Effects of the austenitizing temperature on the microstructure and mechanical properties in multiple-phase medium Mn steel

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Abstract
Medium Mn steel (MMnS) is the good choice for car manufacturers to meet the requirements of reducing the weight of automobiles. Quenching & Partitioning (Q&P) process is an effective method to stabilize austenite in advanced steel, thus prompting the comprehensive mechanical properties of advanced steel. In this article, the Q&P process is applied to the MMnS to explore potential mechanical properties. The effect of austenitizing temperature, one of the significant parameters of Q&P process, on the microstructure and mechanical properties of MMnS was investigated. According to microstructural analyse results, all of the MMnS specimens processed by Q&P treatment with different austenitizing temperatures could obtain multi-phase microstructure, including α′-martensite, ε-martensite and austenite. Furthermore, the highest volume fraction of austenite was observed in the MMnS processed by Q&P treatment at the austenitizing temperature of 920 °C. Due to the facilitated transformation-induced plasticity effect resulted from the high volume fraction of austenite with the austenitizing temperature of 920 °C, the MMnS obtained the high strength, high plasticity and sustaining work-hardening rate.

1. Introduction

Under the background of green and high-quality development of vehicle industry, automobile enterprises are facing the pressure of environmental protection. Lightweight is one of the typical ways to reduce the exhaust emission, therefore, it is usually used as the guideline of automobile design [1–3]. Advanced high strength steels (AHSSs) could obtain high strength and excellent plasticity, so it can be used to meet the lightweight requirement of automobiles. Up to now, three generations of AHSSs were developed, and medium Mn steel (MMnS), one of the 3rd generation of AHSSs, received wide focus because of excellent mechanical properties [4, 5].

The MMnS obtains excellent mechanical properties because of a certain amount of metastable austenite in its microstructure. The microstructure of MMnS is tailored by the intercritical annealing process, also referred as austenite reversion treatment (ART) during the intercritical region. During the intercritical annealing process of MMnS, austenite formed from the martensite phase and it can be stabilized to room temperature owing to the diffusion of carbon and manganese elements [6–8]. With the different intercritical annealing temperatures and durations, the MMnS will obtain the different austenite volume fractions and stabilities. Therefore, ART parameter has a vital influence on the microstructure of MMnS. Due to the effect of intercritical annealing process on the microstructure of MMnS, lots of efforts have been made to pursue the optimal ART parameters [6, 8].
Except for the ART treatment, the quenching & partitioning (Q&P) process is another significant method to acquire the austenite in the microstructure. Since originally proposed by Speer [9, 10], Q&P process has been used to stabilize the austenite in lots of advanced steels, including the low carbon steel [11, 12], high-aluminum steel [13], low silicon boron steel [14] and medium Mn steel (MMnS) [15, 16]. The wide application of Q&P process prompts the development of advanced materials with excellent mechanical properties. However, for MMnS, the research on effects of Q&P parameters on the microstructure and mechanical properties mainly focuses on the steel with Mn content of 3~7 wt%. It is difficult to find the investigation of 7~9 wt% Mn steel processed with different Q&P parameters, especially with different austenitizing temperatures. While, indeed, the 7~9 wt% Mn steel is promising materials for the automobile body due to multi-phase microstructure including $\alpha''$-martensite, $\varepsilon$-martensite and austenite [17, 18]. Therefore, it is crucial to understand the relationship between austenitizing temperatures and mechanical properties of 7~9 wt% Mn steel.

This work aims to research the effect of austenitizing temperature on the microstructure and mechanical properties in multi-phase 9Mn steel. The relationship between the mechanical properties and microstructure of MMnS was analyzed using scanning electron microscopy (SEM), electron back-scattered diffraction (EBSD), transmission electron microscopy (TEM) and tensile test analyses. Besides, a schematic was summarized to interpret the mechanical properties and microstructure of investigated steel with different austenitizing temperatures based on the experimental results.

2. Experimental procedure

The chemical composition of the medium Mn steel investigated in this study is Fe-0.20C-9.10Mn-1.60Si (wt%). The investigated steel was melted using a vacuum induction melting furnace under Ar atmosphere, followed by forging processing. The dimensions of forged ingots are 70 mm $\times$ 80 mm $\times$ 35 mm. After forging processing, the ingots were subjected to hot rolling via 5 passes. The start temperature and the end temperature of the hot rolling temperature are 1000 $^\circ$C and 900 $^\circ$C, respectively. The final thickness of hot-rolled steel is 3 mm. The hot-rolled steel was cold rolled to 1.2 mm thickness via 8 passes at ambient temperature. After cold rolling, the steel was subjected to three heat treatments processes to investigate the effect of austenitizing temperatures. The three heat treatments are with an austenitizing temperature of 890, 920 or 950 $^\circ$C for 300 s, followed by cooling to 60 $^\circ$C for 10 s at the rate of 50 $^\circ$C s$^{-1}$. Subsequently, the samples were reheated to the partitioning temperature of 450 $^\circ$C, followed by duration of 300 s, and then directly quenched at the rate of 50 $^\circ$C s$^{-1}$ to room temperature. The heat treatment processes of the investigated steel are also provided in figure 1 and the specimens treated with different heat treatments are labelled as QP890, QP920 and QP950, respectively.

Uniaxial tensile tests were carried on using a SANS test machine with a dog-bone specimens size of 25 mm (gauge length) $\times$ 6 mm (gauge width) $\times$ 1.2 mm (thickness). The loading velocity of tensile tests is 1 mm min$^{-1}$ and the gauge length of specimens is along the rolling direction. Microstructures for QP890, QP920 and QP950 specimens was observed by SEM, EBSD and TEM. The preparation process of specimens for SEM, EBSD and TEM can be found in our previous research [19, 20].
3. Results and discussion

3.1. Mechanical properties of the medium Mn steel
The engineering stress-strain curves and work-hardening rate curves of the MnS are provided in figure 2. It can be seen from figure 2(a) that all the specimens exhibit high strength, especially the QP920 specimen and the QP950 specimen whose ultra tensile strength are around 1.6 GPa. Furthermore, the QP920 sample show better total elongation than the QP950 sample and the QP890 sample, which means intermediate austenitizing temperature resulting in the high strength and plasticity during the Q&P process. From the work-hardening rate against true strain curve (figure 2(b)), all the specimens could obtain a high work-hardening rate after Q&P process. It is noted that the QP920 specimen display sustaining work-hardening rate that delays the fracture process, thus causing the high total elongation.

3.2. Dilatation-temperature curves during the Q&P process
Figure 3 shows the dilatation as a function of temperature during the Q&P process. It is found that the Ms temperature increases with the increasing austenitizing temperature, indicating that the increase in prior austenite grain size leads to an increase in Ms temperature due to the high austenitizing temperature [21–24]. It is also found that all samples have a significant length decrease during the partitioning process, suggested by the high magnification figure. According to Speer et al [9], the diffusion of C and Mn atoms from martensite to austenite occurred during the partitioning process. Following Speer, the diffusion has been extensively studied to increase the stability of austenite [25–27]. Moreover, the diffusion of C and Mn atoms to austenite could cause
the slight increase of austenite volume fraction, resulting in the volume shrinkage of specimens. Therefore, the length decrease is probably due to the diffusion of C and Mn atoms during the partitioning process.

3.3. Microstructure analyses of the MMnS
SEM micrographs and phase maps combined by image quality map of specimens processed with Q&P treatment at different austenitizing temperatures are displayed in figure 4. The microstructure of the MMnS after Q&P treatment is composed by different proportions of austenite and martensite. An interesting phenomenon is that ε-martensite is also observed except for α'-martensite in the QP890, QP920 and QP950 samples. The occurrence of ε-martensite has been confirmed by the phase maps combined by image quality map (figures 4(d)–(f)). The orientation relationship of ε-martensite and austenite in the white rectangle area of the figure 4(e) is shown in figure 5. The coincidence between the \{111\} pole of bcc structure and the \{0002\} pole of hcp structure is illustrated by red arrows in figures 5(a) and (b), which highlights the nearly \{111\}γ//\{0002\}ε orientation relationship. Moreover, the coincidence suggested by red allows in figures 5(c) and (d) highlights the nearly \{-110\}γ//\{11-20\}ε orientation relationship. These orientation relationships have been reported in previous research [28, 29], and the orientation relationships indicate that the ε martensite is transformed from austenite due to the low cooling rate or strain-induced [30, 31]. It is noticed that the ε martensite is observed in high manganese steel or stainless steel [28–31]. However, the microstructure of QP steel usually consists of austenite and α'-martensite [10, 20, 32–35], and some of them may include ferrite after intercritical annealing & quenching partitioning (IA&QP) process [19, 36]. In this paper, the Mn content of the investigated steel is relatively higher than that in previous literature [32–36]. Moreover, in the recent research [27], the ε martensite is also measured by x-ray diffraction in 10 Mn steel that is close to the investigated steel in this research. Therefore, the occurrence of ε-martensite, in this paper, is probably due to the relatively high Mn content.

![Figure 4. Microstructures and phase maps combined by image quality map of the medium Mn steel.](image)

![Figure 5. EBSD pole figure of austenite and ε martensite orientations of the white rectangle area in the figure 4(e).](image)
Figure 6 provides the volume fraction of α′-martensite, ε-martensite and austenite in the medium Mn steel with different Q&P processes. It is found that the volume fraction of ε-martensite is relatively low in all specimens processed by the different austenitizing temperatures treatments, and it decreased slightly with the increasing austenitizing temperature. Different from the ε-martensite phase, the austenite and ε-martensite deeply affected by the austenitizing temperature. The volume fraction of austenite is highest in the QP920 specimen, while the volume fraction of α′-martensite is highest in the QP950 specimen. According to Zhang et al. [37] and Wang et al. [38], the austenite phase has three effects on ductility during the deformation process, (i) transformation-induced plasticity (TRIP) effect, (ii) blocking microcrack propagation (BMP) effect, and (iii) dislocation absorption by the austenite (DARA) effect. Due to the TRIP and BMP effects of considerable quantity austenite, the local stress concentration was relaxed and the microcrack propagation was blocked. In this paper, the QP920 specimen obtained the highest volume fraction of austenite, possessing the most TRIP and BMP effect, therefore causing best ductility in the QP890, QP920 and QP950 specimens. Different from the TRIP and BMP effect, the DARA effect could decrease the average dislocation density of α′-martensite [37], which causes the increasing deformation ability of the α′-martensite phase. Thus, the increasing deformation of α′-martensite is probably another factor that enhances the ductility of QP920 specimen.

Figure 7 displays the microstructure of QP890, QP920 and QP950 specimens observed by TEM. The lamellar α′-martensite and ε-martensite can be observed in figure 7(a), while the ε-martensite is not clearly observed in figures 7(b) and (c). The aforementioned phenomenon is in agreement with the result in figure 6. In figure 6, the volume fraction of ε-martensite decreased with the austenitizing temperature increased. Especially in the austenitizing temperature of 950 °C, the ε-martensite volume fraction is 0.89%, thus the ε-martensite being hard to observe. It is also found that the average lath width of α′-martensite increases with austenitizing temperature increases, which is due to the increase in prior austenite grain size at high austenitizing temperature.
Detailed microstructure of QP920 specimen at the strain of 0.05 is provided in figure 8. Austenite can still be found in figure 8(a), which is confirmed by the dark field image and selected area diffraction patterns (SADP) in figures 8(b) and (c). Moreover, it can be found that the stacking faults (SF) occur in the QP920 specimen during deformation process, which is also confirmed by the SADP. According to Venables [39], Whelan [40] and our previous research [19], SF could be enhanced by applying mechanical load. With further increasing strain, there was even greater stacking fault. Moreover, the stacking fault occurred during deformation process could facilitate the martensitic transformation. Thus, the QP920 specimen could obtain excellent mechanical properties due to the facilitated transformation-induced plasticity (TRIP) effect.

From the results above, the microstructure evolution of medium Mn steel with different Q&P processes (schematically illustrated in figure 9) could be interpreted and summarized as follows. High austenitizing temperature (950 °C) leads to a large prior austenite grain size that results in the high Ms temperature (confirmed by dilatation-temperature curves in figure 2) and the wide width of martensite lath (illustrated by figure 7). According to Koistinen-Marburger equation (equation (1)) [41, 42], the volume fraction of the primary martensite increases with increasing Ms temperature. Thus, the volume fraction of austenite is low when the specimen is quenched and partitioned at high austenitizing temperature.

\[
V_{\alpha'}_{primary} = 1 - \exp \left[ -0.011 \times (M_s - T) \right]
\]

Where \( V_{\alpha'}_{primary} \) is the volume fraction of primary martensite, \( T \) is the quenching temperature, °C.

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Figure 8. Microstructure of QP920 specimen at the strain of 0.05. (a) Bright field image (b) Dark field image (c) Selected area diffraction patterns (SADP) illustrated the austenite phase in figure 8(a).

Figure 9. Schematic showing the microstructure evolution of MMnS with different Q&P processes.
Furthermore, with the austenitizing temperature decreases (920 °C), the prior austenite grain size is small. The small prior austenite grain size leads to the low \( M_t \) temperature and the narrow martensite lath width, which results in the high volume fraction of austenite. Due to the facilitated TRIP effect occurring in the austenite phase, the specimen could obtain excellent mechanical properties. With further decrease of austenitizing temperature (890 °C), the prior austenite grain size and the \( M_t \) temperature are much smaller, which in principle should result in the increasing volume fraction of austenite. However, during the partitioning process, the partitioned C and Mn atoms from matrix to austenite are limited [43, 44]. Therefore, some austenite could not obtain sufficient C and Mn elements owing to the increasing total volume fraction of austenite. Moreover, the C/Mn-poor austenite will transform to secondary martensite in the final quenching stage [9, 10]. Therefore, the volume fraction of austenite is also low when the specimen is quenched and partitioned at much lower austenitizing temperature. It is noted that the secondary martensite is more brittle than primary martensite [33, 45]. Therefore, the QP890 specimen obtains lower elongation than that of QP950 specimen.

4. Conclusion

In this paper, the quenching and partitioning (Q&P) process is used to MMnS to obtain multiple phase microstructure with excellent mechanical properties. The conclusions can be summarized as following:

(1) The MMnS could obtain high strength, high plasticity and sustaining work-hardening rate at a moderate austenitizing temperature. With high austenitizing temperature (950 °C), the plasticity of MMnS decreased, while, with low austenitizing temperature (890 °C), the MMnS obtained low strength and low plasticity together.

(2) All of the microstructures of MMnS processed by Q&P treatment with different austenitizing temperatures are composed of \( \alpha' \)-martensite, \( \varepsilon \)-martensite and austenite. The highest volume fraction of austenite was acquired in the MMnS processed by Q&P treatment with the austenitizing temperature of 920 °C. Furthermore, it is found that the average lath width of \( \alpha' \)-martensite increases with increasing austenitizing temperature.

(3) Due to the facilitated transformation-induced plasticity effect resulted from the high volume fraction of austenite, the MMnS obtained the high strength, high plasticity and sustaining work-hardening rate with the austenitizing temperature of 920 °C.

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References

[1] Chu Y, Sun L and Li L 2019 Lightweight scheme selection for automotive safety structures using a quantifiable multi-objective approach J. Clean. Prod. 118316 (https://doi.org/10.1016/j.jclepro.2019.118316)
[2] Kayode O and Akinlabi E T 2019 An overview on joining of aluminium and magnesium alloys using friction stir welding (FSW) for automotive lightweight applications Mater. Res. Express (https://doi.org/10.1088/2053-1591/ab3262)
[3] Zhang Y et al 2006 Lightweight design of automobile component using high strength steel based on dent resistance Mater. Des. 27 64–8
[4] Hu B et al 2019 Super-high-strength and formable medium Mn steel manufactured by warm rolling process Acta Mater. 174 131–41
[5] Benzing J T et al 2019 Multi-scale characterization of austenite reversion and martensite recovery in a cold-rolled medium-Mn steel Acta Mater. 166 512–30
[6] Lee S and De Cooman B C 2013 On the selection of the optimal intercritical annealing temperature for medium Mn TRIP steel Metallurgical and Materials Transactions A 44 5018–24
[7] Sun B et al 2017 Critical role of strain partitioning and deformation twinning on cracking phenomenon occurring during cold rolling of two duplex medium manganese steels Scr. Mater. 130 49–53
[8] Lee S, Lee S J and De Cooman B C 2011 Austenite stability of ultrafine-grained transformation-induced plasticity steel with Mn partitioning Scr. Mater. 65 225–8
[9] Speer J et al 2003 Carbon partitioning into austenite after martensite transformation Acta Mater. 51 2611–22
[10] Speer J G et al 2005 The ‘quenching and partitioning’ process: background and recent progress Mater. Res. 8 417–23
[11] Peng F et al 2019 Interaction of martensite and bainite transformations and its dependence on quenching temperature in intercritically quenching and partitioning steels Mater. Des. 107921 (https://doi.org/10.1016/j.matdes.2019.107921)
[12] Huỳnh P et al 2019 Into the quenching & partitioning of a 0.2 C steel: An in situ synchrotron study Materials Science and Engineering: A 743 175–84
[13] Nyßsson T et al 2019 Crystallography and mechanical properties of intercritically annealed quenched and partitioned high-aluminum steel Mater. Charact. 148 71–80
[14] Kong H et al 2017 One-step quenching and partitioning treatment of a commercial low silicon boron steel Materials Science and Engineering: A 707 538–47
[15] Hidalgo J, Gelada-Casero C and Santofimia M J 2019 Fracture mechanisms and microstructure in a medium Mn quenching and partitioning steel exhibiting macrosegregation Materials Science and Engineering: A 754 766–77
[16] Kim J H et al 2018 Effect of quenching temperature on stretch flangability of a medium Mn steel processed by quenching and partitioning Materials Science and Engineering: A 729 276–84
[17] Ding R et al 2018 Effect of pre-existing austenite on austenite reversion and mechanical behavior of a Fe–0.2 C–8Mn–2Al medium Mn steel Acta Mater. 147 59–69
[18] Han J et al 2014 The effects of the initial martensite microstructure on the microstructure and tensile properties of intercritically annealed Fe–9Mn–0.05 C steel Acta Mater. 78 369–77
[19] Yang Y G et al 2018 Impact of intercritical annealing temperature and strain state on mechanical stability of retained austenite in medium Mn steel Materials Science and Engineering: A 725 389–97
[20] Yang Y G et al 2018 Bending deformation and fracture characterization in quenching and partitioning steel Mater. Sci. Technol. 1–9
[21] García-Junceda A et al 2008 Dependence of martensite start temperature on fine austenite grain size Scr. Mater. 58 134–7
[22] Zhu K et al 2013 The effect of prior ferrite formation on bainite and martensite transformation kinetics in advanced high-strength steels Acta Mater. 61 6023–36
[23] Unemoto M and Owen W S 1974 Effects of austenitising temperature and austenite grain size on the formation of athermal martensite in an iron-nickel and an iron-nickel-carbon alloy Metall. Trans. 5 2041–6
[24] Guimariès R C and Ríos P R 2010 Martensite start temperature and the austenite grain-size J. Mater. Sci. 45 1074
[25] Xie Z J et al 2017 Atom probe tomography and numerical study of austenite stabilization in a low carbon low alloy steel processed by two-step intercritical heat treatment Scr. Mater. 137 36–40
[26] Lee D et al 2017 Microstructures and mechanical properties of Ti and Mo micro-alloyed medium Mn steel Materials Science and Engineering: A 706 1–14
[27] Lee H et al 2018 Novel medium-Mn (austenite + martensite) duplex hot-rolled steel achieving 1.6 GPa strength with 20% ductility by Mn-segregation-induced TRIP mechanism Acta Mater. 147 247–60
[28] Yang X S et al 2017 Shear and shuffling accomplishing polymorphic fcc→hcp ε→bcc ω martensitic phase transformation Acta Mater. 136 347–54
[29] Olson G B and Cohen M 1976 A general mechanism of martensitic nucleation: II. FCC→BCC and other martensitic transformations Metall. Trans. A 7 1903–14 A general mechanism of martensitic nucleation: II. FCC→BCC and other martensitic transformations
[30] Yang P et al 2006 Dependence of deformation twinning on grain orientation in a high manganese steel Scr. Mater. 55 629–31
[31] Yang X S, Sun S and Zhang T Y 2013 The mechanism of bcc ω’ nucleation in single hcp ε laths in the fcc γ→hcp ε→bcc ω martensitic phase transformation Acta Mater. 95 264–73
[32] Edmonds D V et al 2006 Quenching and partitioning martensite—a novel steel heat treatment Materials Science and Engineering: A 438 25–34
[33] De Knijff D et al 2014 Effect of fresh martensite on the stability of retained austenite in quenching and partitioning steel Materials Science and Engineering: A 615 107–15
[34] Speer J G et al 2011 Analysis of microstructure evolution in quenching and partitioning automotive sheet steel Metallurgical and Materials Transactions A 42 3591
[35] Xiong X C et al 2013 The effect of morphology on the stability of retained austenite in a quenched and partitioned steel Scr. Mater. 68 321–4
[36] Zhang J, Ding H and Misra R D K 2015 Enhanced strain hardening and microstructural characterization in a low carbon quenching and partitioning steel with partial austenitization Materials Science and Engineering: A 636 53–9
[37] Zhang K et al 2011 A new effect of retained austenite on ductility enhancement in high-strength quenching–partitioning–tempering martensitic steel Materials Science and Engineering: A 528 8486–91
[38] Wang Y et al 2012 A new effect of retained austenite on ductility enhancement in high strength bainitic steel Materials Science and Engineering: A 552 288–94
[39] Venables A J 1962 The martensite transformation in stainless steel The Philosophical Magazine: A 7 35–44
[40] Whelan M J, Hirschard P B and Horne R W 1957 Dislocations and stacking faults in stainless steel Proceedings of the royal society A 5 524–38
[41] Koistinen D P 1959 A general equation prescribing the extent of the austenite-martensite transformation in pure iron-carbon alloys and plain carbon steels Acta Mater. 7 59–60
[42] Li L, Mi Z L, Wang Zhen, Yang Y G and Yu Z C 2018 Modified quenching temperature selection method for partial austenitization quenching and partitioning steel Mater. Res. Express 5 066555
[43] Luo H 2012 Comments on ‘austenite stability of ultrafine-grained transformationinduced plasticity steel with Mn partitioning’ by S. Lee, S J, Lee and B C. de Cooman, Scripta Materialia 65, 225–228 Scr. Mater. 66 829–31 2011
[44] Wu R M, Li W, Wang C L, Xiao Y, Wang L and Jin X J 2015 Stability of retained austenite through a combined intercritical annealing and quenching and partitioning (IAQP) treatment Acta Metall. Sin. (Engl. Lett.) 28 386–93
[45] Seo E J et al 2016 Microstructure–mechanical properties relationships for quenching and partitioning (Q&P) processed steel Acta Mater 113 124–39