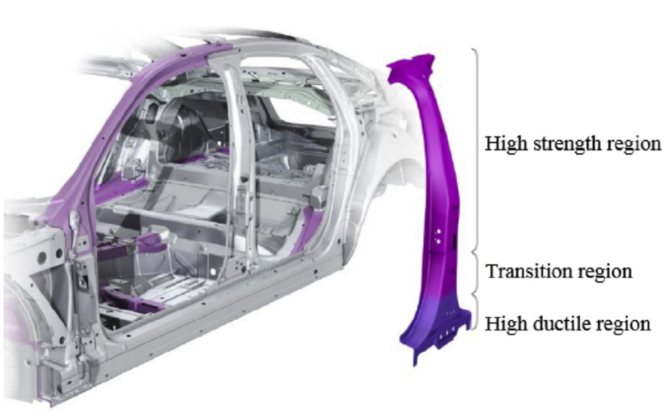


Fig. 1. B-Pillar with tailored properties for both high energy absorption at the lower region and high intrusion resistance at the upper region [8].

Speer et al. proposed a quenching and partitioning method for medium-carbon steel to create a product consisting of carbon-depleted martensite and carbon-enriched retained austenite [15]. Liu et al. conducted a new hot stamping experiment with a quenching and partitioning process in quenchable boron steel [16–18]. The final hot stamped product phase was a nanometric duplex microstructure consisting of ultrafine retained austenite and martensite. Compared to a conventional hot stamped product, this duplex microstructure offers excellent mechanical properties with higher ductility without compromising strength.

In conventional hot stamping, austenization of boron steel is carried out at 900 °C. For uncoated steels, oxide scales are generated at this temperature as soon as the material comes out of the furnace. These oxide layers are usually removed by the shot blasting process. Coated steel substrate is also used to prevent oxide formation. However, both short blasting and coated steel are costly. Therefore, to overcome the above limitations, Naderi, M., et al. evaluated the concept of a semi-hot stamping process. The as-delivered steel material was heated to a temperature of 650 °C and then formed and quenched within closed dies. The as-formed material showed the highest ductility compared to high-strength low-alloy, dual phase, and complex phase steel grades [19]. However, its strength was much lower than the hot stamped products because the steel was not austenised during the forming process, and thus no martensite could be obtained [20]. To overcome the limitations of a conventional high temperature hot stamping process, Ganapathy et al. demonstrated a new process for low-temperature hot stamping of 22MnB5 boron steels to produce B-Pillar automotive components with a significantly reduced cycle time [21]. In this process, the boron steel could be heated to 900 °C for complete austenization and then rapidly cooled to 500 °C by using a pre-cooling station before stamping. Due to the high cooling rate, the austenite phase could be retained at 500 °C for stamping and the subsequent in-die quenching time could be significantly reduced. Sun et al. proposed the optimal process window for a fast-warm stamping technique to form a martensitic steel MS1180 into a complex-shaped component with a post-form strength of 1140 MPa. The optimal forming temperature range of 400–450 °C with heating rate over 50 °C/s was suggested through thermo-mechanical experimental investigation and post-form property analysis [22]. To produce a component with a martensite and retained austenite microstructure, Xu et al. proposed a combination of hot stamping and non-isothermal quenching and partitioning (Q&P) process for QP980 steel, which resulted in a product with higher elongation than the conventional hot stamping process [23]. Horn and Merklein investigated a new process combining local carburization, followed by hot stamping, for manufacturing functionally-optimised components, which enables local strengthening of hot-stamped sheets [24]. These attempts at integrating various heat treatments with hot stamping, as novel processes to achieve controlled microstructures for desirable material properties, have also been applied to the hot stamping of other alloys [25]. However, investigation of heat treating 22MnB5 as-quenched martensitic steel and its post-form properties has not been found in the literature so far.

In this paper, a new process of warm forming as-quenched martensitic 22MnB5 boron steel was proposed, for the main purpose of reducing forming cycle time, in order to increase productivity and reduce costs. As schematically illustrated in Fig. 2, first, the as-received 22MnB5 boron steel is austenized at 900 °C and quenched to achieve a martensitic phase in the steel which typically arises in the hot stamped product; second, the as-quenched martensitic steel is heated to warm-forming temperatures

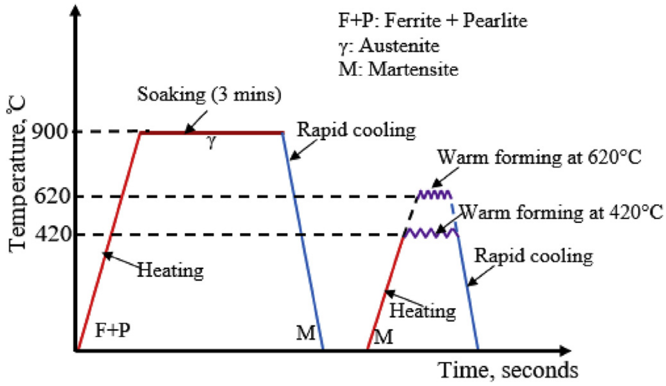


Fig. 2. Schematics of a proposed process for warm forming of as-quenched martensitic 22MnB5 boron steel.

(420 °C–620 °C) and fast deformed, followed by rapid cooling to room temperature. To investigate its feasibility, a series of experiments were conducted to simulate the different steps of this process in practice, to examine the material deformation behaviours and the post-form mechanical properties during and after this new forming process, respectively.

2. Material and experimental details

An uncoated 22MnB5 boron steel with a thickness of 1.5 mm provided by Tata Steel was used as the test material. The initial microstructure of the test material is ferrite–pearlite and its chemical composition is given in Table 1. The continuous cooling transformation (CCT) diagram for this material is shown in Fig. 3. As the CCT diagram shows, the minimum cooling rate required for 22MnB5 steel grade is 26 °C/s to ensure a completely martensitic phase in the final product. All the material test samples used for this study were machined from the same batch of boron steel sheets.

2.1. Heat treatments for martensitic 22MnB5 boron steel

In the metallurgical process, the cooling rate is critical for phase transformation and can be varied with the type of cooling medium. In the present work, the 22MnB5 boron steel was heated up to 900 °C at a heating rate of approx. 6 °C/s in an induction furnace and soaked for 3 min for austenization and homogenization. To attain a fully martensitic phase, the austenized boron steel was then quenched from 900 °C to room temperature by using both water cooling and cold plates contact cooling. The temperature profile of this heat treatment process is shown in Fig. 4. The metal plates for contact cooling were made of AISI H13 tool steel. A K type thermocouple was rigidly inserted into the test sample along the thickness direction. The thermocouple (TC) was connected to a Pico USB TC-08 thermocouple data logger to record the temperatures during both the heating and quenching periods. To ensure fully martensitic transformation after quenching, the Vickers hardness (under 10HV) was measured for all of the as-quenched samples. For each

Table 1
Chemical composition of a 22MnB5 boron steel produced by Tata Steel, in weight %.

Material grade	C	Mn	Si	Cr	S	B	Ti	Nb	Ni
22MnB5	0.20	1.17	0.25	0.20	0.002	0.0029	0.028	0.001	0.023

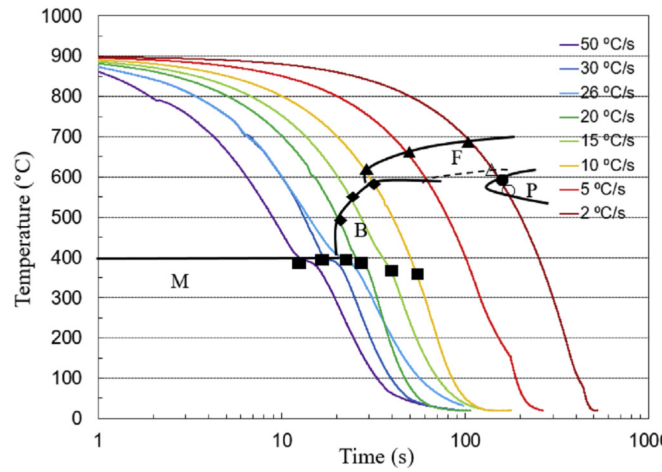


Fig. 3. CCT diagram of the 22MnB5 boron steel.

sample, at least five measurements were conducted and the average value was calculated as the final result.

2.2. Thermo-mechanical tensile tests of as-quenched martensite under proposed warm-forming conditions

To investigate the thermo-mechanical behaviours of as-quenched martensitic 22MnB5 boron steels under the proposed warm-forming process, a range of isothermal uniaxial tensile tests were conducted on a Gleeble 3800 thermo-mechanical simulator. This simulator is an entirely integrated digital closed loop control thermo-mechanical testing system, consisting of a Gleeble control unit, a test chamber and a computer to command the Gleeble control unit. The design of the test sample is presented in Fig. 5(a). During the test, the temperature was recorded and controlled by using a pair of K-type thermocouples welded to the centre of the sample. The temperature profile of the test processes, consisting of rapid heating, isothermal tension, and quenching, is illustrated in Fig. 5(b). The test material was rapidly heated to warm-forming temperature at a controlled heating rate of 62 °C/s. The isothermal uniaxial hot tensile tests were performed at a range of temperatures between 420 °C and 620 °C, with a defined strain rate of 1/s which is considered to be the most representative strain rate in the forming process. After deformation, the samples were cooled below 250 °C (martensitic transformation completion temperature) at a controlled rate of 60 °C/s by compressed air cooling.

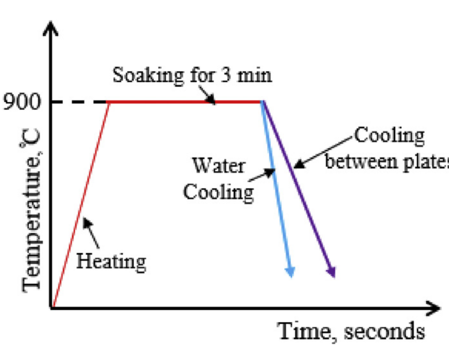
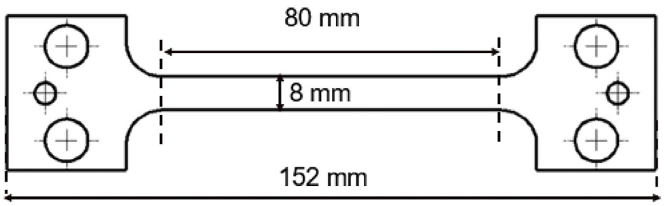
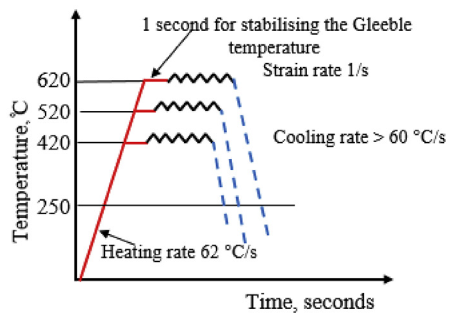


Fig. 4. Heat treatments for producing fully martensitic 22MnB5 boron steels, with two different cooling mediums, for the subsequent warm forming process.



(a) Test sample geometry



(b) Temperature profile

Fig. 5. Uniaxial tensile tests to simulate the warm forming of the martensitic 22MnB5 boron steel at various temperatures. (a) Test sample geometry. (b) Temperature profile.

2.3. *Tempering of as-quenched martensite and as-tempered properties*

To assess the feasibility of the proposed process, the as-formed mechanical properties of the final products must be studied. In practice, the heating rate of steels in a furnace is normally much lower than the defined rate (62 °C/s) in the earlier experiment and a soaking time at a target temperature for homogenization is normally required, which could potentially cause tempering of the material. The primary material mechanism in this new warm-forming process corresponds to the tempering of martensite during heat treatment. To understand the effect of tempering under different heat-treatment conditions on the properties of final product, a set of experiments was designed: first, the as-quenched martensitic boron steels were tempered under designed conditions in a furnace and then quenched to room temperature by using a pair of cold plates; second, the as-formed (i.e. as-tempered) boron steels were assessed through Vickers hardness and uniaxial tensile tests at room temperature.

Fig. 6 shows the different heat treatment conditions for the tempering. Two warm forming target temperatures of 420 °C and

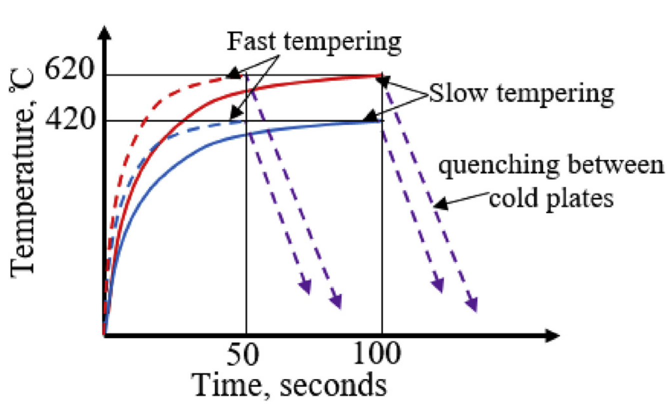


Fig. 6. Heat treatment profiles to simulate the tempering of martensitic 22MnB5 boron steel in the proposed warm forming processes.

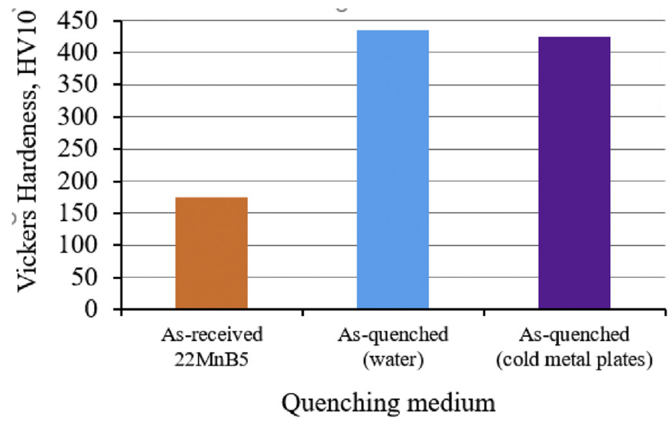


Fig. 7. Vickers hardness of as-delivered and as-quenched (through two cooling methods) 22MnB5 boron steels.

620 °C were defined; for each temperature, both slow tempering and fast tempering were conducted, which took ~100 s and ~50 s, respectively, to reach the target temperature. Quenching was applied immediately after the target temperatures were achieved.

The Vickers hardness (under 10 HV) of all as-tempered samples was measured, through the same procedure as the hardness tests on the as-delivered and as-quenched samples. The same tensile test sample design, as shown in Fig. 5(a), was used for the room-temperature tensile tests. To better understand the mechanism of tempering effects on boron steel properties, microstructural observation was conducted on all as-tempered samples, as well as the as-delivered and as-quenched (untampered) samples, by using a scanning electron microscope (SEM).

3. Results and discussion

3.1. *Hardness of as-quenched boron steels*

Fig. 7 shows the hardness of the studied 22MnB5 boron steel before and after the heat treatments. For each material sample, the hardness was measured five times at different locations. It was observed that variations in the five measurements were negligible

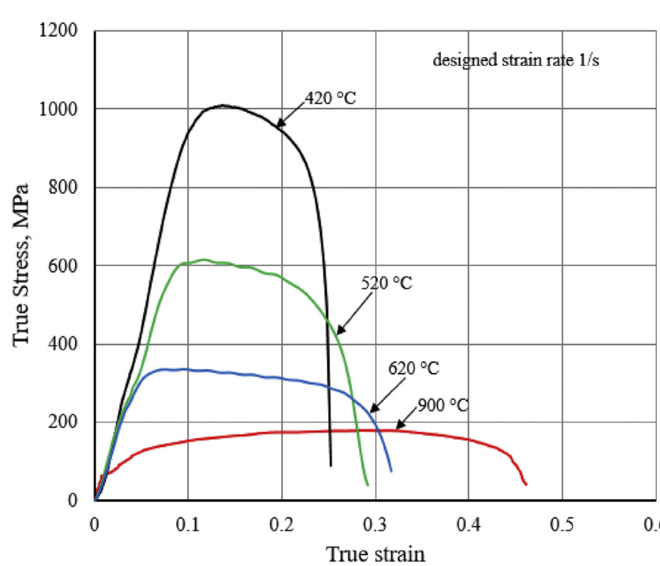


Fig. 8. Stress–strain curves of martensitic 22MnB5 boron steel under warm-forming conditions.

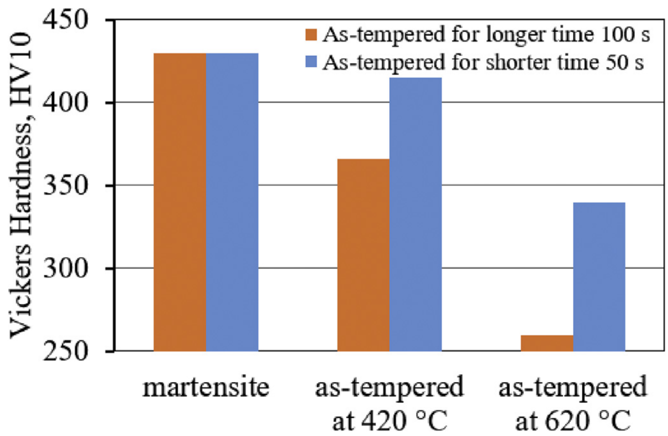


Fig. 9. Effect of the tempering temperature and duration on the Vickers Hardness of as-quenched martensite in a 22MnB5 boron steel.

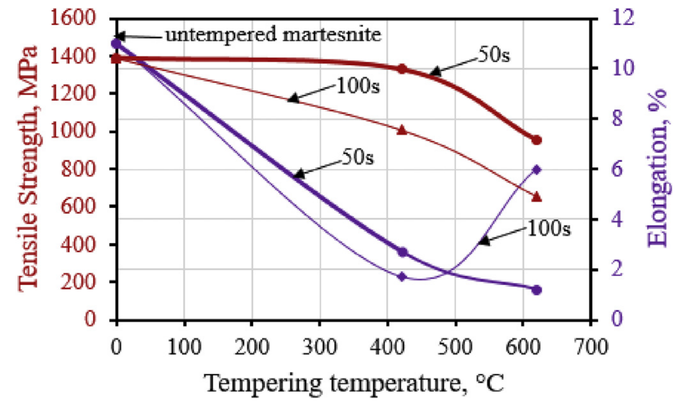


Fig. 11. Effect of tempering conditions on the post-form tensile strength and ductility (elongation, %) of martensitic 22MnB5 boron steel in the proposed warm forming process.

(all within ±5 HV) and the averaged values were calculated and presented in the figure. The Vickers Hardness of the initial as-received material was 170 HV; the Vickers Hardness of the samples quenched by water and cold plates were both confirmed to be greater than 425 HV. Based on the study by Naderi et al. [26], complete martensitic transformation could be taken as practically achieved through both quenching methods. The method of contact cooling by using a pair of cold metal plates was adopted to conduct all of the following experiments.

3.2. Tensile properties under proposed warm forming conditions

Fig. 8 shows the results of isothermal tensile tests conducted under the simulated warm forming temperature range, with a strain rate of 1/s. As expected, with increasing deformation temperature, the strain to failure increased; at the same time, significant reduction in flow stress was observed. The peak stress under 420 °C was near 900 MPa, which is quite high and not favoured by forming due to the potential for causing tool wearing and spring-back of formed parts. By increasing the temperature by about 200 °C (i.e. to 640 °C), the peak flow stress could be reduced by only one third (i.e. by around 300 MPa) which is a reasonable stress level for a forming process; at the same time, the ductility of the material was increased to 0.32. However, significant strain softening was observed for all stress–strain curves in the temperature range of 420 °C–620 °C, which would increase the tendency of necking during stamping.

3.3. As-tempered mechanical properties and microstructures

The feasibility of a forming process depends on not only the material's behaviours under forming conditions, but also its as-formed properties. In this study, the latter aspect was examined by focussing on the effect of tempering which would occur during the proposed warm forming process.

Fig. 9 shows the comparison of the hardness values of untempered martensite (i.e. as-quenched) and martensite tempered under various conditions (tempering temperature of 420 °C and 620 °C, and heating time of 100 s and 50 s). It was observed that

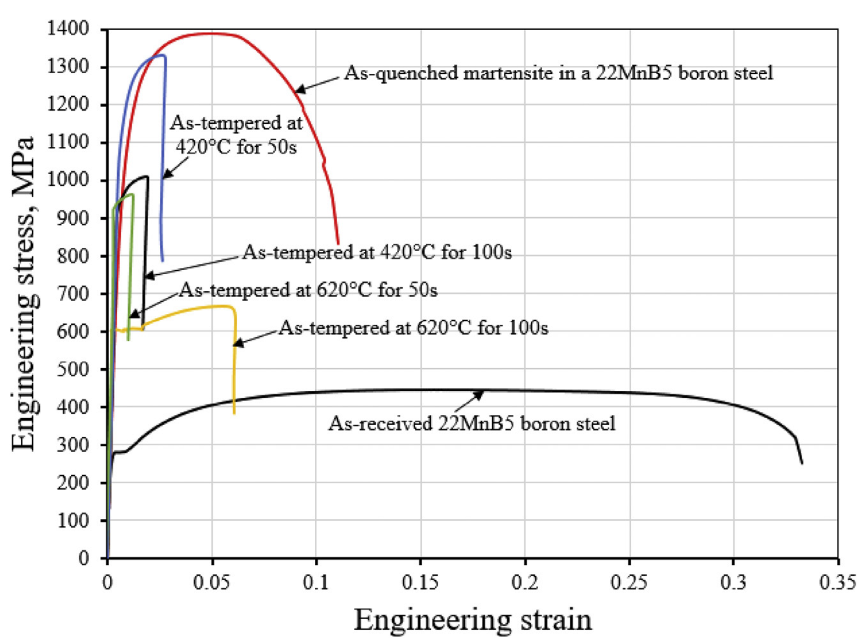
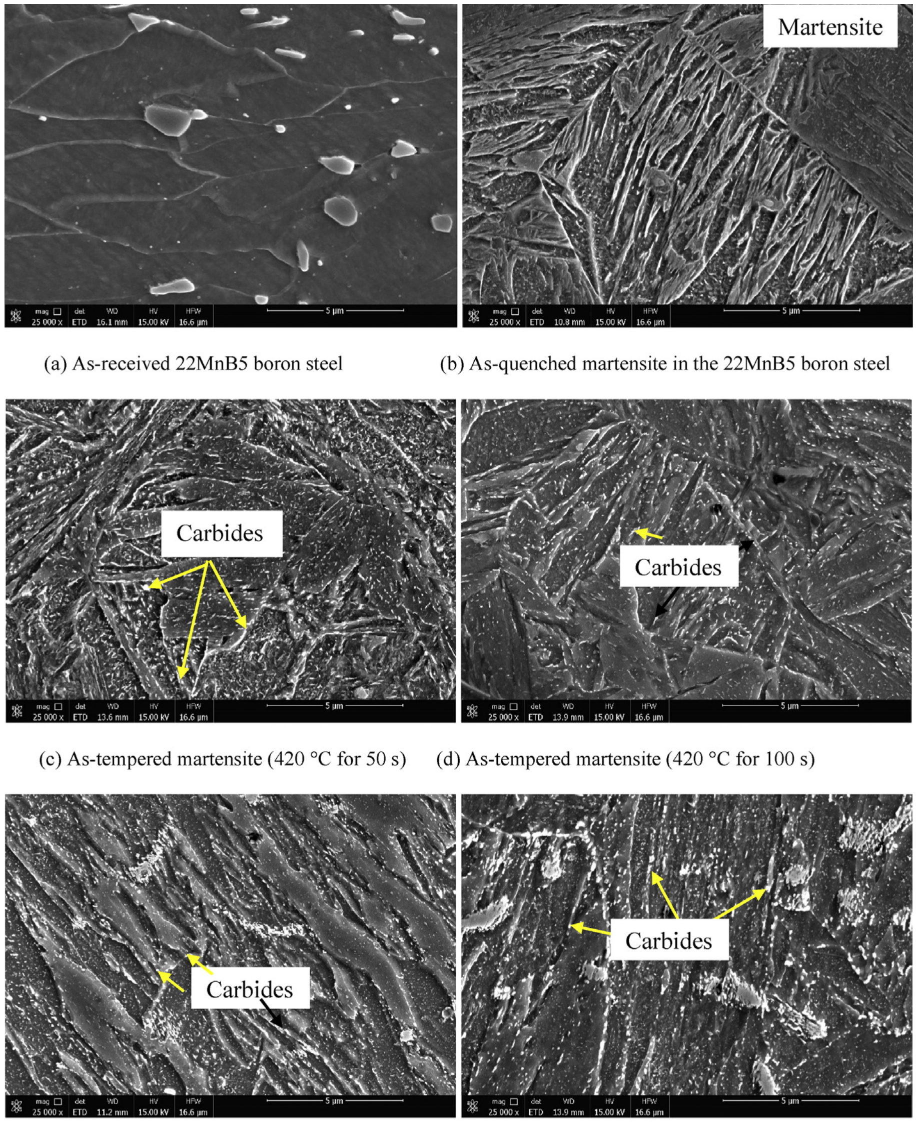


Fig. 10. Summary of uniaxial tensile stress–strain curves of the as-tempered, as quenched (untampered), and as-delivered 22MnB5 boron steels, tested at room temperature.



(a) As-received 22MnB5 boron steel (b) As-quenched martensite in the 22MnB5 boron steel

(c) As-tempered martensite (420 °C for 50 s) (d) As-tempered martensite (420 °C for 100 s)

(e) As-tempered martensite (620 °C for 50 s) (f) As-tempered martensite (620 °C for 100 s)

Fig. 12. Effect of tempering processes on the microstructure of the martensitic 22MnB5 boron steel. (a) As-received 22MnB5 boron steel. (b) As-quenched martensite in the 22MnB5 boron steel. (c) As-tempered martensite (420 °C for 50 s). (d) As-tempered martensite (420 °C for 100 s). (e) As-tempered martensite (620 °C for 50 s). (f) As-tempered martensite (620 °C for 100 s).

tempering of martensite under all test conditions caused a reduction in the hardness of the material. This reduction was more significant under a longer heating time at the same tempering temperature. For instance, by increasing the heating time from 50 s to 100 s, the as-tempered material hardness dropped from 430 HV to 366 HV for the tempering temperature of 420 °C, and dropped from 340 HV to 260 HV for 620 °C. It is also obvious to see that, using the same heating time, increasing the tempering temperature from 420 °C to 620 °C resulted in a dramatic decrease of the material hardness.

Fig. 10 shows the results of room temperature uniaxial tensile tests of as-tempered martensite, compared with the tensile properties of the boron steel in both as-delivered and as-quenched states. Excessive reductions in ductility were observed for all as-tempered samples, together with a decrease in tensile strength. For better analysis, the tensile strength and ductility (elongation, %) of samples tempered under different conditions are summarised and compared with that of untempered (as-quenched) martensite, shown in Fig. 11. The decrease in tensile strength is in monotonic relation with the tempering temperature and time. Regarding the reduction in ductility, a different trend was observed at the higher temperature (620 °C). Compared to the excessively brittle feature (elongation of 1.2%) corresponding to 50 s tempering, the ductility experienced a dramatic increase (to 6%) when the tempering duration was extended to 100 s, while the strength level dropped significantly, consistent with the tested hardness values.

It can be seen that the properties of 22MnB5 boron steel in the as-tempered states are much inferior compared to the as-quenched martensitic state. This means that the proposed warm forming of as-quenched martensitic 22MnB5 boron steel is not beneficial to the post-form properties when compared to products produced through hot stamping.

From the microstructural analysis, it was evident that the reason for the loss of strength and ductility was due to the precipitation of carbides around the grain boundaries in the 22MnB5 boron steel, as shown in Fig. 12(b)–(f), compared to the as-received ferrite/pearlite

(Fig. 12(a)) and as-quenched martensite microstructures (Fig. 12(b)). This effect is known as one step temper martensite embrittlement [27,28] and a similar effect was observed by Sun et al. for martensitic steel MS1180 [22]. Since important properties depreciate rapidly with tempering at a relatively high temperature [>400 °C], the tempering of martensitic boron steel should be avoided for automotive components. Nevertheless, it was found that tempering of martensite in the paint baking cycle at 180 °C for 20 min does not affect the material's strength and ductility [29].

4. Conclusions

A feasibility study on warm forming of an as-quenched 22MnB5 boron steel was performed for proof of concept in automotive applications. It was found that, under the proposed warm-forming process conditions (420 °C–620 °C), the ductility of as-quenched martensite in a 22MnB5 boron steel could be improved, but significant strain softening was observed, which would increase the tendency of necking during stamping. Moreover, the heating of martensite in a 22MnB5 boron steel to higher temperatures (>400 °C) induced tempering effects and adversely affected its post-form hardness, strength, and ductility. This could be explained by the observation that, during tempering at high temperatures, carbon atoms migrated to grain boundaries and formed cementite precipitates; in addition, grain boundaries might also hold mechanically-unstable retained austenite. According to the results obtained based on the conditions examined in this study, warm-forming of as-quenched 22MnB5 boron steel may reduce the strength of formed parts by more than 50% in comparison to the highest strength that the material could achieve under the investigated process.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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