PAPER

Effects of cooling method and elements segregation on the martensite-pearlite banded structure of high carbon bearing steel

Yun-long Wang, Wei Yu and Yin-li Chen
1 Institute of Engineering and Technology, University of Science and Technology Beijing, Beijing 10083, People’s Republic of China
2 Collaborative Innovation Center of Steel Technology, University of Science and Technology Beijing, Beijing 100083, People’s Republic of China
E-mail: yinli_chen@ustb.edu.cn

Keywords: high carbon bearing steel, banded structure, elements segregation, cooling

Abstract
In this study, the effects of the cooling method and alloying element segregation on the abnormal zonal structure of high-carbon bearing steel were investigated by reheating, controlled rolling, and controlled cooling of the sample. The microstructure and alloy segregation characteristics of the abnormal strip structure in the hot-rolled plate of the steel were revealed by optical microscopy, scanning electron microscopy, transmission electron microscopy, and electron probe x-ray microanalysis. The JMatPro thermodynamic software was used to examine the relationship between the alloy elements and banded structure defects of the hot-rolled sheet and analyse the causes of the defects and their elimination methods. The results show distinct positive segregation of Cr/Mn and negative segregation of C in martensite–pearlite banded structure defects in hot-rolled plates. The martensite–pearlite banded structure is formed by the interaction between the cooling rate and the segregation of alloying elements after hot rolling. Studies have found that segmented cooling (slow cooling–air cooling) can eliminate the martensite–pearlite banded structure.

1. Introduction
High-carbon bearing steel is widely used in the manufacture of various industrial products, such as bearing balls, rollers, and ferrules. The bearing parts are largely affected by alternating stress during use. Therefore, uniform mechanical properties are required. The microstructure uniformity of steel plays a crucial role in the mechanical properties. The existence of a banded structure in hot-rolled steel plate causes anisotropy, reduces plasticity [1, 2], and impacts the toughness of steel [3, 4]. It further affects the fatigue life and wear resistance, and considerably reduces the service life of bearings. Moreover, the presence of a banded structure during heat treatment can lead to the deformation of steel, quenching cracking, and other defects [5], which affect the product yield and increase energy consumption and cost [6]. Thus, it is necessary to analyse and eliminate the banded structure in bearing steel to improve the service life, reduce cost, and save energy.

Recently, several studies have examined the mechanism and effects of the hypoeutectoid steel banded structure. Thompson, Howell et al [7, 8] used electron probe x-ray microanalysis (EPMA) to investigate the structure of hypoeutectoid steel and found that the microsegregation of alloying elements was the main cause of the banded structure. The analysis also revealed that the austenite-to-ferrite/pearlite transformation at a lower cooling rate can lead to a distinct banded structure, which does not occur at a higher cooling rate. Reference [8] demonstrated that an increase in the cooling rate reduces the $A_{13}$ temperature difference between the poor solute region and the rich solute region, thus reducing the banded degree. Majka [9] assumed that with an increase in cooling rate, the driving force of proeutectoid ferrite nuclei increases, and, consequently, the difference in the $A_{13}$ temperature between the poor solute region and the rich solute region reduces the effect on the banded structure.

A few studies show that depending on the heat treatment process, the banded structure is characterised by carbide bands of different concentrations in the matrix (ferrite, pearlite, bainite, or martensite) [10]. The
majority of research on the banded structure of hypereutectoid steel (including high-carbon bearing steel) focuses on the banded structure of secondary carbide. Hellner and Normann [11, 12] observed a banded structure in high-carbon chromium-bearing steel using EPMA and found that the banded morphology changes with the distribution of alloy elements, and the secondary carbide precipitated by solid-phase transformation spreads to the area where the carbide-formed elements were enriched, forming a high-concentration carbide-banded structure. Based on the current metallurgical production of large-sized bearing steel billets in China, it is difficult to assess their quality due to carbide defects. There is a certain gap in the production level of high-end bearing steel in the world. In China, producers rely on homogenising heat treatment of the billet (placing it in the rolling-reheating furnace for an extended duration for heat preservation) to eliminate carbide defects to a certain extent [13]. Currently, due to various kinds of smelting technology, domestic companies have not come to a unified understanding of heat preservation temperature and time. The heat preservation temperature is typically ∼1200 °C. The shorter heat preservation time is 2–3 h, while the longer time is 5–6 h [14]. Soaking treatment currently holds only empirical value; long-term heating and insulation not only increase the duration and economic cost, but also reduce the production efficiency. Khan et al. [15] demonstrated complete dissolution of the raw carbide of a casting billet after soaking treatment at 1200 °C for 4 h. Su et al. [16] examined the distribution of C and Cr in the microsegregation of iron-bearing 1G–1.42CR steel by numerical simulation and heat treatment experiments. The temperature and duration of the complete carbide dissolution of bearing steel were investigated, and the results showed that bulk carbide dissolved in 60 min after homogenising treatment above 1260 °C. Walker et al. [17] analysed 100CrMNNMoS18–4–6 bearing steel, and showed via simulation that the homogenisation effect was most significant during the first 2 h of heat treatment at 1250 °C. Increasing the simulation time from 8 h to 12 h did not significantly reduce the segregation of chromium and manganese in the steel. Manganese has high diffusivity and homogenises faster than chromium. The calculations of this model were consistent with those in our previous study on homogenisation, in which the heat preservation times were taken as 2 h, 4 h, 6 h, 8 h, and 10 h, respectively [18]. The experimental results are consistent with Walker’s simulation results. Walker et al. also investigated the influence of hot rolling on microsegregation by EPMA, and employed thermodynamics combined with a nucleation and growth dynamics model to examine the influence of microsegregation on the microstructure. They found that these microstructural changes lead to the occurrence of a carbide-banded structure in rolled bearing steel. Liu et al. [19] demonstrated that GCr15 bearing steel can be heated to 1200 °C for 45 min without deformation, and the carbides in the same completely dissolve within this duration. However, a region with a high concentration of elements with a banded structure of carbides is observed in the final product.

To ensure complete dissolution and uniform distribution of the primary carbides (for potential interdendritic carbon segregation) and cementite in the pearlite casting billet, a high concentration of residual carbide in the banded structure after rolling should be avoided. Considering practical production conditions and several studies, the most efficient soaking treatment before rolling was established at a temperature of 1200 °C with 2 h of heat preservation.

Few studies have investigated the control of banded structures by the reduction of soaking duration and control of post-rolling cooling of high-carbon bearing steel billets. Wu et al. [20] examined the influence of three different cooling methods (furnace cooling, air cooling, and water cooling) on the formation of carbide belts after the spheroidisation of hot-rolled SUJ2 steel. The results indicated that after austenitisation and spheroidisation, chromium segregation occurred in the carbide belts and the C content increased. The diffusion of C in the microsegregation zone can be inhibited by increasing the cooling rate, and at high cooling rates, the formation of carbide belts can be avoided. In this study, based on industrial production, a homogenisation treatment scheme with a short homogenisation treatment time and a constant temperature was selected to investigate the influence of different cooling methods; a homogenising treatment time of 2 h was considered after hot rolling.

The formation of hypereutectoid steel carbide belts has been well documented. However, when heated at 1200 °C for 2 h after hot rolling, we found an abnormal martensitic–pearlite banded structure in the experimental steel. Previous studies have also reported abnormal martensite/austenite banded structures in subeutectoid steel, and the diffusion of C to the Mn segregation area was found to be its cause [21, 22]. Ye et al [23] controlled the diffusion of C in the phase transition process by supercooling (at a rate of 40 °C s⁻¹) after rolling, which significantly altered the C distribution and eliminated the abnormal martensite–austenite banded structure. Under a high cooling rate, the ferrite-shaped nucleus and rapid growth were refined effectively, which restricted the diffusion zone of C and reduced the enrichment of C in the Mn segregation zone, thus improving the banded structure. Liu et al. [19] found that at 1200 °C–1280 °C, heating and holding for at least 3 h can eliminate the banded structure on GCr15 bearing steel. Our previous study on the influence of uniform heating treatment on the strip structure of high-carbon bearing steel demonstrated that the abnormal martensitic–pearlite strip structure can be eliminated under air-cooling conditions after a temperature of 1200 °C for more than 3 h [18]. However, the method was unable to meet practical production demands.
In this study, the microstructure of a hot-rolled high-carbon bearing steel sheet under air-cooling conditions was observed and a distinct band structure was found. The macroscopic morphology was observed using a laser confocal microscope. The banded microstructure was observed and analysed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM), and the distribution of alloy elements in the samples was analysed using EPMA under different cooling rates. Moreover, the influence of alloying elements on the undercooled austenite transformation was investigated using JMatPro thermodynamic software. The cause of formation of the martensitic–pearlite banded structure was analysed systematically. The phase transition behaviour of the hot-rolled high-carbon bearing steel under the influence of alloy element segregation was revealed. After analysing the cause of banded formation, the improved treatment method eliminated the martensitic–pearlite banded structure in the high-carbon bearing steel. This study provides theoretical guidance for the reduction and elimination of the martensite–pearlite banded structure in practical production.

2. Material and experimental

2.1. Material details and heat treatment

The composition of the investigated steel studied in this work was 1.1C-0.21Si-0.35Mn-1.5Cr (wt%). The experimental samples were taken from 350 mm × 280 mm × 80 mm casting billets and processed into 60 mm × 20 mm × 20 mm rectangular samples, as shown in figure 1(A).

The distribution of the alloying elements in the casting billet and homogenised sample was observed. Consider the rectangular sample of 15 mm × 15 mm × 10 mm at position O in figure 1. The samples were uniformly coated with an anti-oxidation coating and heated to 1200 °C in a furnace for 0 h, 2 h, and 10 h, and quenched. The samples were ground and polished, and lightly eroded by 4% nital. Qualitative (surface scanning) and quantitative analyses (point scanning) were performed by EPMA.

To simulate practical hot rolling production conditions, 60 mm × 20 mm × 20 mm rectangular specimens were homogenised at 1200 °C for 2 h and then hot-rolled to a thickness of 7 mm at an open rolling temperature of 1000 °C and a finishing temperature of 950 °C. To investigate the effect of post-rolling cooling on the abnormal band structure, three different cooling processes were employed; in all cases, the same homogenisation and rolling conditions were considered. One group of rolled samples (group A) was directly air-cooled to room temperature (process (a)). After analysis of these samples, an improved process was proposed. The rolled samples (group B) were promptly placed in a slow cooling box, wrapped with high-temperature resistant asbestos, and the temperature of the samples was measured by a contact thermometer. After the samples cooled to 600 °C, the cover of the slow-cooling box was removed and the samples were cooled to room temperature (process (b)). The third group was used as a control. The rolled sample (group C) was cooled in a furnace (process (c)). The original furnace temperature was 950 °C, and the process route is shown in figure 2.

2.2. Microstructural characterisation

The three groups of samples were polished and corroded with 4% nital for several seconds. The microstructures were observed using a laser confocal microscope and SEM. The EPMA of the alloy element distribution in the microstructure of the experimental samples was performed using a JEOL JXA8230 scanning electron microscope with an accelerating voltage of 20 kV, a 10 nA beam in the focusing probe, a step length of 0.2 μm, and scanning area of 1.7 mm × 1.7 mm. The twin-jet polishing technique (3% perchlorate alcohol at −30 °C,
applied potential of 50 V) was implemented to prepare thin foil samples for TEM observation (JEM 2100, Japan Electronics Co., Ltd, Tokyo, Japan).

3. Results and discussion

3.1. Element distribution characterisation

The elemental analysis of the casting billet O is shown in figure 3. A distinct positive segregation of chromium, manganese, and carbon is observed. Figure 5 shows the alloying element distribution after homogenisation at 1200 °C for 10 h. Although the chromium–manganese segregation was weakened, homogeneous distribution could not be achieved, as shown in figures 5(b) and (c). Homogeneous distributions for carbon and silicon were obtained after a short period of heat preservation, as shown in figures 4(d) and (e). A comparison of figures 4 and
reveals that homogenising treatment was unable to provide a homogenisation distribution of chromium–manganese and other alloying elements, thus resulting in the widening of their segregation bands, and increase of the grade of the banded structure.

Our previous work demonstrated that at a constant temperature, the longer the homogenisation time, the wider was the positive segregation band of chromium and manganese \[18\]. In this study, the preservation time
was the same (10 h) at 1200 °C, as shown in figure 5. After homogenisation, the chemical segregation band of alloying elements widened. After hot rolling, this widened band influenced the post-rolling phase transition process [17]. If the homogenisation time is improper, the banded structure after rolling deteriorates.

3.2. Microstructure under different cooling methods

By combining the fitting curves of furnace and air cooling, the furnace cooling rate is estimated to be approximately 0.5 °C s⁻¹ (figure 6(b)), while the cooling rate of air cooling is approximately 1 °C s⁻¹ (figure 6(a)). The simulation of the continuous cooling transformation of rolling revealed that when the cooling rate is lower than 5 °C s⁻¹, as shown in figure 7, high-carbon bearing steel undergoes early cementite phase transformation and pearlite transformation, but not martensitic transformation. However, in the rolling experiment, the banded martensite structure does occur under air-cooling conditions. This may be related to the kind of deformation and its degree. The thermal simulation shows compression with slight deformation, while the deformation during the rolling experiment is relatively higher. The segregation zone becomes thinner and longer along the rolling direction, and the concentration of alloying elements is higher. In the cooling process after rolling, the hardenability of the high-concentration zone increases, resulting in an abnormal martensite band structure in the high-concentration zone under air-cooling conditions.

The microstructures of the samples at different cooling rates are shown in figure 8. A noticeable difference is observed in the microstructures of the three groups of samples. Under the condition of air cooling, the microstructure of group A exhibits a distinct banded distribution, while under slow cooling–air cooling, the samples of group B exhibit no banded distribution and the microstructure is uniformly distributed. Under the cooling condition of the furnace, the microstructure of the group C samples presents a typical carbide ribbon structure, as shown in figure 8(c). The banded microstructure along the rolling direction under the condition of
air cooling is shown in figure 9(a). The white band observed with an optical microscope is martensite, and the microscopic morphology of the sample is shown in figures 9(a) and (b). The microstructure of group A consists of banded martensite, pearlite, and cementite; the network of cementite is distributed along the grain boundary, and the crystal shows a pearlite layer structure. With a decrease in the cooling speed at the high-temperature stage, that is, under the condition of slow cooling–air cooling, the microstructure is shown in figures 8(b) and 9(c), (d). The disappearance of martensite bands was observed by an optical microscope, and the corresponding transformation of austenite into fine lamellar pearlite and continuous cementite distributed along the grain boundary was observed. The microstructure exhibited the morphology of fine pearlite and reticular cementite.

SEM illustrated the banded microstructure. To more accurately observe the morphology of the white-banded microstructure in the air-cooled optical microscope, TEM was used to characterise the samples of groups A and B, as shown in figure 10. The TEM results indicate a distinct martensite–pearlite banded structure (consistent with optical microscopy (OM) observations) in the high-carbon steel bearing direct air-cooled samples (group A) after hot rolling; the martensite defects appear as an entanglement phenomenon, as shown in figure 10(a).

3.3. Influence of alloying element segregation on microstructure

The previous section discussed the SEM and TEM microstructural observations and showed that the white band observed by OM was martensite. This section analyses the distribution of alloying elements by EPMA of the samples of groups A and B to explore the cause of the martensite banded structure. Under the influence of segregation of the alloying elements, the nucleation and growth mechanisms of undercooled austenite in high-carbon bearing steel under different cooling conditions are revealed.

Under the condition of air cooling, EPMA results of group A samples are shown in figure 11. In the backscattering mode of the EPMA tester, the martensite exhibits a white bright band-like morphology, and the band structure has poor continuity and a large difference in width, as shown by the red double arrow in figure 11. There is a distinct enrichment of chromium and manganese in the martensite region, and the horizontal width of the segregation zone is relatively uniform, as shown by the black double arrow in figures 11(c) and (e); further, there is a distinct negative segregation of carbon, as shown in figure 11(b). Reference [24] demonstrated that the enrichment of chromium and manganese improves the stability of the undercooled austenite in the transition zone, particularly in the low-temperature transition zone, and makes the continuous cooling transition curve.
shift to the right, resulting in a decrease in the critical cooling rate of martensite. Under the condition of air cooling, a banded martensite structure appears in the group A sample with Mn and Cr segregation.

JMatPro thermodynamic software was used to investigate the influence of different chromium and manganese concentrations on the isothermal transition curve (TTT curve) of high-carbon steel, and the results
are shown in figure 12. With an increase in chromium concentration, the incubation period of transformation in the pearlite zone was prolonged and the stability of the undercooled austenite increased. The TTT curve shifted to the right, as shown in figures 12(a)–(c). Manganese has consistent influence rules, as shown in figures 12(d)–(f). Therefore, the positive segregation region of chromium–manganese has a high stability of undercooled austenite, and the incubation period of the pearlite transformation is prolonged, which is different from the nucleation driving force of undercooled austenite in the negative segregation zone of the alloying elements.

In summary, the cause of this banded structure is the interaction of the undercooled austenite transformation of the hot-rolled metal with the segregation of alloying elements. In the case of element segregation, the austenite nucleation driving forces of the enriched chromium and manganese alloy element region and the poor element region are different. This results in air-cooling conditions and a high stability of undercooled austenite in the region enriched with chromium and manganese; however, the nucleation driving force of austenite is not reached, and the aforementioned characteristics are temporarily retained. Undercooled austenite nucleates preferentially in the negative segregation zone of alloying elements to form secondary cementite and pearlite. As the temperature continues to decrease and the pearlite transition zone is missed, the driving force of the undercooled austenitic nuclei enriched with chromium and manganese alloy increases and enters the martensite transition zone, where martensite transformation occurs, forming banded martensite distributed along the alloying element segregation zone. Moreover, positive segregation of the chromium and manganese alloy elements also increases the hardenability of the region [25], and accordingly, martensite transformation is more likely to occur. Carbon is easy to diffuse uniformly, while other alloying elements are difficult to diffuse for homogenisation [26–28]. When pearlite transformation occurs in the negative chromium and manganese segregation zone, the carbon element diffuses from the rich chromium and manganese zone to the poor chromium and manganese zone and participates in the pearlite transformation preferentially, which leads to the negative segregation of carbon in the banding zone.

Figure 11. Microstructure and element distribution of sample A. (b) carbon (c) chromium (d) silicon (e) manganese.
Regarding the effect of cooling methods on the microstructure of hot-rolled products, some researchers have adopted ultra-rapid cooling [23] in the high-temperature zone to control the abnormal martensitic band structure in the core of the hypoeutectoid steel; a very good effect was reported. Peng et al [29] used a two-stage cooling method of ultra-fast + slow cooling to increase the ferrite phase variable and refine the ferrite grains. Some studies used two-stage cooling for hypereutectoid steel to control the organisational structure. Huo et al proposed a two-stage cooling process to suppress the formation of proeutectoid cementite and used it to control the formation of network carbides [30]. In the analysis of the cause of the banded martensite, the segmented slow cooling–air cooling method is adopted, as shown in process (b) in figure 2. Among the aforementioned methods, the purpose of slow cooling to 600 °C is to increase the nucleation point of the pearlite transformation of the undercooled austenite, increase the high-temperature phase transformation time, and ensure complete pearlite transformation of the undercooled austenite region of the rich alloy elements, reducing the rate at which the temperature falls to the low-temperature zone. EPMA results of the group B samples are shown in figure 13; despite distinct segregation of manganese and chromium in the sample, no martensite structure appears, and no negative segregation of carbon occurs.

The segregation of chromium and manganese alloy elements in high-carbon bearing steel does not necessarily lead to the appearance of banded structures. Control of the cooling rate after rolling is crucial; when the cooling rate is too low, secondary carbide banding is prone to occur. When the cooling rate is too high, martensite banding is likely to occur, and the controlled cooling process can eliminate the banded structure.

4. Conclusions

(1) The experimental results indicate that after soaking treatment at 1200 °C for 2 h, furnace cooling, two-stage cooling, and rolling, chemical segregation zones of chromium and manganese appeared in the sample; no abnormal martensite–pearlite band structure was observed. However, this structure appeared in the sample during air cooling. Thus, the abnormal martensite–pearlite band structure defects are caused by the interaction of the alloying element segregation and cooling method after rolling.

(2) Positive segregation of chromium and manganese alloy elements and negative segregation of carbon elements were found in the martensite banded structure.

(3) Following the implementation of different cooling methods, the sample structure morphology revealed that the use of a two-stage cooling + air cooling process resulted in a structure containing fine pearlite and a small amount of network cementite; an abnormal martensite–pearlite band structure and carbide band structure were not observed.

Figure 12. TTT curve at different chromium and manganese concentrations.
Figure 13. Microstructure and element distribution of sample B. (b) carbon (c) chromium (d) silicon (e) manganese.

ORCID iDs

Yun-long Wang © https://orcid.org/0000-0001-9597-6927
References

[1] Ervasti E and Stålhberg U 2000 Transversal cracks and their behaviour in the hot rolling of steel slabs Journal of Materials Processing Tech 101 312–21
[2] Fang W et al 2013 Current research situation of alleviating or eliminating band structure in steel Hot Working Technology 42 52–4
[3] Khalid F A, Farooque M, ul Haq A and Khan A Q 1999 Role of ferrite–pearlite banded structure and segregation on mechanical properties of microalloyed hot rolled steel Mater. Sci. Technol. 15 1209–15
[4] Shannugam P and Pathak S D 1996 Some studies on the impact behavior of banded microalloyed steel Eng. Fract. Mech. 53 991–1005
[5] Ha I S and Fleury E 1998 Small Punch Tests to Estimate the Mechanical Properties of Steels for Steam Power Plant. II. Fracture Toughness 75 707–13
[6] Peng-yuan Z et al 2010 Banded structure in mm-bearing structural steel and its influence on mechanical properties Angang Technology 05 24–7
[7] Greuterfinden R et al 1992 Formation of pearlitic banded structures in ferritic-pearlitic steels Steel Res. 63 331–6
[8] Thompson S W and Howell P R 1992 Factors influencing ferrite–pearlite banding and origin of large pearlite nodules in a hypoeutectoid plate steel Mater. Sci. Technol. 8 777–84
[9] Majka T F, Matlock D K and Krauss G 2002 Development of microstructural banding in low-alloy steel with simulated Mn segregation Metallurgical and Materials Transactions A (Physical Metallurgy and, Materials Science) 33 1627–37
[10] Verhoeven J D 2000 A review of microsegregation-induced banding phenomena in steels J. Mater. Eng. Perform. 9 286–96
[11] Hellner L and Norrman T O 1968 Banding in alloy steels Jernkontorets Ann 152 269–86
[12] Adishesha P K 2002 Effect of Steel Making and Processing Parameters on Carbide Banding in Commercially Produced Iron and Steel Products collection 46 168–96
[13] Yu F et al 2020 Current status of metallurgical quality and fatigue performance of rolling bearing steel and development direction of high-end bearing steel Acta Metall. Sinica 56 153–62
[14] Lü-Z. Q et al 2016 Large carbide dissolution in GCr15 continuously cast billet core Int. J. Mater. Res. 107 272–380
[15] Khan F 2018 The effect of soaking on segregation and primary-carbide dissolution in ingot-cast bearing steel Metals 8 800
[16] Su F et al 2020 Simulation and experimental study on carbide dissolution process of Fe-1C-1.42Cr-bearing steel Heat Transfer 49 249–57
[17] Walker P F F et al 2015 Modelling of micro-segregation in a 1C-1.5Cr type bearing steel ASTM Special Technical Publication 53 54–80
[18] Wang Y-L, Chen Y-L and Yu W 2020 Effect of Cr/Mn segregation on pearlite–martensite banded structure of high carbon bearing steel Int. J. Miner. Metall. Mater. 12 238–49
[19] Jing L et al 2008 Study of temperature and carbide solution-diffusion for GCr15 bearing steel Heat Trant. Met. 033 87–90
[20] Wu H-Y et al 2020 Effect of cooling rate on carbide banding in high-chromium bearing steel after spheroidization Metallurgical and Materials Transactions A 51 4471–82
[21] George K 2003 Solidification, segregation, and banding in carbon and alloy steels Metallurgical & Materials Transactions B 34 781–92
[22] Penha R N, Vatavuk J and Couto A A 2013 Effect of chemical banding on the local hardenability in AISI 4340 steel bar Eng. Fail. Anal. 53 236–48
[23] Qi-bin Y E et al 2017 Effect of ultrafast cooling on preventing abnormal microstructural banding at centerline of steel plate Journal of Northeastern University Natural Science 38 1696–701
[24] Guo H et al 2017 Effects of Mn and Cr Contents on Microstructures and Mechanical Properties of Low Temperature Bainitic Steel 24 290–5
[25] McMahon C J 1980 The role of solute segregation in promoting the hardenability of steel Metallurgical and Materials Transactions A 11 531–5
[26] Wang C Z and Zhang Z X 2005 Research on carbon migration in steel by the plasma surface alloying process Journal of Beijing Polytechnic University 16 622–5
[27] Liang J et al 2018 Improved microstructural homogeneity and mechanical property of medium manganese steel with Mn segregation banding by alternating lath matrix Materials Science and Engineering: A 711 175–81
[28] Offerman S E et al 2002 Ferrite/pearlite band formation in hot rolled medium carbon steel Mater. Sci. Technol. 18 297–303
[29] Peng N Q, Tang G B and Liu Z D 2013 Effect of two-stage cooling rate on austenite-ferrite phase transformation in high temperature transition region J. Mater. Eng. 3 11–5
[30] Huo X et al 2019 Research and control of network carbide in GCr15 bearing steel Mater. Res. Express 7 54–68