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INFLUENCE OF INTERNAL CRACKING ON CARBIDE PRECIPITATION IN CONTINUOUS CASTING BLOOM INDUCED BY SOFT REDUCTION TECHNOLOGY AND THE RESULTING SEGREGATED BAND IN HOT-ROLLED WIRE RODS

Internal cracking surrounding primary carbides in high carbon steel as-cast blooms induced by soft reduction is investigated to elucidate their influence of internal cracking on carbide precipitation and the resulting segregated band in hot-rolled wire rods. The primary carbides precipitation in high carbon steel has been investigated using both experimental observations and finite element simulations for as-cast blooms induced by soft reduction. It is found that the carbides precipitation in the vicinity of existing internal cracks is often located midway between the surface and centreline of the bloom, further increases the occurrence of the segregated bands in the hot-rolled wire rods. In addition, the growth of primary carbides surrounding the internal cracking are based on the chemical driving force and high density precipitate zones have been clarified in continuous casting bloom induced by soft reduction. It clearly shows that the spatial distribution of internal cracking surrounding primary carbides that play a key role in the formation of the segregated bands in the final steel products.

Keywords: internal cracking; carbide precipitation; segregated band; soft reduction technology

1. Introduction

Serious performance problem of the final steel products is partly dominated by the inhomogeneity and instability of the hot rolling products originated from continuous casting blooms. Macro-segregation, which is the non-uniform chemical composition throughout the cross-section of solidified casting, is one of the major defects that occur in as-cast products. To meet such strict requirement, many researchers [1-9] have investigated soft reduction technology to minimize center segregation of bloom. When an improper reduction zone [1-2] and/or an improper reduction amount [3-6] is implemented, center segregation is not eliminated effectively and internal cracks are subsequently formed in as-cast products, meaning a trade-off between center segregation and internal cracks. Therefore, macro-segregation and cracking are considered as major defects in as-cast products and the occurrence of these two defects is connected through caster detail and operating conditions.

Strecken et al., [10] pointed out that central zone of continuous casting bloom contained the equiaxed crystals, and it has a great influence on the formation of pattern segregation of the as-cast products. Furthermore, Krauss [11] specifically confirmed that centerline of high carbon blooms in a longitudinal section takes place of serious partitioning of solute elements, resulting in the macro-segregation defects in as-cast products. On decreasing temperature of solidification, the micrometer scale eutectic carbides are nucleated at the grain boundaries of preexisted austenitic, and starting from a certain solidification point, preexisted grains start to interact with each other to form a continuous skeleton of the solid phase. The liquid films of eutectic carbides, which strongly reduces the dendrite coherence, exist between the dendrites and spread out over the grain boundary surface. Eskin et al., [12] have reported that the grain boundary displacement is the main deformation of a semi-solid body. Deformation of continuous casting bloom leads to an increase of migrations, linearity and sensibility to grain boundaries within the brittle temperature region, which also indicates an increase tendency to internal crack. Amram et al., [13] proposed a brittle intergranular cracking will occur if the liquid flow are not sufficient to accommodate the displacement induced by deformation.

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Roussel et al., [14] demonstrated that carbides easily nucleate along dislocations due to the nucleation barrier could be reduced in the vicinity of already existing carbides. Tsuchida and Sugawara [15] found that the severe macro-segregation was difficult to be minimised/eliminated by the following heat treatments and hot rolling processes. This segregation of the as-cast products is the main reason for the banded structure of high carbon steel in hot-rolled products, lead to property variations, and cracking initiates and propagates along the banded structure of the finished end product.

There are few interesting features about the carbide precipitation and growth mechanisms of continuous casting bloom induced by soft reduction, and the spatial distribution of primary carbides surrounding the internal cracking and high density precipitate zones have not been fully clarified. In this paper, we investigate the carbides precipitation in the vicinity of existing internal cracks by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). Cracking induced chemical composition gradients, especially the carbon atoms released by the displacement of grain boundaries, was clearly exhibited in the continuous casting bloom. A simple precipitation model based on chemical composition gradients induced by soft reduction is then proposed to analyze the precipitation of primary carbides and to explore the transformation of carbides with significant chromium depletion in the vicinity of primary carbides. The relationship between the severe segregation of as-cast products and their effect on the segregated bands in the hot-rolled wire rods was accordingly investigated.

2. Experimental Section

2.1. Casting parameters of plant trials

The continuous casting blooms with 280×325 mm rectangular section of the high carbon steel were taken from a special steel factory in China. The plant trials of this investigation involved samples collection from both continuous casting blooms and hot-rolled wire rods. As one of the most commonly used high-chromium bearing steels, GCr15 steel (AISI-52100) has the characteristics of high wear resistance, corrosion resistance and good dimensional stability. It has been widely used in manufacturing bearing ring, ball screw and other mechanical components. The average chemical composition is shown in Table 1, whereas Table 2 illustrates the basic operating conditions of the caster for plant trails.

TABLE 1

Average chemical compositions of the high carbon steel (wt%)

C	Mn	P	S	Cr	Si	Ni	Al
1.00	0.30	0.01	0.002	1.43	0.25	0.01	0.012

Typical internal cracks are often located midway between the surface and centreline of the bloom under the above caster detail and operating conditions, samples obtained from longitudinal section of continuous casting bloom were prepared for quantitatively evaluation of the internal cracks and precipitated carbides. The blooms were rolled into hot-rolled wire rods with the diameter of 20 mm, the presence of segregated bands was examined in longitudinal section of the hot-rolled wire rods.

TABLE 2

Caster detail and operating conditions

Casting speed/(m min^{-1})	0.70
Superheat/^{o}C	20
Maximum current of M-EMS/A	380
Frequency of M-EMS/Hz	3.5
Soft reduction amount/(mm)	11.5

2.2. Examination of internal cracking in continuous casting samples

A high tendency of internal cracking in the continuously casting bloom forms exclusively in the midway region between the center and surface of bloom, as shown in Fig. 1. Internal cracks of bloom in the longitudinal section are specially a certain angle to the bloom casting direction. Analyzing the morphologies of internal cracking, it is possible to learn the crack formation stage between uncracked stage and stabilized cracking stage. When the continuously casting blooms reach stabilized cracking stage, crack spacing in inside cracking zone is much shorter than that in case of outside cracking zone. Moreover, crack length in inside cracking zone during soft reduction is bigger than that in case of outside cracking zone. Having analyzed the cracking results, the final crack length in inside cracking zone is on average 45% larger than it is in outside cracking zone.

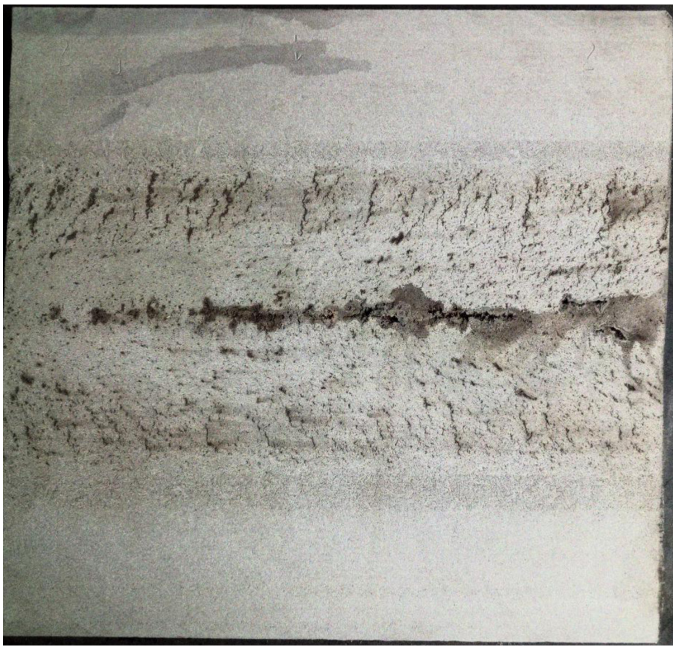

Fig. 1. Internal cracks of bloom in the longitudinal section

In order to characterize the distribution and shape of internal cracks in continuous casting bloom, specimens are sliced from the brittle temperature range of a bloom illustrated in Fig. 2. The crack formation site for breaking crack may initiate and then propagate to the subsurface along a certain path. To ensure better observation of internal crack morphology induced by a reduction process, the optical microscope (OM) and scanning electron microscope (SEM) method are employed.

Fig. 3 presents an illustrative photographs of crack pattern for continuous casting blooms from the plant trials. The photographs are obtained from the samples of the soft reduction tested. It is apparent that the crack spacings and crack widths are

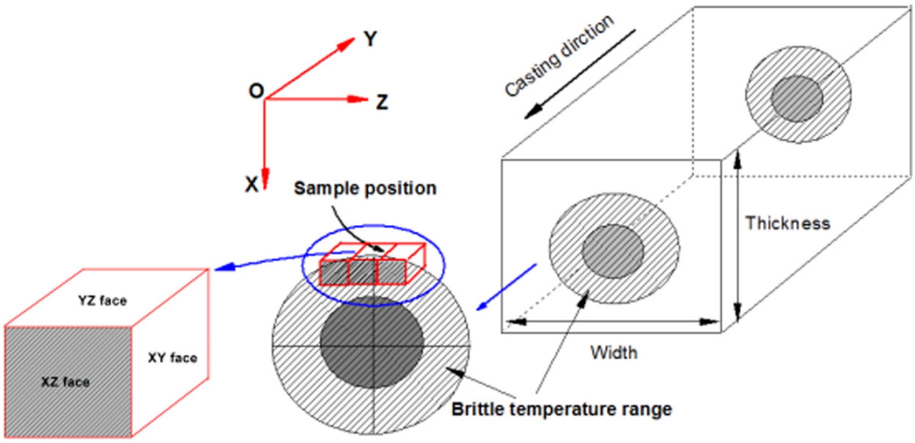

Fig. 2. Illustration of the sample point and sample place in bloom

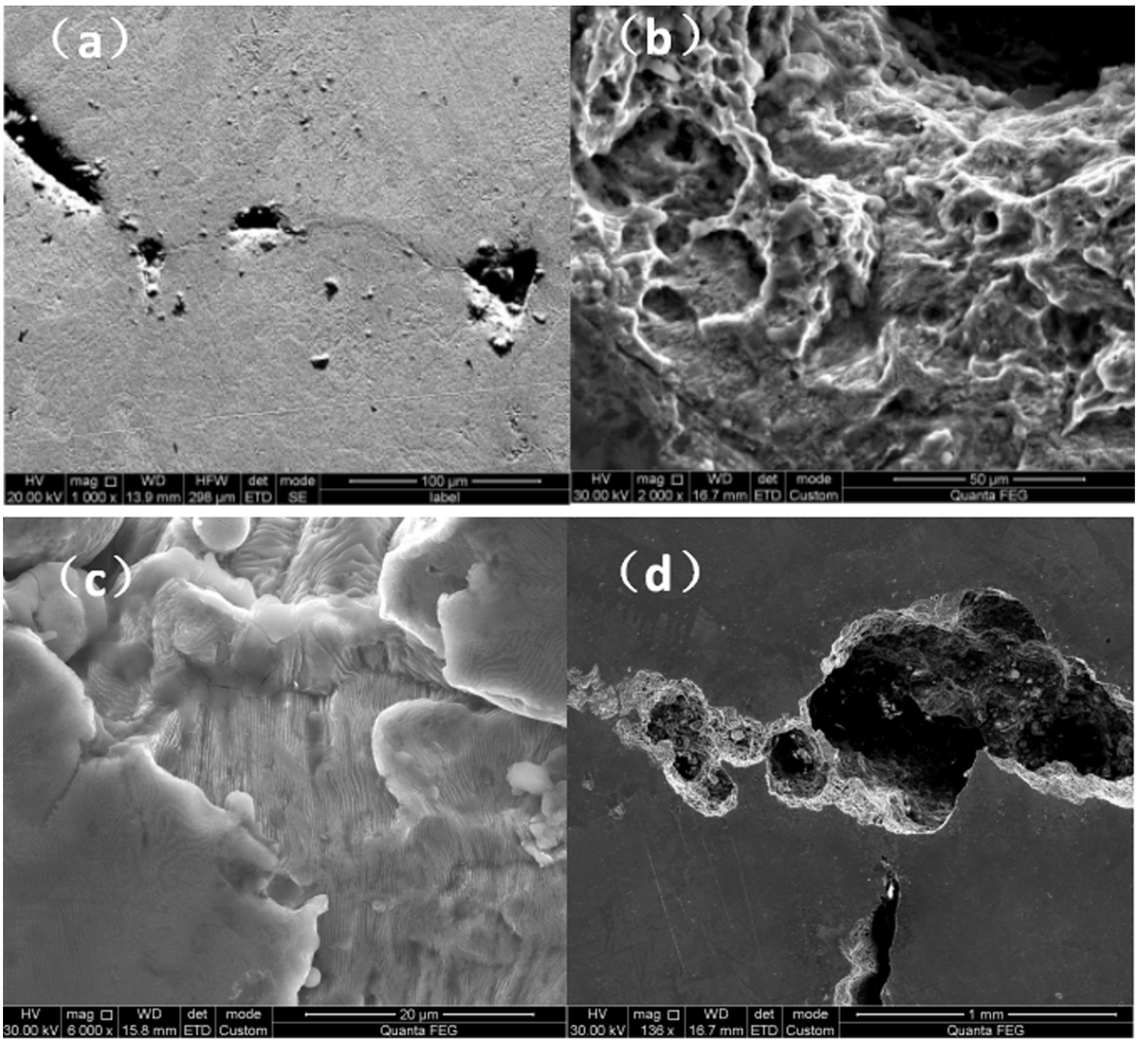

Fig. 3. SEM Images showing a typical crack initiation site and a crack propagation through the grain boundaries. (a) a crack initiation site; (b) a magnification of crack tips; (c) a microstructure near crack tips; (d) a crack propagation

more irregular on the YZ face of specimens. Cracking moment passing from the uncracked stage to the cracked one is depicted in Fig. 3(a). It was observed that crack spacing and crack width considerably influence the crack pathway. As a tensile stress is occurred at boundaries of crack formation, these micro cracks become sensitive to cracking and propagate into larger dominant cracks further. The regions can act as crack initiators due to the stresses from solidification and thermal gradients. Internal cracks of continuous casting blooms were typically found to initiate from a crack initiation site or defects, as shown in Fig. 3(b). A plastic zone is normally formed near the tip of the crack, a microstructure near crack tips is shown in Fig. 3(c). Microstructural changes are formed at prior austenite grain boundaries induced by the deformation, thereby leading to a crack propagation.

To understand the effect of bloom's location on the feature of precipitated carbides, the samples were extracted from the continuous casting bloom to detect the morphology of carbides. Meanwhile, the observation of carbides morphology was shown in Fig. 4, and carbides precipitated along preexisted austenitic grain boundaries. The morphology of carbides was influenced by the local concentration of solute atoms during the solidification process, compound carbides could be divided into two types, one is individual carbides (Fig. 4(a),(b)), the other is coupled carbides containing a certain amount of internal cracking (Fig. 4(c),(d)). Moreover, crack length of coupled carbides is bigger than that of individual carbides. It can be known that the coupled carbides exhibits more serious harm than the individual carbides, this coupled carbides may be attributed to the cracking formation of continuous casting bloom during soft reduction process, due to solute atoms were generally promoted into internal cracking area during solidification.

3. Results and discussion

3.1. Estimation of stress concentration in the bloom due to deformation behaviors

In order to obtain the distribution of stress in the bloom during soft reduction operation, 3D finite element models of bloom passed a simple pair of reduction rollers have been developed using the commercial software ABAQUS®. Local stress concentrations obtained from a finite element model has been taken to evaluate the crack formation and then applied to the crack propagation analyses. The temperature distribution of the blooms when it is in the reduction region has been calculated firstly, which was introduced in detail elsewhere [16]. Then the temperature fields were transferred to the reduction model as the initial temperature fields. The 3D finite element model based on ABAQUS/Explicit is developed to calculate the stress and strain fields in the blooms. Reduction rollers and blooms are assumed to be discrete rigid and deformable body, respectively. Fig. 5 shows 3D finite element model of bloom for reduction deformation analysis, which is carried out for

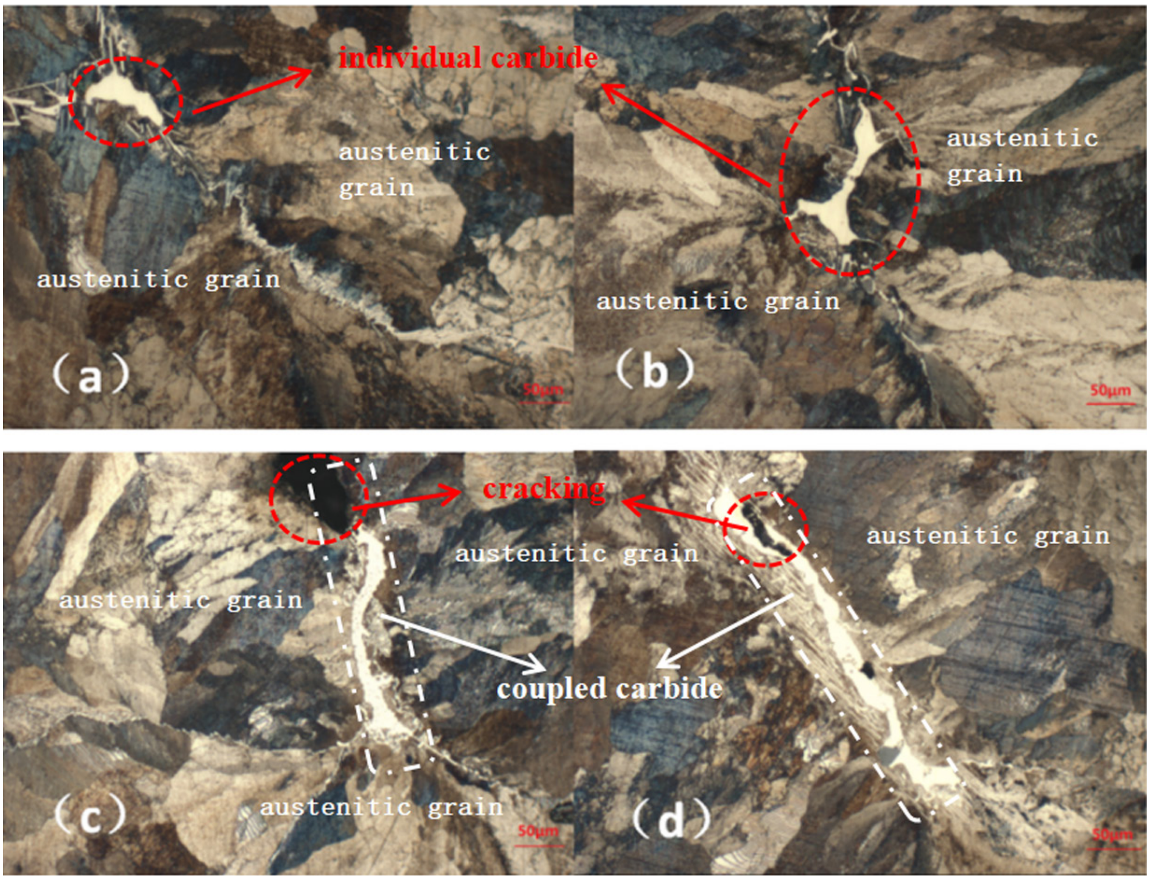

Fig. 4. Morphologies of precipitated carbides: (a), (b) centre region of bloom.; (c), (d) cracking range of bloom

a bloom under various reduction amounts with a cross section of 280 mm by 325 mm. In addition, the casting speed of bloom is 0.70 m/min.

In this paper, a special steel was chosen to illustrate calculation process of soft reduction in detail. The chemical composition of the steel in this study is shown in Table 1. In the finite element model of the bloom induced by deformation behaviors, the thermal parameters were calculated by weighted averaging of the phase fraction with the specific calculation equations [17-18]. In order to obtain accuracy of deformation behavior, mechanical properties based on temperature intervals have been established. In addition, the material properties of mechanical properties, elastic modulus and Poisson's ratio have been described in the present authors' previous work [3-5].

Main inclination angles between continuous casting direction and internal cracks were ranged 30 degrees to 60 degrees in the longitudinal section of continuous casting bloom. Internal crack initiators can occur in the brittle temperature region and provide a fracture path around the boundaries of tensile stress concentrations. In the direction of the bloom thickness, the reduction deformation transferred from the bloom surface to the center gradually, as shown in Fig. 6. When the reduction roll was pressed through the continuous casting bloom, the stress concentrations of the bloom inner surface are much higher than that of the

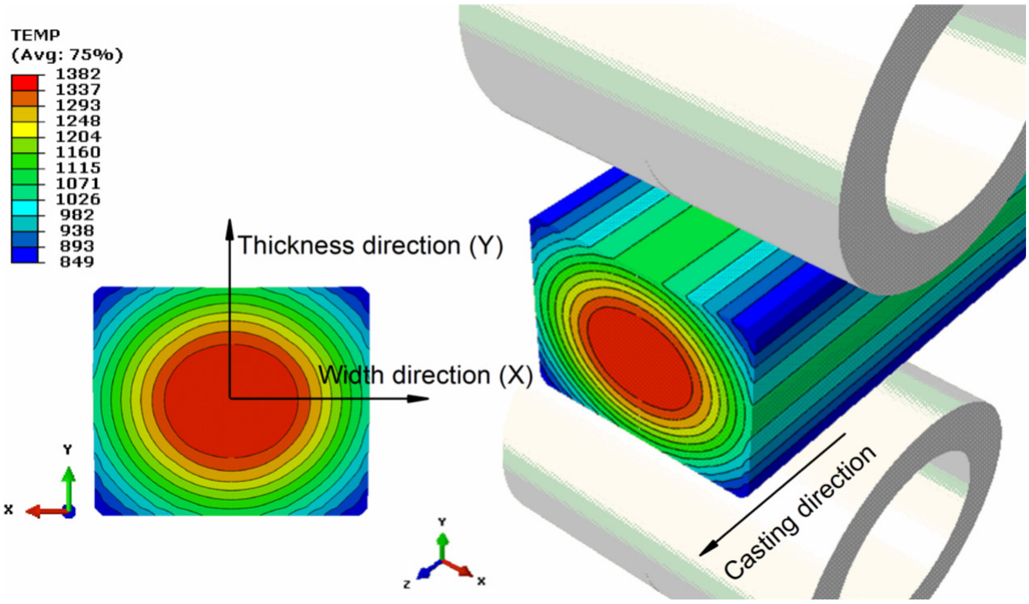

Fig. 5. 3D finite element model for reduction deformation analysis

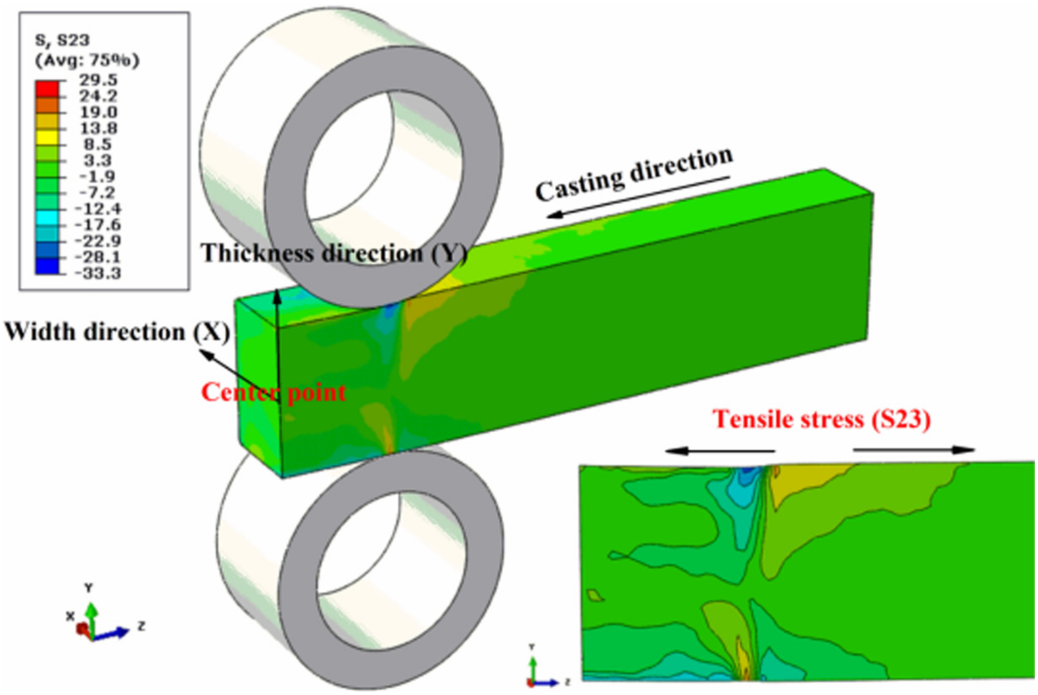

Fig. 6. Distribution of the tensile stress induced by reduction deformation

bloom exterior surface due to its larger deformation induced by the soft reduction. In addition, intermediate cracks were formed due to the tensile stress occurred at the boundary of the brittle temperature range. The maximum tensile stress is appeared at the boundary of the brittle temperature range to generate larger cracks.

3.2. Effect of cracking induced composition gradients on carbide precipitation

The morphologies of internal cracking were observed at the grain boundaries of the specimen, as shown Fig. 7, some coarse carbides precipitated around multiple micro-cracks and kinked macro-crack, and some carbide grew into the matrix near one or both sides of the grain boundaries, as shown Fig. 7(a).

Continuous casting steels tend to develop low melting segregates along the grain boundaries during the final stages of solidification. Internal cracking is generally believed to derive from the low melting eutectics and stress concentration. Typically, the grain boundaries of the continuous casting steels are connected before deformation behaviors. With respect to deformation behaviors of steels induced by soft reduction, the grain boundaries are separated and a number of cracks have generated at the grain boundaries. The precipitation of carbides occurs selectively at a grain boundary and the carbides are related closely to deformation at the grain boundaries.

The crack nucleation is encountered in the areas related to grain boundary, and the crack propagation deviates from its original crack direction and carbides precipitation. When the tensile stress is large enough, the carbide breaks first and crack propagation is generated at the grain boundaries. This can be attributed to the decrease of chromium concentration in the matrix due to the coarse carbides precipitated at the grain boundary during the deformation behaviors. The grain boundaries are separated by the coarse carbide after deformation behaviors due to the carbide is brittle and there is low bond strength between the carbide and matrix.

Non-uniform distribution of alloying elements is one of the most important phenomena which occur during steel solidification. Line scanning of solute elements in internal cracking along the grain boundaries is shown in Fig. 8. There are distinct differences in composition along the trail (line A-A'), which reflects the visual difference of carbon element and chromium element between the boundaries of crack formation in the SEM image. Carbon element is concentrated on the boundaries of internal cracking, which is related to red lines in Fig. 8(a). However,

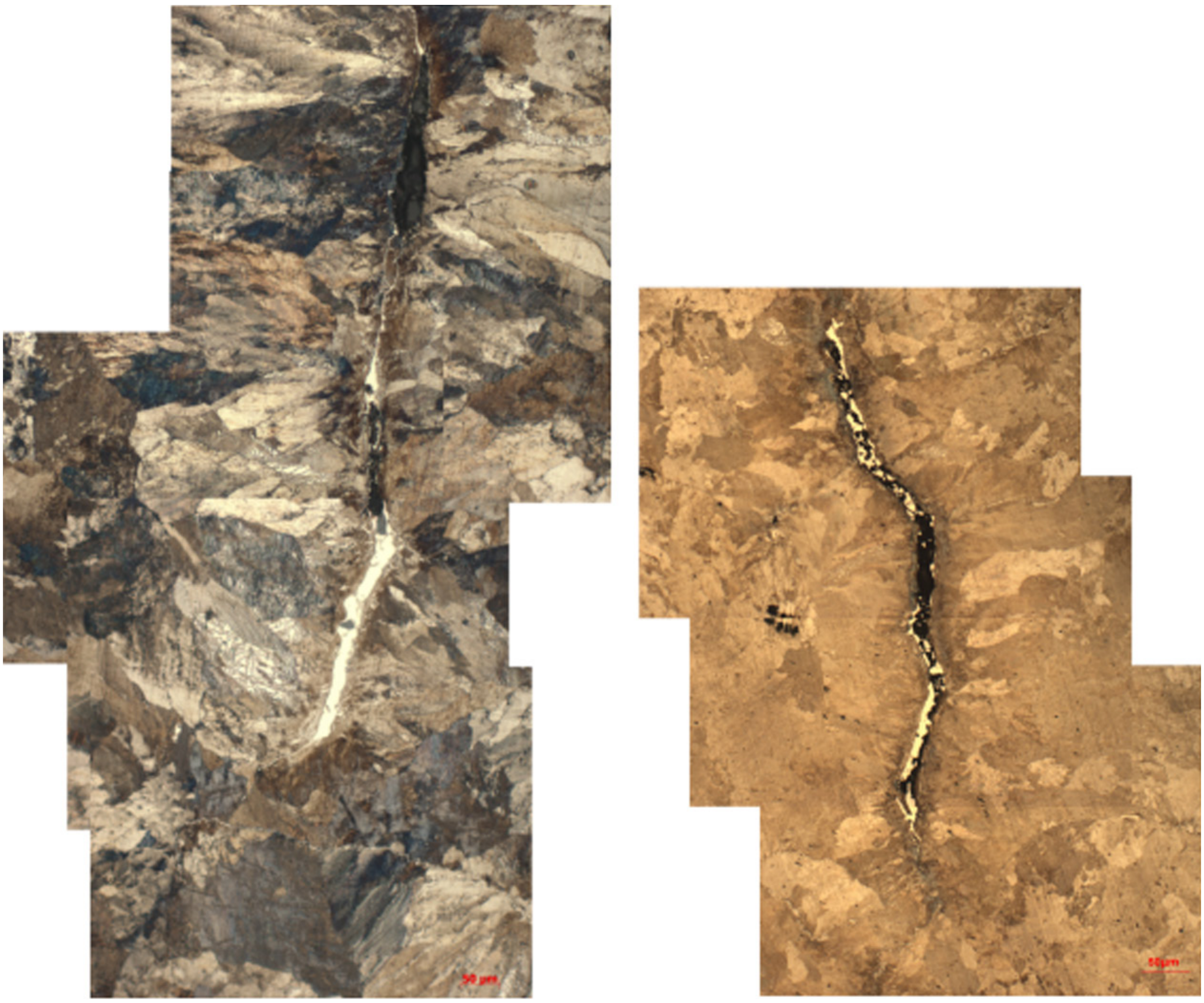

Fig. 7. Optical micrograph of internal cracks with primary carbides in as-cast specimens

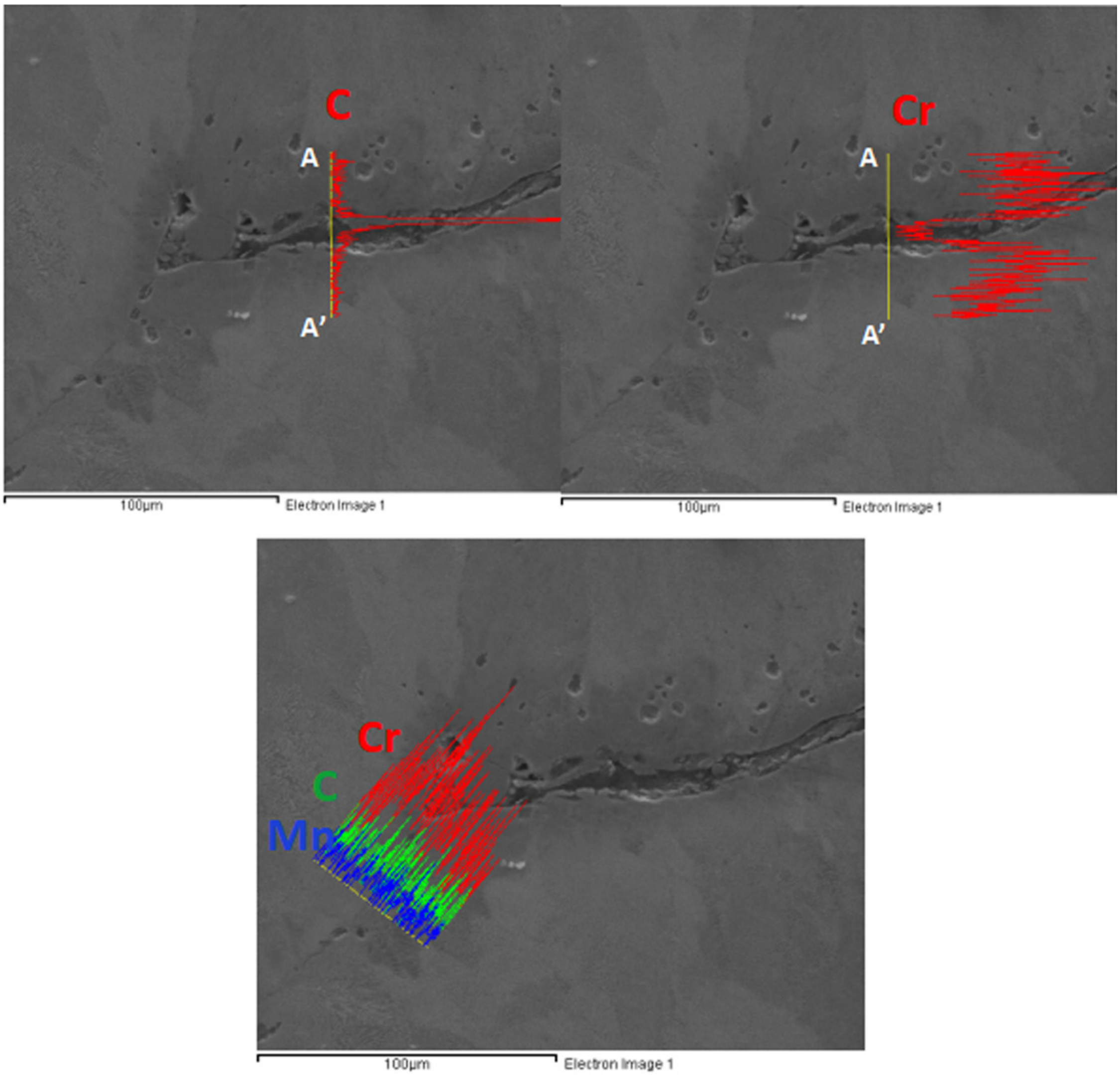

Fig. 8. Line scanning of solute elements in internal cracking along the grain boundaries

chromium element is decreased at the internal cracking boundary, which is related to red lines in Fig. 8(b). The distribution of chromium carbides acted as dislocation sources, increasing the crack tip stress concentrations. This can be attributed to the decrease of chromium concentration in the matrix due to the coarse carbides precipitated along the grain boundaries, as shown in Fig. 8(c). Therefore, it is important to learn carbide precipitation concentrated on the boundaries of internal cracking induced by soft reduction. The resistance to cracking propagation will be decreased since the carbide has low bond strength between carbide and matrix, stress concentrations will lead to intergranular cracking at grain boundaries. SEM/EDS (Fig. 9) revealed no significant carbon peak and a large peak for chromium, carbide precipitation occurs at the grain boundaries, lots of chromium atoms in the matrix are consumed and bulk chromium concentration decreases. Chromium element plays an important role in the strength of the alloy, and the alloy strength decreases with decreasing chromium concentration.

Schematic diagram for the internal cracking on carbide formation induced by deformation behaviors is presented in Fig. 10. The solidification process can be divided into two stages of interdendritic feeding (Fig. 10(a)) and interdendritic separation (Fig. 10(b)). In the region of the interdendritic feeding, the solute enrichment area has the ability to flow through the dendritic crystal network, liquid film has formed surrounding the grain boundaries of the semi-solid body. A large freezing range alloy promotes the solute enrichment to spread over the grain boundary, which strongly reduces the dendrite coherence. In the region of the interdendritic separation, the permeability of the dendritic spacing becomes too small for the liquid to flow with increasing solid fraction, which thin liquid films exist between the dendrites. Dendrites from the austenitic phase are surrounded by micrometer scale eutectic carbides surrounding the grain boundaries, and these carbides are often directly formed in continuous casting conditions, further deformation behaviors of the dendritic network will cause grain boundary sliding to form dislocations or cracking of a semi-solid matrix. The driving force for cracks propagation located in the grain boundaries, a concentration gradient of carbon content may develop across the crack boundaries induced by deformation behaviors.

Due to the concentration gradient of carbon content, the initial premiere cracks might nucleate from one grain bound-

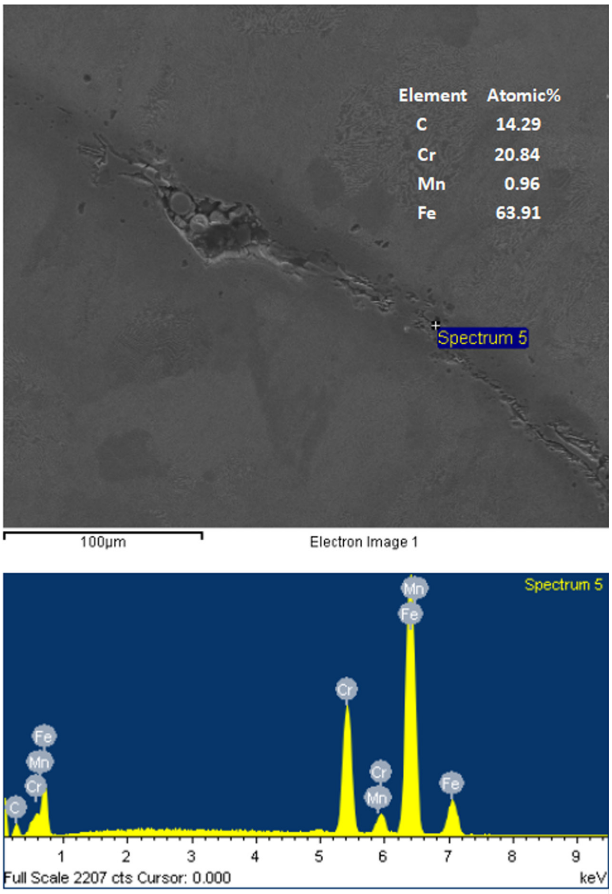

Fig. 9. SEM/EDS results for points in internal cracking along the grain boundaries

ary to other grain boundaries. The transformation of carbon atoms is accompanied by the formation of internal cracking, and a concentration gradient of chromium content may develop across the grain boundaries induced by deformation behaviors. When the composition of residual liquid steel reached eutectic point during solidification of liquid steel, primary carbides precipitated along preexisted austenite. Due to the elastic distortions resulting from the deformation behaviors, the nucleation barrier of carbides could be reduced in the vicinity of already existing cracks, leading to some typical rows of carbides. Therefore, controlling the number and the size distribution of these internal cracks is a key issue to decrease the driving force for carbides precipitation in the continuous casting steels.

3.3. Corresponding segregated band in wire rods induced by internal cracking in blooms

The quality of continuous casting blooms has a hereditary effect on the properties of finished hot-rolled wire rods obtained from them. With respect to deformation behaviors of soft reduction, a number of cracks have generated at the grain boundaries and promoted coarse carbides formation. We have researched the specimens of hot-rolled wire rod from selected continuous casting blooms with internal cracking. The presence of internal cracking with coarse carbides in the blooms creates a high degree of non-uniformity, this article examines the hereditary effect of microscopic dendritic segregation in the continuous casting

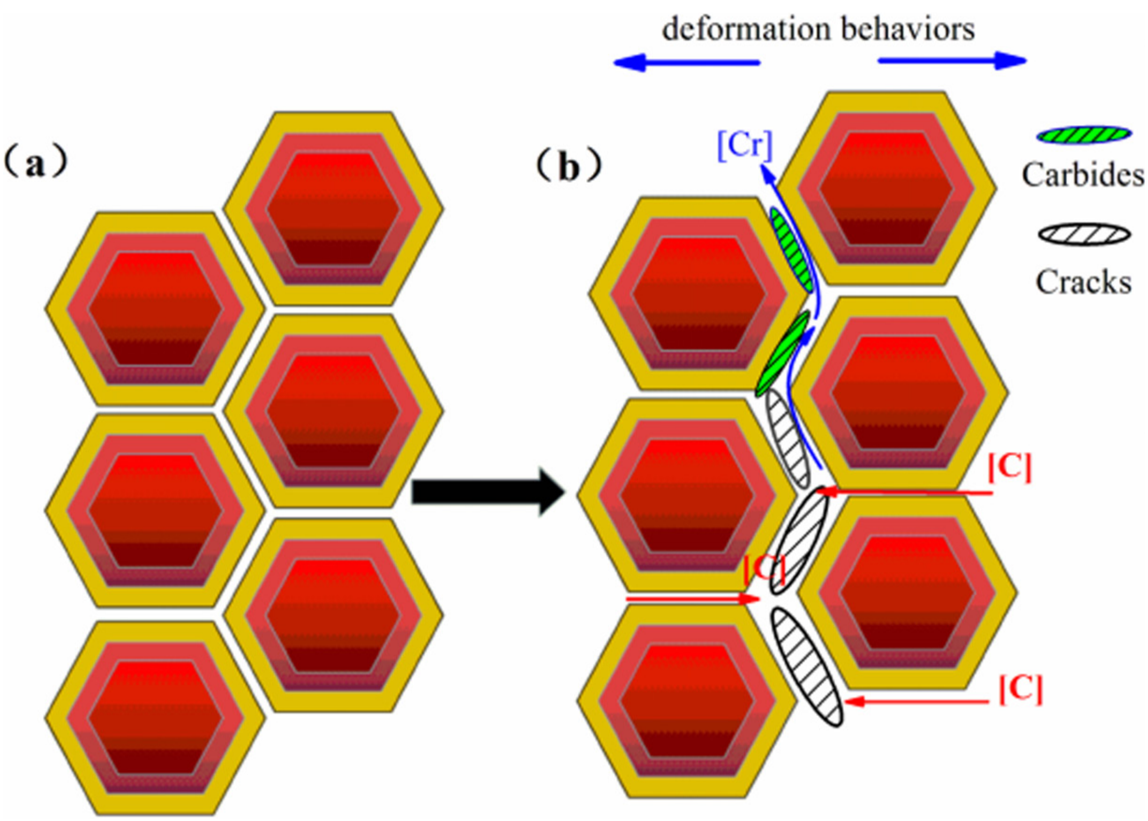

Fig. 10. Schematic diagram for the internal cracking on carbide formation induced by deformation behaviors: (a) Interdendritic feeding; (b) Interdendritic separation

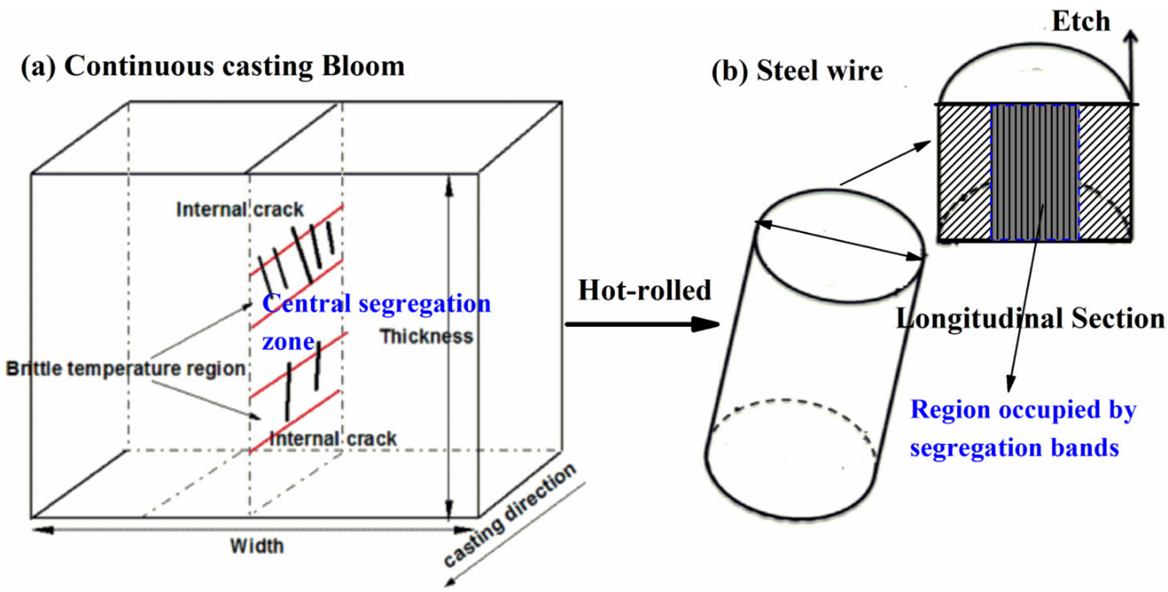

Fig. 11. Schematic diagram of the segregation zones: a) continuous casting bloom; b) hot-rolled wire rod

blooms on the segregated band and their distribution over the cross section in wire rods. Fig. 11 shows the schematic diagram of the segregation zones. The longitudinal sections of the hot-rolled wire rods were selected to observe the morphology of the segregated band.

The effect of the inherited macrostructure of the continuously casting blooms on the presence and location of segregated bands in the hot-rolled wire rods was examined in central longitudinal sections of the hot-rolled wire rod using the schemes depicted in Fig. 11. Segregation defects mainly exist in the center equiaxed area of continuously casting blooms. In addition, more coarse carbides are also precipitated along the grain boundary in internal cracking zone.

The most intensive segregation processes are located in both the center equiaxed zone and the internal cracking zone. The severe segregation of C, Mn, and Cr in the segregated bands is in accordance with that in the segregation behaviors in the continuously casting blooms. Therefore, internal cracking in continuously casting blooms induced by soft reduction are investigated to elucidate their effect on the segregated bands in the hot-rolled wire rods. Distribution of segregated bands in the steel wire rods are shown in Fig. 12, the severe segregated bands are located at the central segregation zone in the longitudinal sections of the wire rod (Fig. 12(b)), which is caused by the degree of the central segregation zone. In addition, a high tendency of severe segregated bands forms exclusively in the midway region between the center and surface of wire rod, as shown in Fig. 12(a). The distribution of segregated bands in the longitudinal sections of the wire rod confirms that the formation of the segregated bands is in accordance with the internal cracking zone of the specimen.

According to the experimental results, it is necessary to control the degree of the internal cracking in as-cast products to suppress the formation of the segregated bands in hot-rolled wire rods. Therefore, the longitudinal section in wire rod is mainly affected by segregation in the center equiaxed zone and internal cracking zone of continuously casting blooms.

This internal quality defect brings many adverse effects on mechanical properties of the final products. In order to significantly improve the internal quality and the product efficiency, optimization of soft reduction process aims to effectively decrease the risk of internal cracks, low cost and efficient heat treatment technology are the suitable solutions for minimizing these harm.

4. Conclusions

Plant trials and laboratory experiments are conducted to elucidate the effects of the internal cracking on carbide precipitation in as-cast blooms induced by soft reduction and the resulting segregated band in hot-rolled wire rods, the major conclusions in this paper are listed as follows:

1) Most of carbides precipitation randomly distributed in the vicinity of existing internal cracks, which is often located midway between the surface and centreline of the bloom. Internal cracking surrounding primary carbides is closely related to the the displacement induced by deformation.
2) Deformation of continuous casting bloom leads to an increase of migrations, linearity and sensibility to grain boundaries within the brittle temperature region, which also indicates an increase tendency to internal crack. The liquid films of eutectic carbides, which strongly reduces the dendrite coherence, exist between the dendrites and spread out over the grain boundary surface. Carbides easily nucleate along dislocations due to the nucleation barrier could be reduced in the vicinity of already existing carbides.
3) The growth of primary carbides surrounding the internal cracking are based on the chemical driving force and high density precipitate zones have been clarified in continuous casting bloom induced by soft reduction.

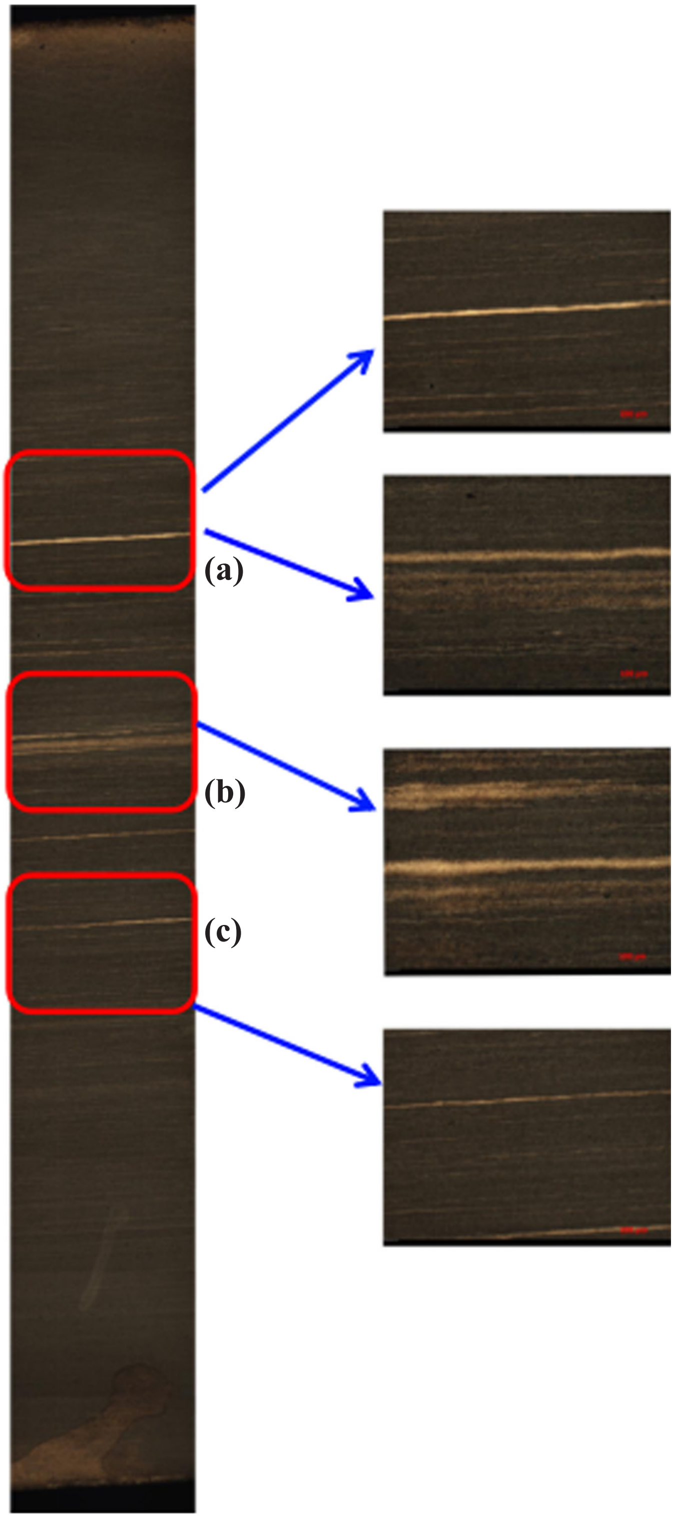

Fig. 12. Distribution of segregated bands in the steel wire rods: a) near the inner wall; b) the center area; c) near the external wall

4) Internal cracking surrounding primary carbides in high carbon steel as-cast blooms influences the resulting segregated band in hot-rolled wire rods. Both the number and the width of the segregated bands increase with the internal cracking surrounding primary carbides in as-cast blooms.

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