Recrystallisation before austenitization for improved microstructure and properties in automotive steel sheets with high product of strength and elongation

Fei Huang, Heng Zhang, Jialin Qi, Qiwei Chen and Hanlin Ding

1 School of Materials Science and Engineering, Anhui University of Technology, Maanshan 243002, People’s Republic of China
2 School of Iron and Steel, Soochow University, Suzhou 215006, People’s Republic of China
* Authors to whom any correspondence should be addressed.

E-mail: agdcqw@163.com and dinghanlin@suda.cn

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Abstract
This study investigated the effect of recrystallization before austenitizing transformation (i.e., pre-recrystallization) on the microstructure and properties of 22Mn2Cr cold-rolled automotive steel sheets based on continuous annealing at 700 °C for various holding times. Subsequently, the samples were heated to an austenitizing temperature of ~850 °C, which led to the formation of a fine austenite grains via nucleation at the dislocations during reheating. The austenite grain size was more refined when samples were pre-recrystallized at 700 °C for several minutes compared to those directly heated to 850 °C, which was attributed to combined grain refinement from recrystallization and austenite phase transformation. This refined austenite grain size led to a finer bainite grain size in the cooled final product. The strength of the steel decreased slightly (~1200 MPa), but the elongation (~19%) and product of strength and elongation (~23 GPa%) were significantly enhanced by the pre-recrystallization treatment.

1. Introduction

Automotive steels that offer both ultra-high strength and good plasticity allow for the production of light-weight vehicles with a lower fuel consumption and high safety level [1–5]. Further, the application of these steels in new electric vehicles could help increase their mileage [6, 7]. Safety is a vital consideration in the development and application of light-weight materials in vehicles, especially when used in the car cockpit. Specifically, ultra-high strength is required to withstand the application of a force and good elongation allows for the absorption of energy during impact to maximize passenger safety. Therefore, the product of strength and elongation is the key parameter when evaluating the mechanical properties of automotive steels. The third generation of automotive steels was proposed in October 2007 by the American Automotive Steel Alliance, which based on first generation of advanced high-strength steels (AHSS) and the second generation of twinning induced plasticity (TWIP) steels [8]. These third-generation automotive steels must have a product of strength and elongation of ~30 GPa% and a strength of >1000 MPa, and have been extensively researched and developed [9–14].

Quenching and partition (QP) steels and medium-Mn steels are representative automotive steels with a high product strength and elongation. The basic principle of QP steels is that carbon partitioning occurs during annealing of cold-rolled sheets, which increases the carbon content of austenite. This leads to improved austenite stability and a higher content of residual austenite for enhanced ductility [15]. However, on-line quenching and distribution is often limited by the practical conditions of the line and process control difficulties, while the practical implementation of off-line distribution is even more difficult. QP steels have a low alloy content due to their low-cost alloy design, thus the increase in residual austenite content is currently limited to ~10%. Unfortunately, further increases in the product of strength and elongation have not yet been achieved [16]. At present, the industrial production and application of QP steels is mainly focused on QP 980, which...
offers a strength of \( \sim 1000 \text{ MPa} \), elongation of \( \sim 20\% \), and product of strength and elongation of \( \sim 20 \text{ GPa}\% \). In addition, QP 1180 offers a higher strength of \( \sim 1200 \text{ MPa} \), lower elongation of \( \sim 13\% \), and lower product of strength and elongation of \( \sim 16 \text{ GPa}\% \) \cite{17}. Medium-Mn steels offer an enhanced austenite stability mainly due to higher Mn content. Further, the residual austenite is increased via austenitizing reversed transformation (ART), thereby improving the strength and ductility \cite{18,19}. An increased residual austenite content relies on increasing the Mn content of the steel. However, a higher Mn content can lead to various issues, specifically regarding continuous casting, rolling, and application, which has limited large-scale industrial application \cite{20}. Good mechanical properties have been previously reported in laboratory-scale studies, but the addition of a large number of alloying elements resulted in a higher cost, and production and application difficulties \cite{21–23}. The research and development of third-generation automobile steels have demonstrated that the mechanism for enhanced strengthening and ductility is dependent on residual austenite. As the content thereof is closely related to the content of alloying elements, alloying contents should be increased. Therefore, there must be a pay-off between achieving a high product of strength and elongation and the cost and ease of production of automobile steels.

Strength and plasticity can be investigated using multidimensional methods \cite{19}, where a novel 20Mn2Cr automobile steel was recently developed based on a Cr–Mn alloy. This low-alloy design was developed based on existing industrial production equipment technology, and resulted in a novel ultra-high strength and high product of strength and elongation automotive steel. The mechanical properties of this steel were adjusted and optimized by controlling the grain refinement, microstructural composition, and second-phase particle regulation. Another study \cite{24} reported that continuous annealing of cold-rolled sheets of this novel Cr–Mn low-alloy steel at 850 °C for 3 min followed by air cooling to 300 °C for aging led to better mechanical properties. A cold-worked deformation microstructure was observed in the cold-rolled sheet before continuous annealing, thus interactions between recrystallization and phase transformation during continuous annealing was expected. The grain size could be refined as recrystallization processing and subsequently refinement of martensite structure and even precipitation of carbide \cite{25}. The structural refinement would bring significant influence on the mechanical properties such as work-hardening behaviors, texture \cite{26–28}, TRIP effect \cite{29}, the formation of austenite during heating, and the microstructure and properties during subsequent cooling, and so on. Thus, it is important to explore the effect of prior recrystallization on behaviors of phase transformation and mechanical properties.

This study aimed to investigate the effect of pre-recrystallization below the phase transition temperature on the microstructure and properties of the previously reported Cr–Mn low-alloy automotive steel to provide a scientific basis for further improvements in its strength and elongation.

### 2. Materials and methods

C–Mn–Cr low-alloy steel was used, where its main chemical composition is listed in Table 1. The steel was produced in a vacuum induction furnace, forged into billets \((250 \times 150 \times 40 \text{ mm})\) at 1200 °C, and hot-rolled into steel plates \((\text{thickness} = 4.4 \text{ mm})\). The plates were held at 650 °C for 1 h after hot-rolling, and cooled to room temperature. The plates were pickled in HCl solution and cold-rolled with 10 passes to a thickness of 2 mm. The cold-rolled sheets were used as the experimental steel. The cold-rolled sheets were cutting into \(20 \times 15 \times 2 \text{ mm}\) block specimens and a number of tensile specimens by wire-cutting as shown in figure 1. The microstructural observation direction was parallel to the rolling direction of the cold-rolled sheets. The tensile specimens was flat and its direction was parallel to the rolling direction of the cold-rolled sheets, as shown in figure 1.

![Figure 1](image.png)

The start temperature of pre-recrystallization during continuous heating was determined by heating the experimental steel with 2 °C s\(^{-1}\) to either 600, 650, 700, or 800 °C for 3 min with subsequent water-quenching for microstructural observation. Recrystallized grains were observed in the samples heated at 700 °C and above. Therefore, a pre-crystallization temperature of 700 °C was chosen, where the experimental steel was held for either 3 or 6 min to investigate the effect of pre-recrystallization time on the final microstructure and mechanical properties. After pre-recrystallization, the experimental steel samples were reheated to 850 °C for 3 min for austenite formation, and air-cooled naturally (AC) to 300 °C for 10 min (figure 2). Samples directly heated to 850 °C for 3 min and air-cooled naturally to 300 °C for 10 min were also prepared for comparison.

### Table 1. Chemical composition of the C–Mn–Cr low-alloy steel (wt%).

| Specimen | C   | Cr  | Nb  | Mn  | Si  | Ti  | S   | P   | Fe  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 20Mn2Cr  | 0.21| 1.30| 0.009| 1.69| 0.04| 0.002| 0.005| 0.007| balance |
The microstructure was observed using an optical microscope (Axio Observer A1m, Zeiss) and a scanning electron microscope (SEM; JSM-6610, JEOL). The samples were abraded using silicon carbide sandpaper to 2000#, and subsequently polished using diamond paste (1.5 μm). Etching was performed in 4 vol% perchloric acid in ethanol for general microstructural observation, or in ET06 etching reagent for austenitic grain size observation. The microstructure was further evaluated using transmission electron microscopy (Tecnai G2 F30, FEI) at an accelerating voltage of 40 kV. The TEM samples were prepared using a twin-jet machine with a mixture of 8 vol % perchloric acid and 92 vol % acetic acid at 20 °C at a voltage of 30 V. The mechanical properties of the samples were evaluated based on tensile testing using a universal testing machine (Z050, Zwick) at a strain rate of 10 MPa/s according to the Chinese standard (GB/T 228.1–1010 Method B).

3. Result and Discussion

3.1. Recrystallization behavior during continuous annealing
The microstructure of the water-quenched experimental steel samples after heating at different temperatures for 3 min is visualized in figure 3. The original microstructure of cold-rolled sheet is ferrite (F) and pearlite (P) elongated along the rolling direction and appears fibrous. Heating of the alloy to 600 °C and 650 °C did not lead to the formation of equiaxed recrystallized grains, thus recrystallization did not occur (figures 3(b) and (c)). However, heating to 700 °C led to the appearance of fine equiaxed grains within the microstructure of the experimental steel due to partial recrystallization (figure 3(d)). Further, the microstructure after heating to 750 °C exhibited martensite and ferrite with a band-like distribution, which was indicative of interaction between phase transformation and recrystallization (figure 3(e)). Overall, these observations demonstrated that the recrystallization temperature was above 650 °C.

The microstructure of the water-quenched sample after heating at 700 °C for 3 min exhibited an elongated grain morphology with obvious recrystallized grains. However, martensite transformation was not observed. Thus, heating to 700 °C allowed for partial recrystallization while preventing austenitization. The temperature of the transformation from pearlite to austenite ($A_C$) in 20Mn2Cr steel is 727 °C according to the continuous...
cooling transformation (CCT) curve (figure 4). This confirms that austenitization does not occur during heating to 700 °C. Further, the sample entered the partially austenitized transformation phase zone during heating to 750 °C, thereby forming martensite and ferrite in the water-quenched sample.

The microstructures of the water-quenched samples after heating at 700 °C for 3 and 6 min are visualized in figure 5. The sample heated for 3 min did not undergo complete recrystallization, while the sample heated for 6 min was almost fully recrystallized with some grain growth. Recrystallization is a diffusion process of thermal activation, and is a function of temperature and time. Thus, a longer holding time led to an increased recrystallization volume fraction and grain size.

3.2. Effect of pre-recrystallisation on the microstructure

The original austenite morphology and grain size distribution of the pre-recrystallized and directly heated experimental steel was shown in figure 6. The austenite grain size was significantly smaller in the pre-recrystallized sample compared to the directly heated sample. Despite this large difference in grain size, the original austenite grain size in both samples was relatively small (<10 μm). Specifically, the average grain sizes of austenite in the samples held at 700 °C for 3 and 6 min were ~3.9 and 4.6 μm, respectively, while that of the original austenite obtained after direct heating was 5.8 μm. This was attributed to the presence of a large
dislocation density in the cold-rolled deformed microstructure (∼50% cold-rolled deformation), which could promote nucleation for austenite transformation during the post-heating phase transformation to refine the austenite grains. Recrystallization refinement allowed for the recrystallization of ferrite before heating, which led
700°C for 3 min and cooling to 300°C for 10 min, (b) pre-recrystallization at 700°C for 3 min followed by heating at 850°C for 3 min and cooling to 300°C for 10 min, and (c) pre-crystallization at 700°C for 6 min followed by heating at 850°C for 3 min and cooling to 300°C for 10 min.

Figure 7. SEM images of the microstructure of experimental steels processed under different conditions, namely (a) direct heating to 850°C for 3 min and cooling to 300°C for 10 min, (b) pre-recrystallization at 700°C for 3 min followed by heating to 850°C for 3 min and cooling to 300°C for 10 min, and (c) pre-crystallization at 700°C for 6 min followed by heating at 850°C for 3 min and cooling to 300°C for 10 min.

Table 2. Tensile properties of experimental steels processed under different conditions.

| Processing conditions | $R_m$ (MPa) | $R_p0.2$ (MPa) | $A$ (%) | $A_p0.2$ (%) | $R_m \times A$ (GPa·%) | $n$-value |
|-----------------------|-------------|----------------|--------|--------------|-----------------------|----------|
| 850°C for 3 min; 300°C for 10 min. | 1227 | 963 | 15.5 | 6.6 | 19.0 | 0.14 |
| 700°C for 3 min; 850°C for 3 min; 300°C for 10 min. | 1195 | 943 | 19.0 | 7.6 | 22.7 | 0.17 |
| 700°C for 6 min; 850°C for 3 min; 300°C for 10 min. | 1202 | 941 | 18.0 | 7.3 | 21.6 | 0.15 |

to further refinement during the transformation of ferrite to austenite, resulting in finer austenite grains compared to the samples that were not pre-recrystallized. The smaller austenite grain size led to the formation of finer bainite after the phase transformation. The recrystallized grains grew as the holding time was extended from 3 min to 6 min (figures 6(b) and (c)). This was due to an increase of recrystallized grain size as recrystallization time increased, as well as a decrease in strain over time. This decrease in strain led to a reduction in locations for non-uniform nucleation of austenite phase transformation, thereby increasing the austenite grain size.

The SEM morphology of the experimental steel was observed after pre-recrystallization at 700°C for 3 min and 6 min followed by heating to 850°C for 3 min and air-cooling to 300°C for 10 min (figure 7). The resulting microstructures mainly comprised of ferrite (F), lath bainite (LB) and granular bainite (GB) depending on the process conditions, where much smaller bainite was formed in the pre-recrystallized sample. This suggested that refinement of the cold-rolled microstructure occurred via two refining processes during holding at 700°C, namely recrystallization refinement and phase transition refinement. The fine austenite grain size obtained after heating led to refinement of the final microstructure. Slightly coarser bainite was obtained after holding for 6 min compared to 3 min, indicating that coarsening of the austenite grains should be expected with the extension of holding time. This is consistent with the austenite grain size variation rules above.

3.3. Effect of pre-recrystallisation on the tensile properties

The tensile properties of pre-recrystallized and directly heated experimental steel are presented in table 2 and figure 8. Pre-recrystallization led to a slight reduction in tensile strength ($R_m$) compared to the directly heated sample, namely a 32 and 25 MPa decrease in the samples pre-recrystallized for 3 and 6 min, respectively. However, the elongation ($A$) was significantly enhanced, and increased by 3.5% and 2.5% respectively. Thus, the product of strength and elongation increased from 19.0 GPa% in the directly heated sample to 22.7 and 21.6 GPa% in the samples pre-recrystallized for 3 and 6 min, respectively. The strain hardening exponent ($n$-value) is 0.14, 0.17 and 0.15 respectively. The yield stress ($R_{p0.2}$) is 963, 943 and 941 MPa respectively. The uniform elongation ($A_p$) is 6.6%, 7.6% and 7.3% respectively. Thus, the product of the strength and elongation ($R_m \times A$) was significantly improved by pre-recrystallization. Overall, these mechanical properties were significantly better than those of QP 1180 [17]. The analysis suggests that this is due to the fact that pre-recrystallisation refines the grain (section 3.2), because grain refinement can significantly enhance the plasticity of the material [26]. Holding at 700°C for 6 min instead of 3 min led to a 1% decrease in elongation might be due to the more equiaxed structure of the 6 min sample compared to a semi-bimodal structure of the 3 min sample. Also, it could be likely due to the coarser lath and granular bainite in the 6 min sample (figure 7).
The slight decrease in tensile strength and distinct increase in elongation after pre-crystallization was related to the final microstructure of the experimental steel. The microstructure was predominantly composed of bainite. Although refinement has an effect on the strength of steel, the bainite strengthening effect was more dependent on the content of solid solution carbon in the bainite ferrite and the width of the lath. Direct heating without pre-crystallization, the dislocation from deformed structure could be helpful to form austenite. The dislocations could served as high-speed diffusion channels to accelerate the decomposition of carbides, thereby increasing the carbon content of the austenite. Consequently, the supersaturated carbon content of the bainite formed during subsequent cooling was increased, which lowered the bainite transformation temperature and led to less bainite laths in the final microstructure. The TEM images of experimental steel processed under different conditions were shown in figure 9, It can be seen that all the bainite was composed of laths and high density dislocations. The directly heated sample exhibited the narrowest bainite lath width of \( \sim 180 \text{ nm} \) (figure 9(a)), while that of the experimental steel pre-recrystallized at 700 °C for 3 and 6 min was \( \sim 210 \) and 200 nm, respectively (figures 9(a) and (b)). The strength of the material increases as the bainitic lath width decreases [31]. So the phase transformation strengthening effect of the bainite itself was greater than the strengthening effect of the grain refinement. Therefore, the tensile strength of the experimental steel was not significantly affected by grain refinement. However, grain refinement has a significant effect on the strain coordination and strain relaxation, which led to a significant improvement in the ductility of the steel, thereby increasing the product of strength and elongation.

The SEM images of the experimental steel morphology at the tensile fractures revealed that a large number of dimples were formed in all of the process conditions under investigation (figure 10). This indicated that all of the fractures were ductile. The main mechanism is the initiation, growth, and coalescence of microcavities, which gives the fracture surface a characteristic appearance: it consists of small dimples, which represent the microcavities after coalescence [29]. The directly heated sample exhibited the largest dimples, while those of the samples pre-recrystallized at 700 °C were smaller. This corresponded to the density of dimples increases by decreasing grain size [29].

![Figure 8. Stress-strain curves of experimental steel processed under different conditions](image-url)
4. Conclusions

(1) The cold-rolled steel sheets were held at various temperatures for 3 min and water-quenched, which revealed that recrystallization occurred after heating to 700 °C. Further, the deformed grains of the cold-rolled plate could not undergo sufficient recrystallization during continuous annealing below the austenitizing temperature ($A_{C1} = 727$ °C). Therefore, the interaction between recrystallization and phase transformation occurred when the steel was directly heated to 850 °C.

(2) Pre-recrystallisation of the experimental steel at 700 °C led to a finer austenite grain size, which was attributed to both recrystallization refinement and phase refinement. Consequently, finer bainite was formed during cooling. The bainite were slightly coarser when a holding time of 6 min at 700 °C was used compared to 3 min, but the grains obtained by direct heating were substantially coarser.

(3) The tensile strength of the experimental steel was slightly reduced after pre-recrystallisation at 700 °C, while the elongation was significantly increased. Consequently, the product of strength and elongation exceeded 20 GPa%, namely 22.5% and 21.1% for holding times of 3 and 6 min, respectively. The tensile strength of the experimental steel held for 6 min was slightly higher, while the elongation was slightly lower (~1%).

(4) Overall, As the pre-recrystallisation at 700 °C, a finer austenite grain size was obtained through recrystallisation refinement and austenite phase transformation refinement, resulting in a finer bainite during the cooling process. And the fine bainite was conducive to the improvement of plasticity. Therefore, the product of strength and elongation of high-strength automotive plates was increasing. These experimental findings demonstrated the promise of the proposed technical route for regulating the mechanical properties of cold-rolled sheets fabricated using the novel Cr-Mn series automotive steel with ultra-high strength and high product of strength and elongation.

Figure 9. TEM images of the experimental steel processed under different conditions, namely (a) direct heating to 850 °C for 3 min and cooling to 300 °C for 10 min, (b) pre-recrystallization at 700 °C for 3 min followed by heating at 850 °C for 3 min and cooling to 300 °C for 10 min, and (c) pre-crystallization at 700 °C for 6 min followed by heating at 850 °C for 3 min and cooling to 300 °C for 10 min.

Figure 10. SEM images of the tensile fractures in the experimental steel processed under different conditions, namely (a) direct heating to 850 °C for 3 min and cooling to 300 °C for 10 min, (b) pre-recrystallization at 700 °C for 3 min followed by heating at 850 °C for 3 min and cooling to 300 °C for 10 min, and (c) pre-crystallization at 700 °C for 6 min followed by heating at 850 °C for 3 min and cooling to 300 °C for 10 min.
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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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ORCID iDs

Fei Huang https://orcid.org/0000-0002-0696-2724

References

[1] Wang M, Zhang X, Xiao Y, Xu L, Hou S and Li Y 2019 One of the key research progress of steels with high product of strength and elongation for automobiles: research progress of Q&P steel Transactions of Materials and Heat Treatment 40 11–9
[2] Zhang Y, Li Y, Chang Y and Wang T 2017 Properties of high product of strength and elongation hot-rolled medium manganese steels and their application in automotive light-weighting Automobile Technology & Material 7 49–53
[3] Han Z, Zhang M, Xu H, Dong H and Cao W 2016 Research and application of high performance automobile steel Iron & Steel 51 1–9
[4] Kang Y and Zhu G 2014 Development trend of china’s automobile industry and the opportunities and challenges of steels for automobiles Iron & Steel 12 1–7
[5] Kwon O, Lee K Y, Kim G S and Chin K G 2010 New trends in advanced high strength steel developments for automotive application Mater. Sci. Forum 884 336–41
[6] Xiong Z, Qi J, Liu H, Sun L and Liang A 2020 Research status and development trend of new energy car and its lightweight technologies Hebe Metallurgy 7 1–9
[7] Wei J and Song S 2019 The impact of complete vehicle light-weighting on new energy vehicles Auto Time 17 73–5
[8] Dong H, Cao W, Shi J, Wang C, Wang M and Weng Y 2011 Microstructure and performance control technology of the 3rd generation auto sheet steels Iron & Steel 46 1–11
[9] Wang C, Chang Y, Zhou F, Cao W, Dong H and Weng Y 2010 M3 microstructure control technology and theory of the third-generation automotive steels with high strength and high ductility Iron & Steel 71 1–7
[10] Zheng D, Liu Y, Wu and Yu H 2014 Study on stamping formability of third generation HSS Q&P980 for Vehicle car body application China Mech. Eng. 25 2010–3
[11] Liu Y, Pan H, Zhan H and Chi Z 2015 Introduction of several typical 3rd generation AHSS for automotive industry Heat Treat. Met. 40 13–9
[12] Liu T and Zhu Z 2019 Research status of medium manganese steel for the 3rd gernation automobile sheet Ordnance Material Science and Engineering 42 102–8
[13] Huang F, Chen J, Ge Z, Li J and Wang Y 2020 Effect of heat treatment on microstructure and mechanical properties of new cold-rolled automotive steels Metal 10 1414
[14] Fan Y, Wang M, Zhang H, Tao H, Zhao P and Li S 2013 Hot plasticity and fracture mechanism of the third generation of automotive steel Journal of University of Science and Technology Beijing 35 607–12
[15] An K, Liang J, Xing F and Tian Y 2019 Research status of the 3rd generation advanced high strength steels for automobiles-Q&P steels Heat Treat. Met. 44 1–7
[16] Speer J, Matlock D K, de Cooman B C and Schroth J G 2003 Carbon partitioning into austeniteafter martensite transformation Acta Mater. 51(2) 611–22
[17] Diao K, Jiang H, Wang L and Chen X 2012 Experimental Research on Formability of QP Steel China Automotive Lightweight Technology Forum Proceedings 222–7
[18] Liu Q, Zheng X, Zhang R, Tian Y and Chen L 2019 Medium Manganese High Strength Steel for Automotive Application: Status Quo and Prospects Materials Review 33 1213–20
[19] Shao C, Hui W, Zhang Y, Zhao X and Weng Y 2019 Microstructure and mechanical properties of a novel cold rolled medium-mn steel with superior strength and ductility Acta Metall. Sinica 55 191–201
[20] Zhu G, Ding H, Wang X, Wang Y and Chen Q 2018 Research and development of the third generation steels for automobile with ultra-high strength and product of strength and elongation based on strength and plasticity enhancement by multi-dimensions mechanisms Materials China 37 826–36
[21] He B, Hu B, Yen H, Cheng G, Wang Z, Luo H and Huang M 2017 High dislocation density-induced large ductility in deformed and partitioned steels Science 357 1029–32
[22] Shao C, Wang J, Zhao X and Hui W 2020 Microstructure and mechanical properties of intercritically annealed Al-contain medium Mn steel Iron & Steel 55 87–93
[23] Sohn S S, Song H, Jo M C, Song T, Kim H S and Lee S 2017 Novel 1.5 GPa-strength with 50%-ductility by transformation induced plasticity of nonrecrystallized austenite in duplex steels Sci. Rep. 7 12355
[24] Ding H, Zhu G, Xiang C, Pei F, Chen J, Wang Y and Chen Q 2020 Excellent combination of plasticity and ultra-high strength in a low-alloy automotive steel treated by conventional continuous annealing Mater. Sci. Eng A. 791 139694
[25] Akhtar M and Khajuria A 2020 Effects of prior austenite grain size on impression creep and microstructure in simulated heat affected zones of boron modified P91 steels Mater. Chem. Phys. 249 122847
[26] Eskandari M, Mohtadi-Bonab M A, Zarei-Hanzaki A, Szpunar J A and Basu R 2019 Texture and microstructure development of tensile deformed high-mn steel during early stage of recrystallization Phys. Met. Metall. 120 32–40
[27] Gubernatorov V V, Solovei V D, Gevraseva I V, Sycheva T S and Vychuzhanin D I 2012 Effect of tensile deformation rate on texture formation during subsequent rolling and recrystallization of electric steel Phys. Met. Metall. 113 1024–8
[28] Akhtar M, Khajuria A and Bedi R 2020 Effect of Re-normalizing and Re-tempering on Inter-critical heat affected zone(S) of P91B steel manufacturing engineering Lecture Notes on Multidisciplinary Industrial Engineering 255–70
[29] Naghizadeh M and Mirzadeh H 2019 Effects of grain size on mechanical properties and work-hardening behavior of AISI 304 austenitic stainless steel Steel Res. Int. 90 1900153
[30] Tang X, Wang X and Zhang Z 2018 Research on precipitation behavior and strengthening mechanism of low carbon bainitic high strength steel Hot Working Technology 47 92–6
[31] Garciamateo C and Caballero F G 2005 Ultra-high-strength bainitic steels ISIJ Int. 45 1736–40