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Invited Review

Medium-Mn steels for hot forming application in the automotive industry

Shuo-shuo Li and Hai-wen Luo

School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China
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Abstract: Advanced high-strength steels have been widely used to improve the crashworthiness and lightweight of vehicles. Different from the popular cold stamping, hot forming of boron-alloyed manganese steels, such as 22MnB5, could produce ultra-high-strength steel parts without springback and with accurate control of dimensions. Moreover, hot-formed medium-Mn steels could have many advantages, including better mechanical properties and lower production cost, over hot-formed 22MnB5. This paper reviews the hot forming process in the automotive industry, hot-formed steel grades, and medium-Mn steel grades and their application in hot forming in depth. In particular, the adaptabilities of medium-Mn steels and the presently popular 22MnB5 into hot forming were compared thoroughly. Future research should focus on the technological issues encountered in hot forming of medium-Mn steels to promote their commercialization.

Keywords: medium-Mn transformation-induced plasticity steel; hot forming; mechanical properties; retained austenite; baking

1. Introduction

Advanced high-strength steels (AHSS) have been widely used in the manufacture of automotive components to improve the crashworthiness and lightweight of vehicles [1–2]. Complicated shapes become difficult to form as the strength increases [3]. High press force is required and large springback often occurs in the cold forming of high-strength steels because of their high deformation resistance, resulting in poor control of the dimensional accuracy of component parts [4–5]. By contrast, hot forming can solve all these problems because the deformation resistance of steel sheets during hot stamping is much reduced at high temperatures [3]. In particular, hot forming could produce ultra-high-strength steel parts with ultimate tensile strength (UTS) above 1500 MPa, with high dimensional accuracy and no springback [6].

Until now, three generations of AHSS have been developed for the automotive industry. (1) Dual-phase (DP), transformation-induced plasticity (TRIP), complex phase, and martensitic steels are the first generation. All of these steels were developed decades ago and are now widely employed in manufacturing automobiles. Their tensile properties usually include UTS over 600 MPa and total elongation (TE) less than 25% [7–12]. (2) High Mn TRIP and twinning-induced plasticity steels are the second generation. Although they possess high-strength over 700 MPa and excellent ductility exceeding 50% [13–14], they have not yet been produced massively for commercial application because of the high level of Mn (about 20wt%) causing processing difficulties and high cost. (3) Quenching and partitioning (Q&P) [15–18] and medium-Mn TRIP steels [19] are the third generation. Compared with the first-generation steels, the third-generation steels show a much better combination of strength and ductility, and they have much lower manufacturing and alloying cost than the second-generation steels. In addition, medium-Mn TRIP steels show a great potential to combine with hot forming for manufacturing ultra-high-strength steel components for the automotive industry. Therefore, this review summarizes the relevant studies on medium-Mn TRIP steel for hot forming in comparison with the popular hot forming process.

2. Hot forming technology

2.1. Hot forming process

Hot forming, also known as hot stamping or press hardening, has two types: direct and indirect. In the direct method, a blank is heated in a hearth furnace, transferred to a water-cooled forming tool for hydraulic press, and subsequently formed and quenched in this tool until it is finally stamped to a formed part (Fig. 1(a)) [20]. In the indirect method, a blank is first transferred to the forming tool and subsequently stamped to a cold pre-formed part, and then this part is heated in the hearth furnace, transferred to the water-cooled forming

Corresponding author: Hai-wen Luo E-mail: luohaiwen@ustb.edu.cn

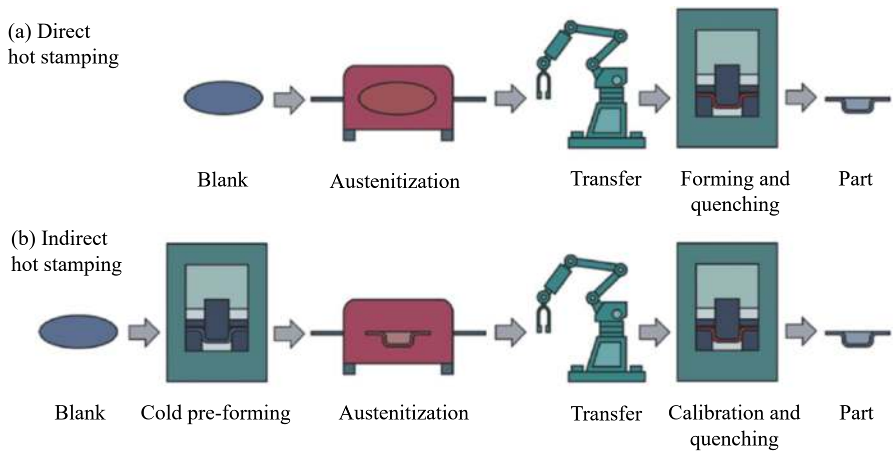

Fig. 1. Schematic of hot forming: (a) direct hot stamping, (b) indirect hot stamping. Reprinted from *J. Mater. Process. Technol.*, 210, H. Karbasian and A.E. Tekkaya, A review on hot stamping, 2103-2118, Copyright 2010, with permission from Elsevier.

tool again, and subsequently calibrated and quenched in this tool until it is finally stamped to a completely formed part (Fig. 1(b)). Given its lower cost and higher production efficiency than the indirect method, the direct method is much more widely used in the automotive industry.

Cold forming is operated at room temperature or below the recrystallization temperature, whereas hot forming is implemented at high temperatures (above the recrystallization temperature), at which internal stress may decrease and work hardening can be eliminated due to dynamic recrystallization [21–22]. Fig. 2 shows the change in the mechanical properties of the typical hot forming steel, such as 22MnB5, during hot stamping. It is initially composed of a ferrite and pearlite with a UTS of about 600 MPa. Then, the blank is heated to 900–950°C for about 5 min for austenitization, during which the steel fully transforms to austenitic microstructure and then has a low strength and high ductility. Afterward, the blank is stamped and quenched simultaneously in a water-

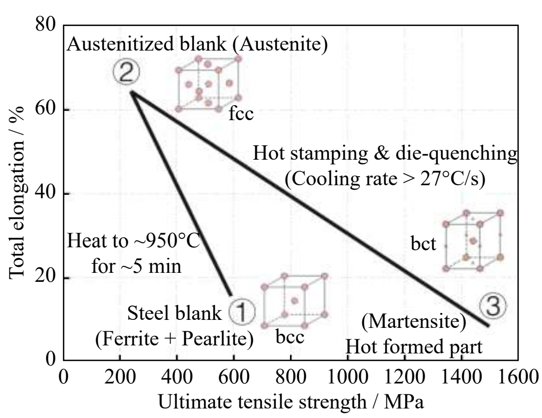

Fig. 2. Evolution of the microstructure and mechanical properties of the typical steel 22MnB5 during hot forming (bcc: body-centered cubic; fcc: face-centered cubic; bct: body-centered tetragonal). Recreated from *Automotive Steels*, 1st edition, E. Billur (R. Rana and S.B. Singh eds.), 12-Hot formed steels, 387-411, Copyright 2017, with permission from Elsevier.

cooled die tool, during which austenite transforms to martensite, leading to a very high strength of about 1500 MPa. The crucial factor is that the cooling rate of steel in the die must exceed approximately 27°C/s [3]. This value is the critical cooling rate for a fully martensitic transformation in 22MnB5 steel, in which the martensite transformation starts at 425°C and ends at 280°C [23]. The hot-formed steel features the optimal microstructure and mechanical properties at each stage of hot stamping, i.e., it is soft during forming but hard in the final part [22].

2.2. Hot forming steel grade

The widely used steel grades for hot forming are Mn–B-alloyed steels [24–25], whose chemical compositions and mechanical properties after quenching are listed in Table 1 [20,26–27]. Among them, 22MnB5 steel is the first commercial grade available and still the most widely used in the automotive industry [3]. It typically has more than 1000 MPa yield strength (YS) and 1400–1600 MPa UTS [24]. Many commercial hot forming 22MnB5 steel grades are from different steel industries, such as USIBOR 1500 from ArcelorMittal [28] and HPF1470 from POSCO [29]. However, all of them actually have similar chemical compositions.

Efforts have been exerted to improve the mechanical properties of 22MnB5 by different alloying strategies, as summarized in Table 2 [30–31]. Results show that alloying of Mo, V, Ni, and Nb can indeed improve UTS and TE.

One effort is to combine Q&P and hot forming to improve the ductility of 22MnB5 (Fig. 3). However, allowing the steel to cool to a temperature between the martensite start temperature (M_s) and the martensite finish temperature (M_f) during quenching and then for the latter partitioning is almost impossible in the real hot forming production line. Instead, two new grades, QFP1500 and QFP1800, were manufactured via a quenching and flash partitioning (Q&FP) process, and they exhibit much higher UTS and fair ductility than 22MnB5 (Fig. 3).

Table 1. Chemical compositions (Fe balanced) and mechanical properties after quenching of Mn–B steels [20,26–27]

Steel	Chemical composition / wt%									Mechanical properties		
	C	Mn	B	Al	Cr	N	Ni	Si	Ti	YS / MPa	UTS / MPa	TE / %
20MnB5	0.16	1.05	0.001	0.04	0.23	—	0.01	0.40	0.034	967	1354	4.7
22MnB5	0.23	1.18	0.002	0.03	0.16	0.005	0.12	0.22	0.040	1010	1478	6.3
27MnCrB5	0.25	1.24	0.002	0.03	0.34	0.004	0.01	0.21	0.042	1097	1611	4.0
28MnB5	0.28	1.30	0.005	—	—	—	—	0.40	—	1135	1740	—
34MnB5	0.34	1.30	0.005	—	—	—	—	0.40	—	1225	1919	—
37MnB4	0.37	0.81	0.001	0.03	0.19	0.006	0.02	0.31	0.046	1378	2040	2.5

Note: YS—yield strength; UTS—ultimate tensile strength; TE—total elongation.

Table 2. Chemical compositions (Fe balanced) and mechanical properties after quenching of Mn–B steels with alloy addition [30–31]

Steel	Chemical composition / wt%									Mechanical properties		
	C	Mn	B	Cr	Si	V	Mo	Ni	Nb	Ti	YS / MPa	UTS / MPa	TE / %
22MnB5(Mo)	0.257	1.18	0.004	0.28	0.202	—	0.218	0.000	—	0.029	1179	1666	9.7
	0.204	1.26	0.004	0.28	0.256	—	0.145	—	—	—	1288	1673	13.09
22MnB5(V)	0.255	1.20	0.003	0.28	0.190	0.097	0.005	0.005	—	0.024	1270	1684	11.0
22MnB5(Ni)	0.255	1.31	0.003	0.28	0.190	—	0.005	0.500	—	0.024	1261	1664	11.6
22MnB5(Nb)	0.191	1.27	0.004	0.28	0.334	—	0.140	—	0.049	—	1269	1730	14.00
	0.198	1.30	0.004	0.28	0.306	—	0.144	—	0.027	—	1339	1732	13.82

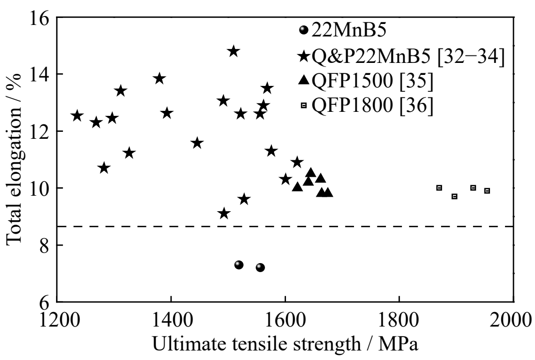

Fig. 3. Mechanical properties of 22MnB5 steels after hot forming, after both hot forming and Q&P processes [32–34], and new grades subjected to quenching and flash partitioning (QFP) process [35–36].

2.3. Advantages and disadvantages of hot forming

Cold-rolled and -annealed steel blanks are usually formed at ambient temperature. This process is the most popular for manufacturing the white-body components of automobiles but faces great difficulties in controlling springback and accurate dimensions of complicated shapes for ultra-high-strength steel components. Hot forming offers an alternative way to produce ultra-high-strength steel components with UTS above 1500 MPa, with no springback and a high dimensional accuracy. Steel is soft in the state of austenite at high temperatures, where it can be easily formed; after hot forming, austenite transforms into the hard martensite during quenching, producing the ultra-high strength required by components. Moreover, the low resistance force and the high formability of steel during hot forming can solve the problems of severe wearing and short life of die mold, which are common in the cold forming of high-strength steels [6]. To further improve crashworthiness and lightweight, hot-formed parts with tailored properties can be synthesized using different process control strategies, such as using a furnace with areas maintained at different temperatures and using tools with different temperatures or with different materials having different thermal conductivities [20,37–39].

Although the hot forming can produce springback-free ultra-high-strength steel parts, it still has some drawbacks. First, it requires expensive facilities, including heating furnaces, press tool, and laser cutting machine [40]. Second, hot forming has lower productivity than cold forming [41] due to its long heating and holding time. Third, the oxidation and decarburization of steel sheets are inevitable when heated to a high temperature; therefore, a coating is required to protect the steel from oxidation, which significantly increases the cost. Fourth, the tool failure and the lubrication at high temperatures are also problematic. Fifth, the heating of steel sheets up to 900–950°C in the furnace for a long time requires considerable energy consumption [42]. Finally, the 22MnB5 steel after hot forming shows poor ductility (TE < 8%), which cannot provide sufficient energy absorption and limits the application of hot-stamped steels [40]. Therefore, new steel grades possessing high strength and super ductility are being searched. Some examples are listed in Table 2 and shown in Fig. 3. Besides, medium-Mn steels are proposed to have even greater potential on improving the mechanical properties for the press hardening application, which is discussed in more details as follows.

3. Application of medium-Mn steel for hot forming

Medium-Mn steels often contain approximately 5–12 Mn, 0.05–0.6 C, 0–3 Si, and sometimes 1.5–6 Al (all in weight percentage unless mentioned elsewhere) [43–49]. Their microstructure is usually martensite after hot and cold rolling, and it changes to dual-phased one after an intercritical annealing, in which the volume fraction of retained austenite (RA) is in the range of 20%–50% [50]. The reverted austenite can be stabilized by partitioned C and Mn [51] and then retained at room temperature; it may transform to martensite during tensile deformation through the TRIP effect, which promotes work hardening during deformation and improves mechanical properties [7,52]. The first medium-Mn steel containing 5.7Mn–0.11C exhibits a UTS of 878 MPa and a uniform elongation (UE) of 34% after annealing at 640°C for 1 h, as reported by Miller in 1972 [53]. Later, Luo *et al.* [54] prepared a Fe–5Mn–0.2C steel possessing 850–950 MPa UTS and 20%–30% TE. Shi *et al.* [55] measured 1420 MPa UTS and 31% TE in 7Mn–0.2C steel. Recently, He *et al.* [56] have managed to manufacture a deformed and portioned steel possessing 2.2 GPa YS and 16% UE with the composition of 10Mn–0.47C–2Al–0.7V. The optimal intercritical annealing of medium-Mn steels containing 5%–7% Mn may lead to the product of UTS and TE exceeding 30 GPa·% [57]. Given their high strength and superior ductility, medium-Mn steels have become increasingly attractive for automobile structures.

Medium-Mn steels fit the hot forming process because of the following reasons.

(1) Much higher Mn content in medium-Mn steel than 22MnB5 leads to the significant decrease in austenitization temperature. Consequently, soaking at low temperatures reduces energy consumption and oxidation. The effect of Mn content on Ac_3 and A_3 transformation temperatures is plotted in Fig. 4, in which Ac_3 decreases to less than 750°C when Mn content is about 7wt% at 0.22wt% C content, which is much lower than that of 22MnB5 (about 850°C) [59].

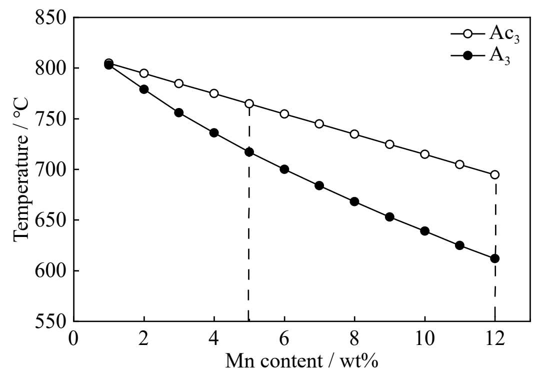

Fig. 4. Effect of Mn content on Ac_3 and A_3 transformation points, in which A_3 was calculated using the commercial software Thermo-Calc and Ac_3 as described by ref. [58], for the Mn-contained steel with 0.22wt% C content.

(2) A high Mn content also leads to significant decreases in M_s (Fig. 5) and M_f, and the latter can be lowered below room temperature [60–61]. This phenomenon causes the incomplete martensitic transformation so that some austenite grains are retained in the martensitic matrix after hot forming, which may help improve the mechanical properties via the TRIP effect.

(3) Such a high Mn content significantly increases the hardenability. Thus, a much lower critical cooling rate is required to initiate martensite transformation (Fig. 5) [60–61], which offers a greater flexibility for the selection of water-

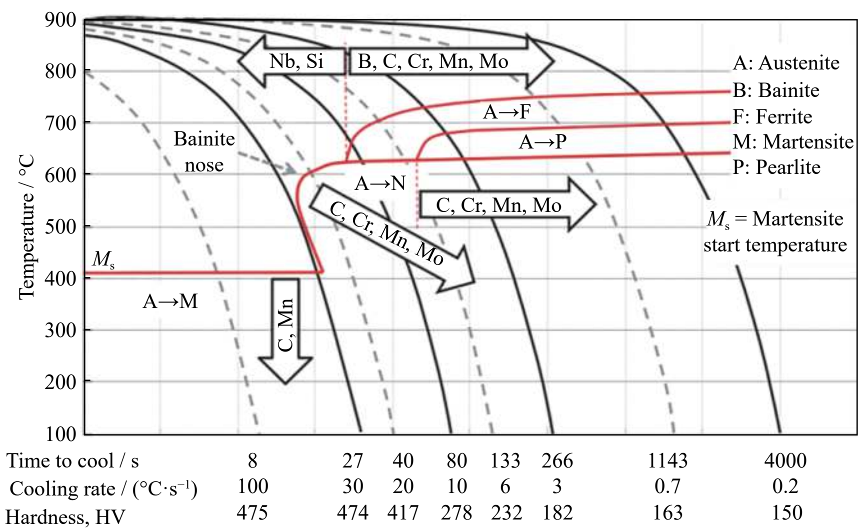

Fig. 5. Effect of the alloy element on the continuous cooling transformation (CCT) diagram of 22MnB5 steel [3]. Reprinted from *Automotive Steels*, 1st edition, E.Billur (R. Rana and S.B. Singh eds.), 12-Hot formed steels, 387-411, Copyright 2017, with permission from Elsevier.

cooled forming dies.

3.1. Medium-Mn steel grades for hot forming

Medium-Mn steels have been adapted to two types of hot forming processes. One is the ordinary hot stamping but at relatively low forming temperature (Fig. 6(a)), sometimes called warm stamping [62–63]; the other is hot forming combined with quenching-baking and partitioning (Fig. 6(b)) [36]. Baking, usually at 170°C for 20 min, simulates the actual paint-baking of the automotive white body. This procedure exerts minimal influence on the ductility of 22MnB5 steel but often improves the ductility of medium-Mn steels [64]. The microstructures of hot-formed medium-Mn steels often possess the martensitic matrix (Fig. 7 [63,65]), leading to the similar strength level to 22MnB5. In addition, the alloying of V, Mo, Nb, and Cr could further improve the mechanical properties of medium-Mn steels [65–66], as summarized in Table 3. The mechanical properties of medium-Mn steels and 22MnB5 are compared in Fig. 8. Some have better ductility than 22MnB5 at the similar UTS level; others even exhibit not only higher UTS up to 1900 MPa but also much better ductility.

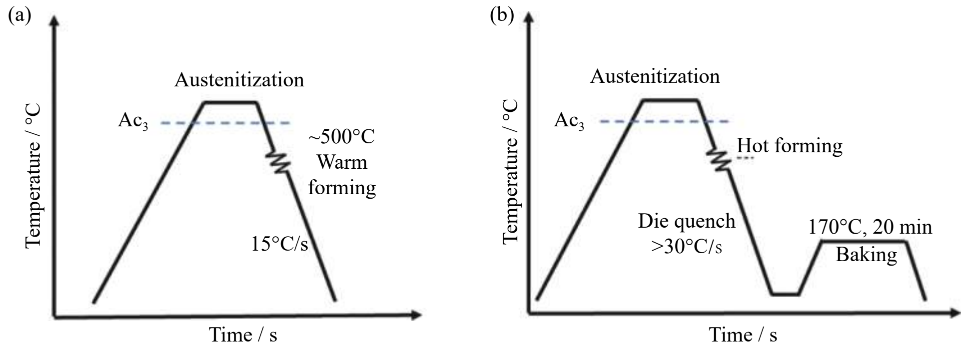

Fig. 6. Schematic of hot forming processes for medium-Mn steels: (a) Hot stamping at relatively low austenitization temperature (warm stamping); (b) hot forming followed by baking and partitioning.

Medium-Mn steels often exhibit much better mechanical properties than the conventional 22MnB5 steel because of the following factors.

(1) Much larger fraction of austenite grains is retained in medium-Mn steels than in 22MnB5, in either lath-like or granular shape (Fig. 9). RA can transform to martensite during deformation, which contributes to work hardening and improves mechanical properties, particularly ductility (Fig. 9(d)).

(2) The prior austenite grain size (PAGS) decreases with the decrease in austenitization temperature in hot forming, as shown in Figs. 10 and 11. Finer PAGS can result in refined microstructures after quenching, including the refinements in the hierarchical martensite and RA grains, which improve strength and toughness [71].

(3) The partition of C atoms from martensite to RA may occur during baking, leading to high C concentration at the martensite/austenite interface [64]. The diffusion distance of carbon into austenite is about 2.7 nm during baking at 170°C for 20 min, as illustrated by the kinetic calculation in Fig. 12. This partition enhances the stability of RA grains, further improving the mechanical properties of medium-Mn steels after hot forming [51].

3.2. Hot forming process parameters

The hot forming process parameters include the temperature and period of soaking for austenitization, deformation temperature, and cooling rate in die. All of these parameters affect the final microstructures and the resultant mechanical properties.

3.2.1. Soaking temperature

A proper soaking temperature should ensure a full austenitization before hot forming. Extremely low soaking temperature causes incomplete austenitization, resulting in untransformed ferrite and reduced fraction of martensite, which decrease the tensile strength. Extremely high temperatures produce coarse austenite grains and coarse martensitic packets/laths, which may decrease strength and elongation.

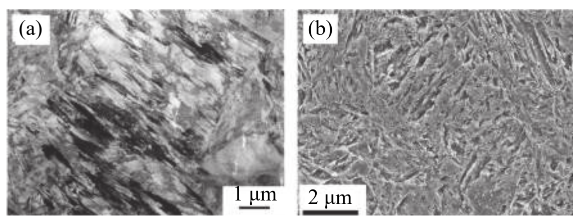

Fig. 7. Martensite matrix microstructure of the hot-formed medium-Mn steel with (a) 5wt% Mn by TEM and (b) 7wt% Mn by SEM. (a) Reprinted from *Mater. Sci. Eng. A*, 679, X.D. Li, Y. Chang, C.Y. Wang, P. Hu, and H. Dong, Comparison of the hot-stamped boron-alloyed steel and the warm-stamped medium-Mn steel on microstructure and mechanical properties, 240-248, Copyright 2017, with permission from Elsevier. (b) Reprinted from *Scripta Mater.*, 162, Z.R. Hou, T. Opitz, X.C. Xiong, X.M. Zhao, and H.L. Yi, Bake-partitioning in a press-hardening steel, 492-496, Copyright 2019, with permission from Elsevier.

Table 3. Chemical compositions and mechanical properties of different hot-formed medium-Mn steels

Steel	Chemical composition / wt%								AT / °C	Mechanical properties			Ref.
	C	Mn	Al	Nb	Mo	Si	V	Cr		YS / MPa	UTS /MPa	TE / %	
1#	0.08–0.2	4–7	0.03	—	—	—	—	—	790–840	1220	1418	11.8	[62]
2#	0.1	5	0.03	—	—	0.23	—	—	800	1050	1520	11.3	[63]
3#	0.14	7	—	—	—	0.22	—	0.08	800	—	1565	11.7	[64]
4#	0.19	7.5	—	—	—	1.2	0.15	—	780	—	1805	16	[65]
5#	0.19	5.6	1.2	0.05	0.22	—	—	—	700	709	1424	22	[66]
									760	852	1717	16	[66]
6#	0.1–0.3	5–8	0.23	0.05–0.15	—	0.38	0.05–0.15	2–4	750	1420	1700	11.8	[67]
7#	—	5–8	—	—	—	—	—	—	760	1442	1880	16	[68]
8#	—	9.67	—	—	—	—	—	—	750–800	642	1409	21	[69]
9#	—	5–12	—	—	—	—	—	—	780–850	915	1800	>10	[70]

Note: AT—heat temperature during hot forming

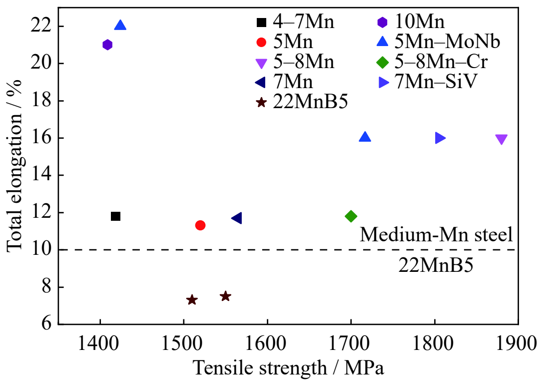

Fig. 8. Comparison of the mechanical properties of hot-formed medium-Mn steel with conventional 22MnB5 steel [62–70].

Therefore, the soaking temperature should be optimized to realize the finest martensitic microstructure as the mere phase for achieving the best mechanical properties. For example, the austenitization temperature for 0.1C–5Mn steel was recommended at 790–840°C [62], as shown in Fig. 13(a). Li *et al*. [74] found that increasing the soaking temperature from 690 to 770°C gradually decreases the ferrite and austenite fractions and increases the martensite fraction in the formed 8Mn steel parts. Park *et al*. [75] investigated the tensile strength of warm-stamped medium-Mn steels as a function of Mn content (3wt%–7wt%) and soaking temperature and found that the 5Mn steel soaked at 770°C can produce martensite without active auto-tempering and high tensile strength.

3.2.2. Soaking time

A sufficiently long soaking time is required to achieve a full and homogenous austenitization. An insufficient soaking may lead to uneven hardness distribution and then low strength. By contrast, over-soaking also results in grain coarsening and reduced hardness. The recommended soaking period is 4–7 min to achieve the desired mechanical properties for 0.1C–5Mn steel (Fig. 13(b)).

3.2.3. Forming temperature

Forming temperature hardly affects the final microstructure (full martensite) but considerably influences the formability of medium-Mn steels during hot forming. The proper forming temperature should promote a sufficient deformation-induced austenite grain boundary migration, which can enclose the cracks initiated at the prior grain boundaries and prevent the propagation of crack effectively [62]. The dimple fracture usually occurs at the forming temperature between 400 and 650°C for 5Mn steel; thus, 450−500°C is recommended for the best hot ductility (Fig. 13(c)). Nam *et al*. [76] described that stamping temperatures ranging from 500 to 700°C hardly influence the strength of the warm-stamped Nb-bearing 6Mn steel, in which nano-sized Nb carbides are dispersed in the fine martensitic structure. By contrast, the tensile strength of 22MnB5 steel is greatly affected by the deformation temperature because austenite with much lower stability could transform to ferrite and pearlite before die quenching at a low deformation temperature, leading to incomplete martensitic transformation [77].

3.2.4. Cooling rate of steel blanks

Due to the high hardenability of medium-Mn steels resulting from high Mn content, a complete martensite transformation can be easily realized during cooling in air, die, and water at the rates of 10, 60, and 600°C/s, respectively [62]. Therefore, the cooling rate exerts a marginal influence on the final microstructure but a considerable influence on the mechanical properties. The fastest cooling rate in water quenching causes a great residual stress, reducing the ductility. A moderate cooling rate could sufficiently release the residual stress, leading to high elongation but slightly low tensile strength (Fig. 13(d)). By contrast, the mechanical properties and microstructure of conventional Mn–B steels are highly dependent on the cooling rate because the full martensite transformation is achieved only when the cooling rate is more than 27°C/s for 22MnB5 [3,78].

Moreover, the Mn content of medium-Mn steels also af-

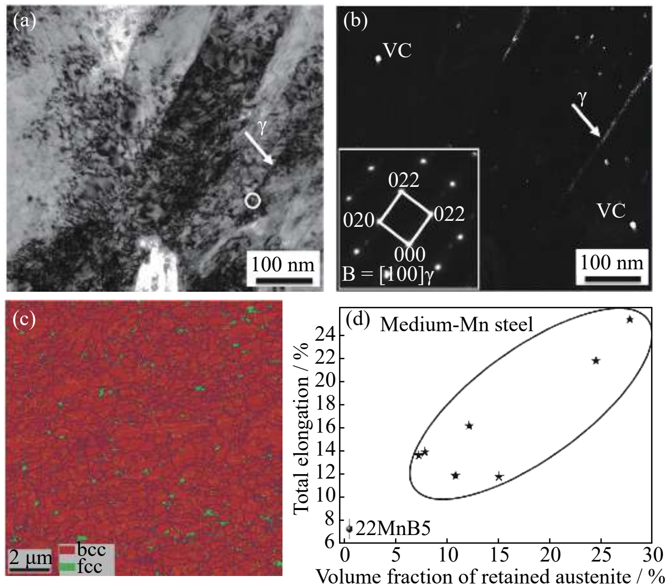

Fig. 9. Retained austenite in the martensite matrix: (a) Bright-field image and (b) dark-field image of TEM revealing the film-like retained austenite [65], reprinted from *Scripta Mater.*, 162, Z.R. Hou, T. Opitz, X.C. Xiong, X.M. Zhao, and H.L. Yi, Bake-partitioning in a press-hardening steel, 492-496, Copyright 2019, with permission from Elsevier; (c) austenite with FCC structure observed by EBSD [67], reprinted by permission from Springer Nature: *TMS 2020 149th Annual Meeting & Exhibition Supplemental Proceedings*, A novel high-strength oxidization-resistant press hardening steel sheet requiring no Al–Si coating, S.S. Li and H.W. Luo, Copyright 2020; (d) distribution of total elongations corresponding to the volume fraction of the retained austenite [64–67].

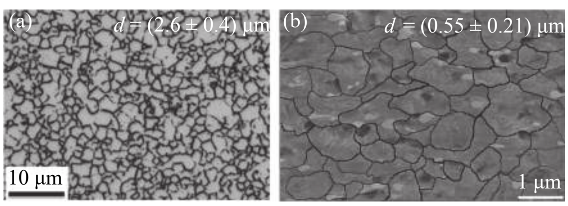

Fig. 10. Prior austenite of the hot-formed Medium-Mn (7wt% Mn) steel at (a) 780°C [65] (reprinted from *Scripta Mater.*, 162, Z.R. Hou, T. Opitz, X.C. Xiong, X.M. Zhao, and H.L. Yi, Bake-partitioning in a press-hardening steel, 492-496, Copyright 2019, with permission from Elsevier) and (b) 750°C [67] (reprinted by permission from Springer Nature: *TMS 2020 149th Annual Meeting & Exhibition Supplemental Proceedings*, A novel high-strength oxidization-resistant press hardening steel sheet requiring no Al–Si coating, S.S. Li and H.W. Luo, Copyright 2020).

fects the microstructure after hot forming. Windmann *et al.* [79] reported that α-martensite is the mere phase in 6Mn steel, while RA and ε-martensite appear in 7.5Mn and 9.5Mn in addition to α-martensite, respectively.

Orthogonal experiments can be used to optimize the above process parameters for outstanding mechanical properties [80–81].

3.3. Numerical simulation for hot-formed medium-Mn steel

Hot forming can be numerically simulated using the finite element method. However, hot forming is much more com-

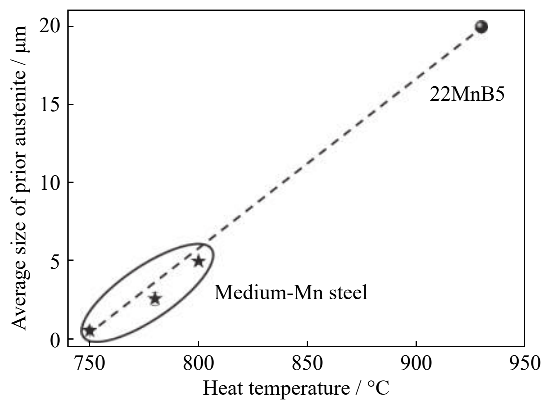

Fig. 11. Distribution of the prior austenite grain size corresponding to austenitization temperature for hot forming [64–65,67].

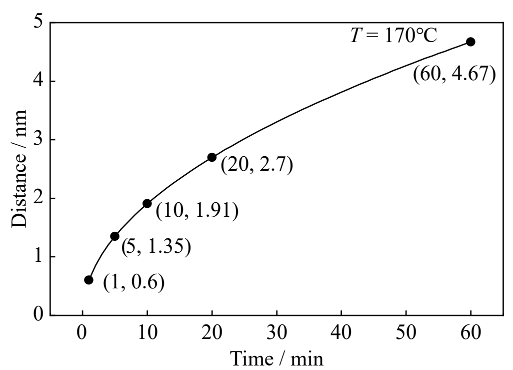

Fig. 12. Calculated diffusion distance of carbon into austenite with time during baking at 170°C [72–73].

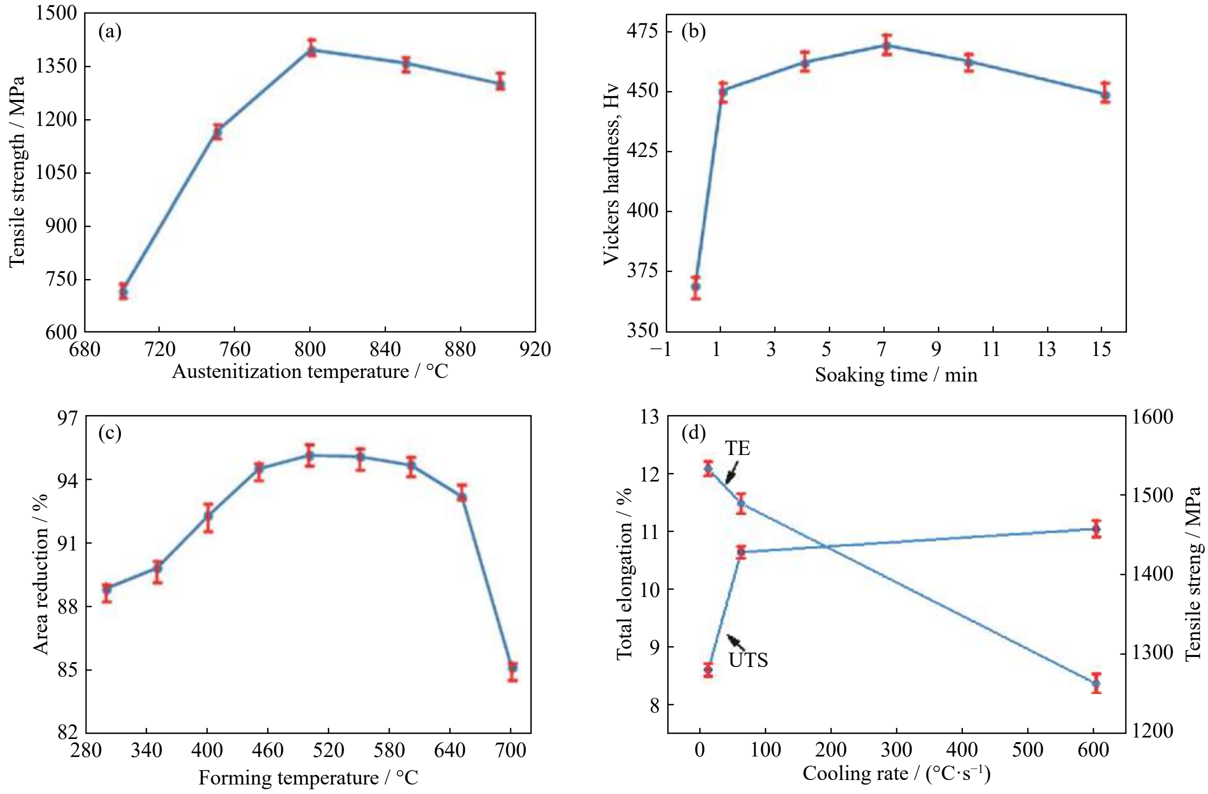

Fig. 13. Effects of process parameters on the mechanical properties of 0.1C–5Mn steel [62]. Reprinted from *Mater. Des.*, 94, Y. Chang, C.Y. Wang, K.M. Zhao, H. Dong, and J.W. Yan, An introduction to medium-Mn steel: Metallurgy, mechanical properties and warm stamping process, 424-432, Copyright 2016, with permission from Elsevier.

plicated than cold forming because the former involves the couple of the thermal, mechanical, and microstructural fields, as illustrated in Fig. 14. When the blank sheet is heated, formed, and cooled, all the physical parameters change with phase transformations. Jin *et al*. [6], Karbasian and Tekkaya [20], and Mori *et al*. [40] have summarized the advances in the numerical simulation of hot-forming steels, including the thermal analysis, material constitutive models, modeling microstructural evolution, and the hardness prediction on the product.

Numerical simulation on the hot forming of medium-Mn steels has just started recently. Zheng *et al*. [82] established a numerical model using LSDYNA and simulated the critical values of ductile fracture to predict the hot forming limit of medium-Mn steel. They demonstrated that the flow stress of medium-Mn steel at an elevated temperature is independent of strain rate and that its formability increases rapidly first and then decreases gradually with the increase in temperature. Chang *et al*. [83] studied the interfacial heat transfer coefficient (IHTC) of warm-formed medium-Mn steel using simulation and experiments and found that the IHTC increases with the increase in stamping pressure and stamping temperature. Zheng *et al*. [84] built finite element simulation models of square-cup deep drawing for medium-Mn and 22MnB5 steels and found that the former has better formability and smaller impact of blank holder force and fillet radius of tools on the hot-formed product than the latter. Chang *et al*. [85] simulated the shearing procedure of medium-Mn steel and found that large shearing clearance deteriorates the macro/micro performance of sheared edge. Chang *et al*. [86] also simulated the one-step formation of medium-Mn steel and found that the part can be formed successfully without cracking. The selection of the deformation temperature can also be determined by numerical simulation [87].

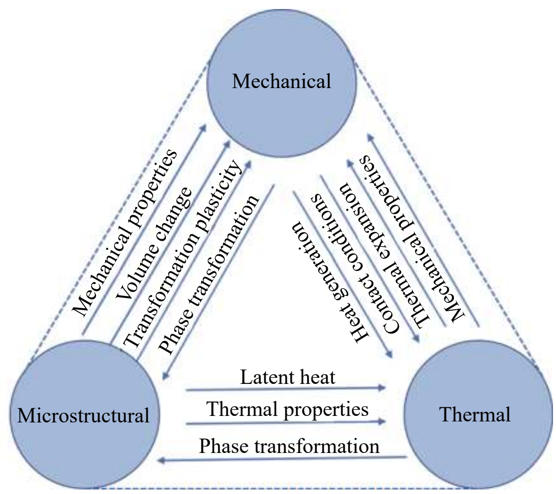

Fig. 14. Interaction between thermal, mechanical, and microstructural fields.

3.4. Advantages of medium-Mn steels for hot forming

Hot-formed medium-Mn steels are superior to the conventional 22MnB5 steel, such as lower austenitization temperature, more austenite retained in the martensitic matrix, greater hardenability and wider cooling rate range [88], all resulting from high Mn content, as mentioned in the "Section 3" above. These properties may reduce the energy consumption during heating, improve mechanical properties, and decrease the requirement for water-cooled forming dies.

Moreover, the hot forming of medium-Mn steels has more advantages. First, the forming temperature and strain rate only exert marginal influence on the M_s temperature of medium-Mn steels, thereby promoting the even distributions of martensite and mechanical properties and then the manufacturing of complex-shaped automotive parts [63,89]. Second, the high hardenability of medium-Mn steels leads to a wide window for choosing alternative cooling approaches and easy forming [62–63]. Third, the oxidization and decarbonization on the surface of hot-formed medium-Mn steels can be significantly reduced and even avoided [90]. Fourth, the low soaking temperature results in fine-grained microstructure in medium-Mn steels, thereby improving total elongation and tear toughness [62]. Fifth, Zheng *et al*. [84] demonstrated that medium-Mn steels have better formability and smaller impact of blank holder force and fillet radius of tools on the hot-formed product than 22MnB5. Li *et al*. [91] and Chang *et al*. [62] indicated that the high UE and hardening index value of medium-Mn steels can reduce the fracture caused by local necking during hot forming. Wang *et al*. [92] compared medium-Mn and 22MnB5 steels for hot forming and found that medium-Mn steels possess low yield ratio, high impact absorbing energy, good connection behavior with other materials through resistance spot welding, fine cold bending property, enhanced collision safety, and superior capability to produce ultra-large and ultra-thin automobile sidewall parts.

4. Future research for hot-formed medium-Mn steels

Although the hot forming of medium-Mn steels has many advantages as discussed above, it is still an immature technology. Several technological issues need to be tackled before its successful commercialization.

4.1. Bendability

The cold bendability of automotive part reflects the crush energy absorption capability and is usually examined in accordance with the VDA238-100 three-point bending test standard, issued by German Automobile Industry Association [93]. Wang *et al*. [92] demonstrated that hot-formed medium-Mn steel features better cold bending properties than 22MnB5 steel because of the refined microstructure of the former. Yi *et al*. [36] and Lu *et al*. [94] also reported that the bendability and fracture strain of hot-formed medium-Mn steel are notably superior to those of 22MnB5 steel. Therefore, additional studies are required to confirm the factors affecting the cold bendability of medium-Mn steels.

4.2. Role of RA on tensile properties

Although many studies revealed a simple relation between large RA fraction and high ductility, others sometimes reported contradictory findings [95]. Therefore, how the fraction, size, morphology, distribution, and mechanical stability of RA grains can affect the tensile properties is still crucial for designing the composition, process, and microstructures of hot-formed medium-Mn steels [96–97].

4.3. Hydrogen embrittlement

Hydrogen embrittlement decreases the toughness and fracture strain of steel parts, leading to severely deteriorated mechanical properties. Han *et al*. [98] found that hot-rolled and cold-rolled Fe–7Mn–0.1C–0.5Si steels have relatively high sensitivity to hydrogen embrittlement, which is denoted by plasticity loss and strength loss. Li *et al*. [99] also presented that medium-Mn steels are highly susceptible to hydrogen embrittlement, particularly when a large fraction of RA is transformed during deformation. The present strategy to improve resistance to hydrogen embrittlement is to tailor the morphology and distribution of RA in medium-Mn steels. Therefore, the relation of hydrogen embrittlement susceptibility and RA should be further investigated in hot-formed medium-Mn steels.

4.4. Blank coating and oxidation

In the hot forming of 22MnB5 steel, Al–Si coatings have been widely employed to protect blanks from oxidation [100], which usually entails a high cost. Hot-formed medium-Mn steels have much reduced oxidization and almost no decarbonization on the surface [63]. Whether the coatings are required for medium-Mn steels during hot forming remains to be verified. In addition, Li *et al.* [67,101] designed a new medium-Mn steel with superior resistance to oxidation for hot forming by combining low heat temperature and the addition of alloying elements resistant to oxidization. The new steel indeed exhibits a better resistance to oxidation than 22MnB5 steel at a high austenitization temperature. Additional studies are expected to develop medium-Mn steels with extraordinary resistance to oxidization and outstanding mechanical properties.

4.5. Weldability

High Mn content apparently increases carbon equivalent, which often deteriorates weldability [102]. Thus, the weldability of medium-Mn steel is inferior to that of 22MnB5. Park *et al*. [103] revealed that the cross-tension strength of medium-Mn steel weldments is lower than that of conventional

TRIP steel with low carbon equivalent and that the brittleness of martensite is the main factor controlling the fracture path. Jia *et al*. [104] indicated that the desired pull-out failure is absent in the tensile test of the resistance spot weldments of 0.1C–5Mn steel. Lun *et al.* [105] investigated the laser welding of Fe–10.4Mn–0.15C steel and observed a brittle fusion zone, leading to the limited stretch formability.

Efforts have been exerted to improve the weldability of medium-Mn steels. Li *et al.* [106] designed a novel shim-assisted resistance spot welding process that greatly improved the mechanical properties of 7Mn–0.14C steel weld by enlarging the nugget size and diluting the alloying elements. Park *et al*. [107] also significantly improved the cross-tension strength of the dissimilar medium-Mn steel/DP steel weldment by the transition of brittle-to-ductile fracture in martensite through a special heat treatment. However, few studies focused on the medium-Mn steel weldment. Di *et al*. [108] found that the ductility of the weld joint in the gas metal arc welding of Fe–6.5Mn–0.98C steel could be improved by refining dendritic grains via adding pulse current. They also pointed out that the microhardness and tensile strength of the simulated heat-affected zone (HAZ) in Fe–8.1Mn–0.98C steel could be improved by the precipitation of VC nanoparticles [109]. Nevertheless, an efficient welding technology for achieving the adequate mechanical properties in the weld and HAZ of medium-Mn steels is still under development and requires further study before its successful commercialization.

5. Summary and outlook

This paper reviewed the hot forming process in automotive, hot-formed steel grades, and medium-Mn steel grades and their application in hot forming. Future researches on the hot forming of medium-Mn steels are suggested. These can be summarized as follows.

(1) Hot forming fully utilizes the different microstructures and mechanical properties of Mn–B alloyed steels at low and high temperatures and is an ideal process of producing springback-free ultra-high-strength steel parts.

(2) The strength and ductility of medium-Mn steels after hot forming can be higher than those of 22MnB5, the typical steel grade for hot forming. This result is mainly attributed to the TRIP effect during deformation, resulting from the refined and mechanically stable RA grains in the martensitic matrix.

(3) The application of medium-Mn steels in hot forming has many advantages over 22MnB5. First, both oxidation on surface and energy consumption are reduced. Second, improved mechanical properties can contribute to the enhanced collision safety and lightweight. Third, medium-Mn steels have much reduced demand for water-cooled forming die, offering much more flexibility during the cooling process.

(4) The cold bendability, weldability, blank coating, and resistance to oxidation and hydrogen embrittlement of hot-formed medium-Mn steels have to be evaluated systematically before they can be used in the automotive industry.

In particular, the standard methods of evaluating the cold bendability, the resistance to hydrogen embrittlement, and weldability for hot-formed medium-Mn steels are still urgently in demand for their commercialization.

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