Alleviation of internal cracks in continuous casting bloom of steel 100Cr6 induced by soft reduction process

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To comprehensively investigate the formation mechanism and alleviation technology of internal cracks in steel 100Cr6 during the soft reduction process, a three-dimensional mechanical model has been developed to obtain equivalent strain of as-cast bloom under different reduction amount and reduction position. The specific relationship between area of cracking zone, centre solid fraction and maximum equivalent strain of cracking zone has been researched under a number of withdrawal units. In the present work, a novel soft reduction technology for eliminating internal cracks, center shrinkage cavities and center segregation of as-cast bloom has been designed, which aims to provide theoretical basis for improving the internal quality of steel 100Cr6. According to the results of optimum designed experiments, the internal cracks were effectively alleviated and center shrinkage cavities were nearly eliminated. In addition, the center segregation generated by the optimum designed experiments of steel 100Cr6 was remarkably improved in comparison with that induced by the conventional soft reduction process.

PAROLE CHIAVE: INTERNAL CRACKS, CENTER SEGREGATION, CENTER SHRINKAGE CAVITIES, SOFT REDUCTION TECHNOLOGY.

INTRODUCTION

High carbon chromium bearing steel 100Cr6 according to EN ISO 683-17, has been widely used for severe working conditions of bearings in engineering system[1]. A lot of effort has been devoted to research the cleanliness in the composition, size, and distribution of inclusions in steels[2-3], and shrinkage cavities and center segregation are also main defects forming at the center position of blooms during continuous casting process[4-5]. To satisfy these needs of engineering application, the internal crack, center segregation and shrinkage cavities of as-cast blooms should be simultaneously eliminated during the soft reduction process. Soft reduction technology has the capacity to alleviate center segregation and shrinkage cavities in many industrial applications, however, internal cracks are always formed in the internal region of as-cast bloom induced by many reduction technologies[6-9].

The compression deformation induced by soft reduction process is inevitably located in the brittleness temperature range of as-cast bloom[4], especially for the large-section size bloom. Seol et al.[10] have reported that the brittleness

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temperature range of steels can be characterized by the zero strength temperature (ZST) and zero ductility temperature (ZDT), the boundaries of ZST and ZDT corresponded to the solid fractions of 0.75 and 0.99, respectively. Wang et al.[11] have analyzed the internal cracks of as-cast bloom induced by soft reduction process, the results have shown that the internal cracks mainly originated from the internal area of the brittleness temperature range. The maximal stress and strain have been calculated to investigate the formation of internal cracks of as-cast blooms.[12] However, the former researchers have done the research on formation and alleviation of center segregation and shrinkage cavities of as-cast bloom respectively, and seldom learned it from the control perspective of internal cracks. Given the high quality demand of steel 100Cr6 has attracted some industries and researchers' attention, many investigations have been urgently needed to simultaneously alleviate center segregation and shrinkage cavities without internal cracks in as-cast blooms with soft reduction technologies. In the present work, a novel soft reduction technology designed for eliminating internal cracks, center shrinkage cavities and center segregation of as-cast blooms, which aims to provide theoretical basis for improving the internal quality of steel 100Cr6.

MODEL DESCRIPTION AND ANALYSIS OF AS-CAST BLOOM INDUCED BY SOFT REDUCTION PROCESS

A three-dimensional mechanical model

A finite element model of as-cast bloom induced by mechanical soft reduction (MSR) has been developed to calculate the strain distribution using the software ABAQUS®. Figure 1 shows the three-dimensional mechanical model, which is a 3-strand straight-arc rectangular bloom continuous casting machine with a section size of 280 mmx325 mm, and its casting speed of as-cast bloom is 0.70 m/min. The MSR is carried out by seven pair of withdrawal units, which are located between 16.19 and 24.49 m of the distance from the meniscus. All withdrawal and straightening units with a pair of 450 mm diameter rolls, were located in the air-cooling zone, and reduction roll gap and rotation speed of each unit could be adjusted by the corresponding hydraulic cylinder and driving motors respectively during the implementation of MSR. Temperature distribution of as-cast bloom has been calculated firstly[6-7,9], which was transferred to as-cast bloom as the initial temperature field in this finite element model.

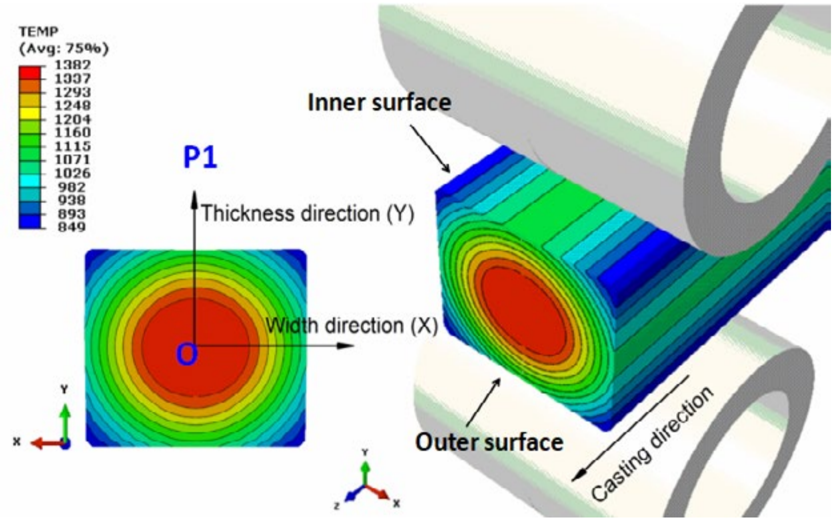

Fig.1 - Deformation finite element model.

In addition, a kind of high carbon chromium bearing steel, 100Cr6 according to EN ISO 683-17, was taken as the research steel grade. Related thermal material properties of material, such as the density, conductivity and enthalpy, can be found in the authors' previous work[6-7,13], and more detailed parameters about steel 100Cr6 can be found in the other previous work[9,14]. Furthermore, Arrhenius-type constitutive equation, which was derived from true stress-strain curves under different strain rates, has been taken in this research to describe the flow behavior of steel 100Cr6 induced by MSR[15].

TEMPERATURE DISTRIBUTION AND CRACKING ZONE OF AS-CAST BLOOM INDUCED BY SOFT REDUCTION PROCESS

All internal cracks of as-cast bloom are generated in the cracking zone, and propagate along the following soft reduction process. Figure 2 shows the temperature distribution and cracking zone under different reduction position, the cracking zone of as-cast bloom is defined as the temperature range between ZST and ZDT[10]. The characteristic point temperature of bloom narrow surface center was measured by a thermal infrared camera at different strand positions. Figure 3 shows the comparison between the measured temperature and the corresponding calculated results.

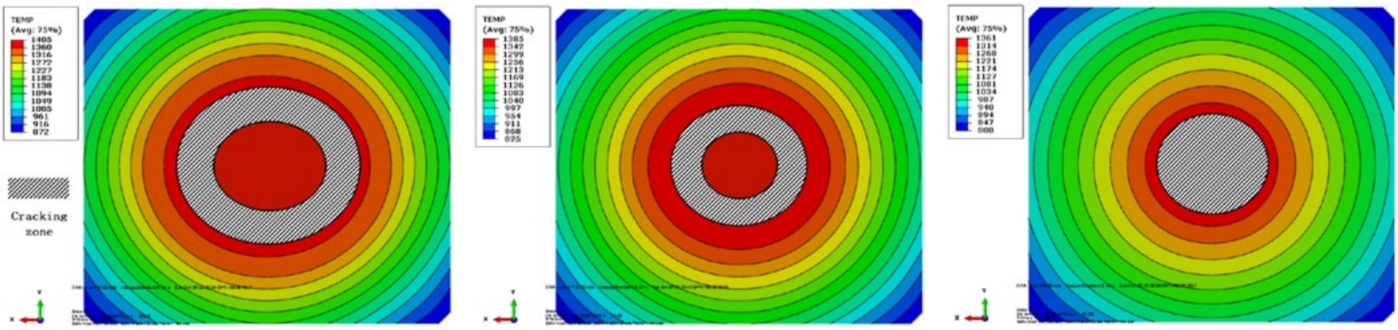

Fig.2 - Temperature distribution and cracking zone under different reduction position.
a) Centre solid fraction 0.55 - b) Centre solid fraction 0.66 -c) Centre solid fraction 0.79

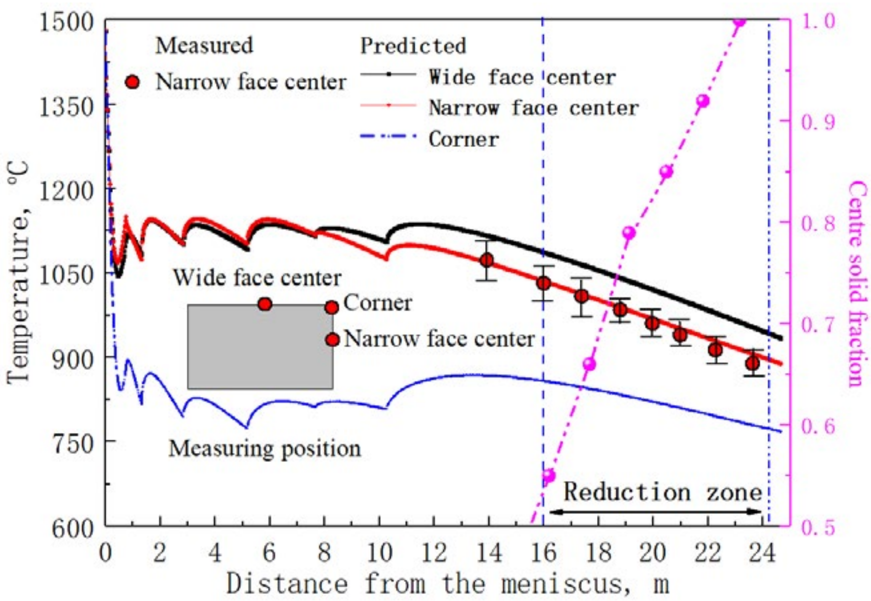

Fig.3 - Comparison between the calculated and the measured temperature of the bloom narrow surface center.

The temperature distribution of as-cast bloom has been calculated to determine the cracking zone as the centre solid fraction increases from 0.55 to 0.79.

RESULTS AND DISCUSSION

Internal cracks of steel 100Cr6 have been developed by deformation finite element model to obtain equivalent strain of as-cast bloom under different reduction amount and reduction position. According to the relationship between area of cracking zone, centre solid fraction and maximum equivalent strain of cracking zone, a novel soft reduction technology designed for eliminating internal cracks, center shrinkage cavities and center segregation of as-cast blooms, which aims to provide theoretical basis for improving the internal quality of steel 100Cr6.

EQUIVALENT STRAIN OF AS-CAST BLOOM UNDER DIFFERENT REDUCTION AMOUNT

Figures 4, 5 and 6 have shown the equivalent strain of as-cast bloom under the centre solid fraction of 0.55, 0.66 and 0.79 respectively. Temperature data of bloom center slowly decreased in the reduction zone of as-cast bloom because of the released latent heat from the mushy region during the continuous casting process.

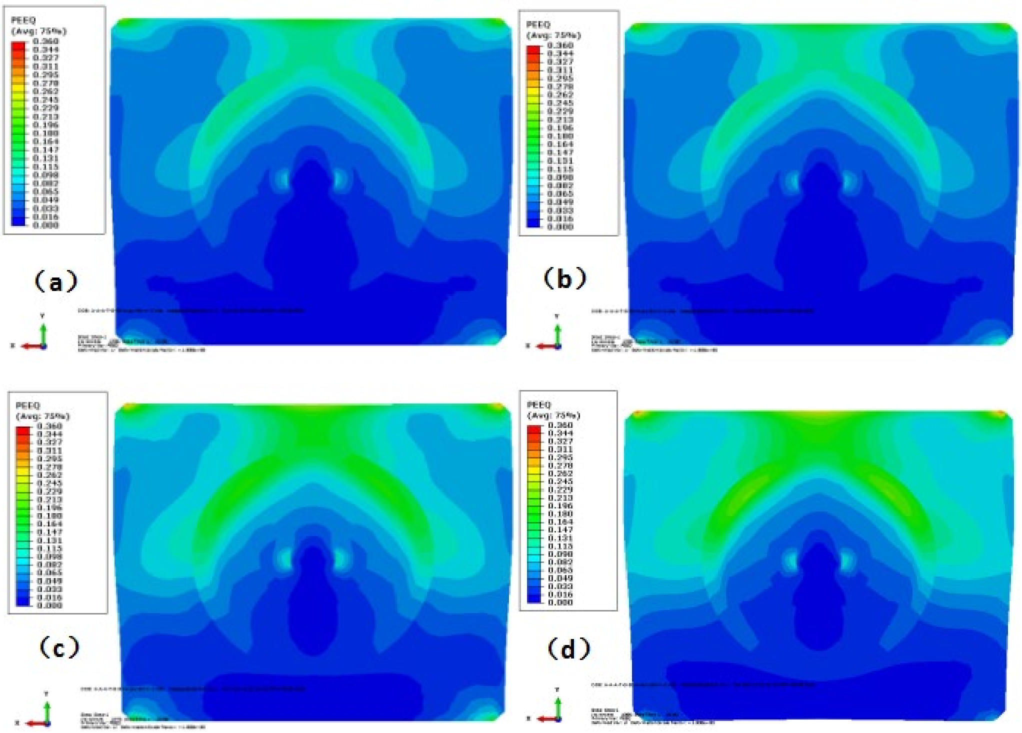

Fig.4 - Equivalent strain of as-cast bloom under different reduction amount (centre solid fraction 0.55): (a) 4mm; (b) 6mm; (c) 8mm; (d) 10mm.

To clarify the deformation difference between as-cast bloom surface corner and its center, equivalent strain of as-cast bloom implemented at different bloom positions was simulated under different reduction amount. The equivalent strain along the bloom thickness direction was a uniform distribution, the variation of the equivalent strain at the bloom inner region was obviously larger than that at location of the bloom outer region.

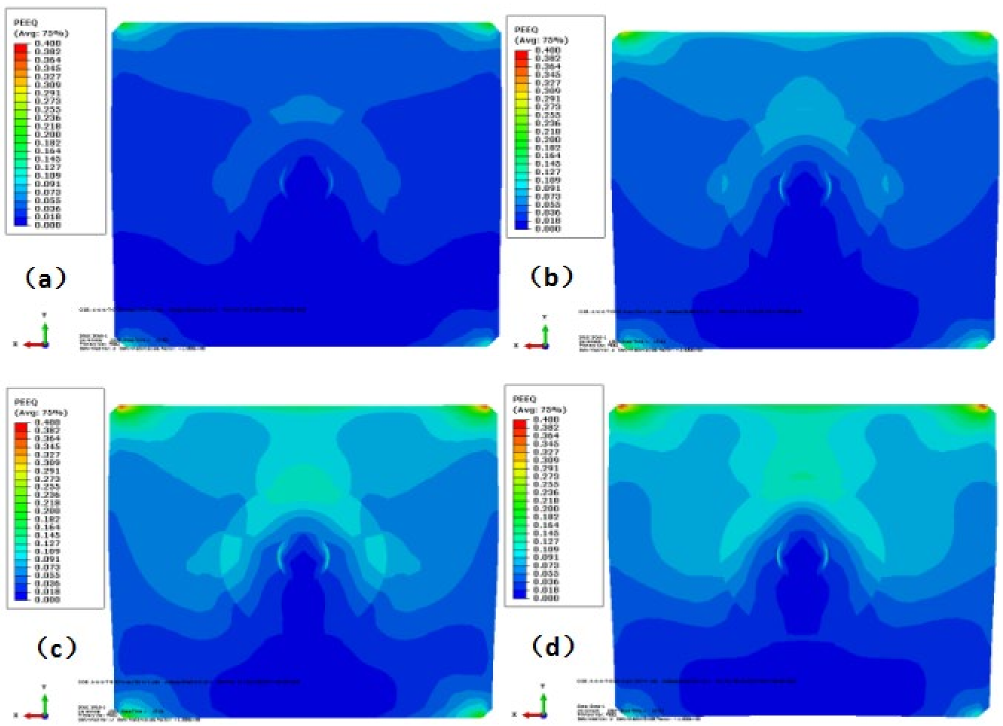

Fig.5 - Equivalent strain of as-cast bloom under different reduction amount (centre solid fraction 0.66): (a) 4mm; (b) 6mm; (c) 8mm; (d) 10mm.

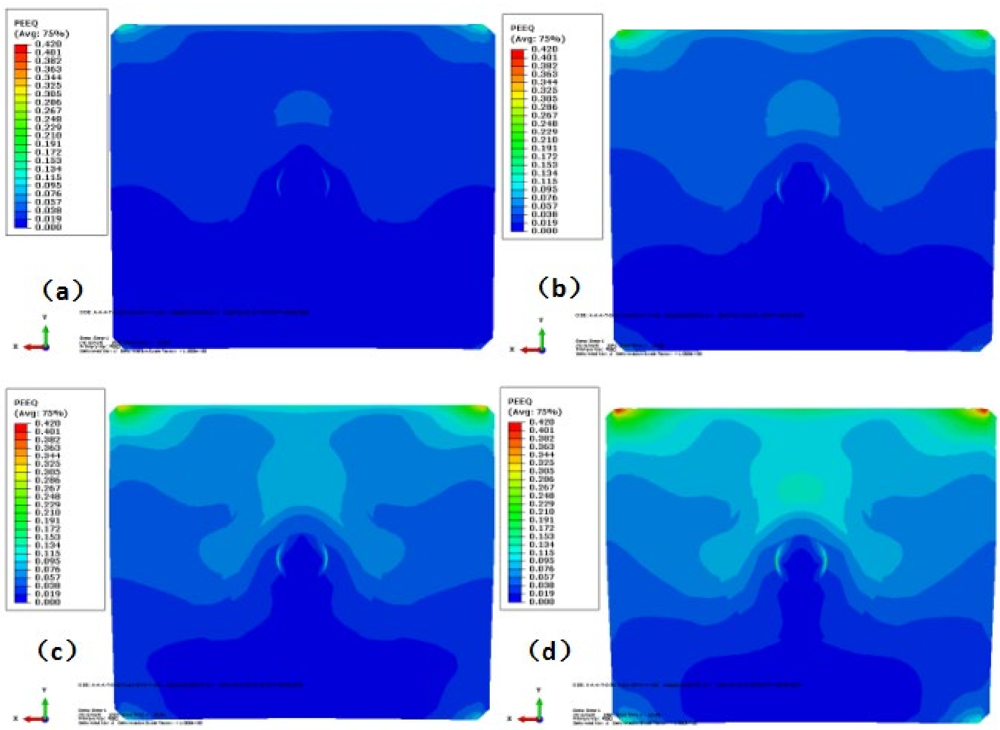

Fig. 6 - Equivalent strain of as-cast bloom under different reduction amount (centre solid fraction 0.79): (a) 4mm; (b) 6mm; (c) 8mm; (d) 10mm.

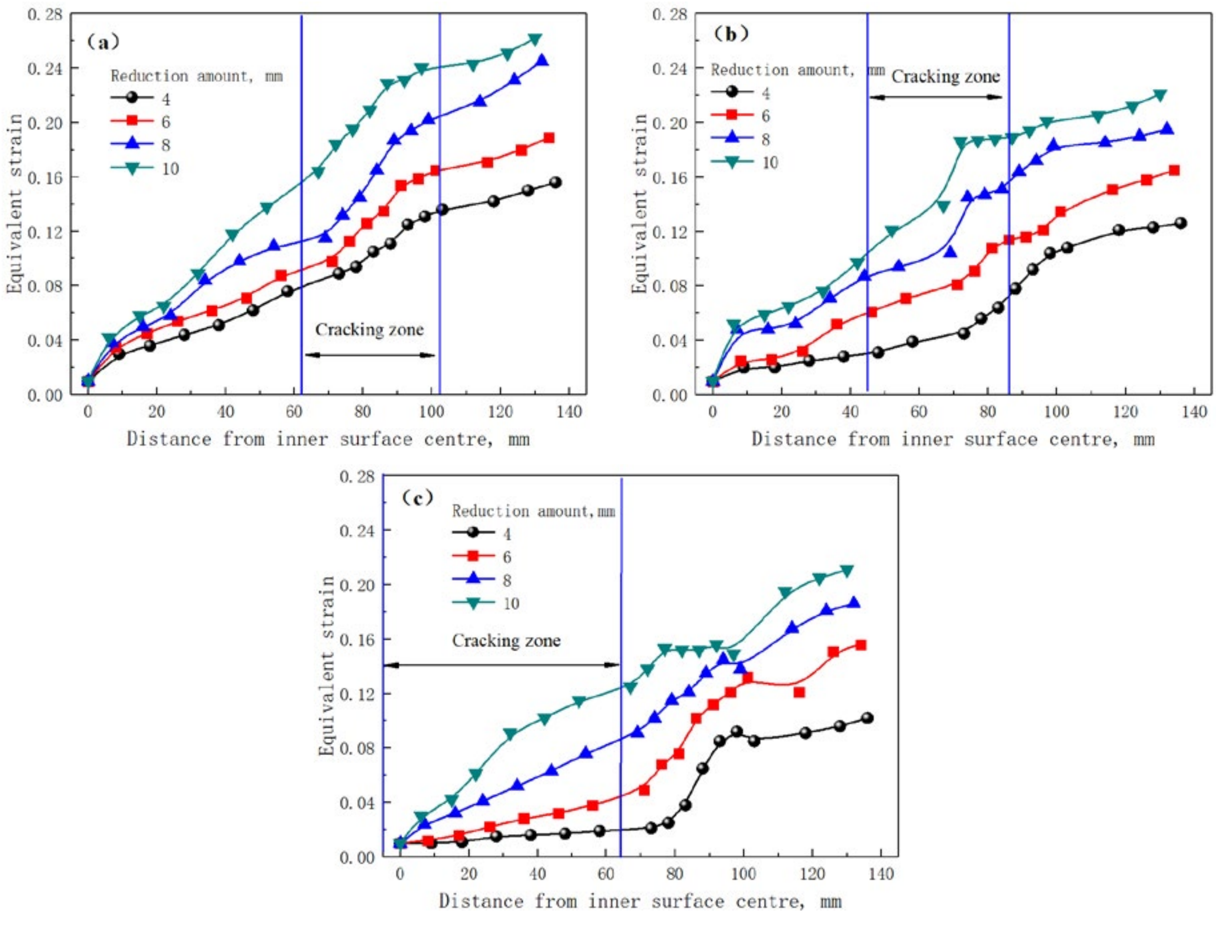

Fig. 7 - Equivalent strain distribution for cracking zone in the inner transverse section of the bloom: (a) centre solid fraction 0.55; (b) centre solid fraction 0.66; (c)centre solid fraction 0.79.

The bloom temperature difference along the bloom cross section can effectively promote the transfer of reduction deformation from the bloom surface into its internal region. Equivalent strain distribution for cracking zone in the inner transverse section of the bloom for different centre solid fraction of as-cast bloom has been shown in Figure 7, the equivalent strain difference between the bloom inner surface and its center gradually increased with the increase of reduction amount under the same centre solid fraction of as-cast bloom. However, the equivalent strain between the bloom inner surface and its center gradually decreased with the increase of centre solid fraction of as-cast bloom under the same reduction amount, and the equivalent strain in the bloom internal region also had a similar declining trend.

RELATIONSHIP BETWEEN AREA OF CRACKING ZONE, CENTRE SOLID FRACTION AND MAXIMUM EQUIVALENT STRAIN OF CRACKING ZONE

The internal cracks is hardly to prejudge and control in the actual production process of as-cast bloom induced by soft reduction process. Therefore, most scholars have taken the equivalent strain to analyze and estimate the internal cracks of as-cast bloom. When the equivalent strain is larger than the critical strain, internal cracks will be generated, the critical strain of steel 100Cr6 was taken as 0.015[16], and its deformation strain rate is from 10^{-2} to $10^{-4}s^{-1}$. Influence of reduction amount and reduction zone on the maximum equivalent strain of cracking zone has been shown in in Figure 8. When the total strain exceeds the critical strain, the internal cracks are formed between the columnar crystals and located midway between the surface and centre of as-cast bloom.

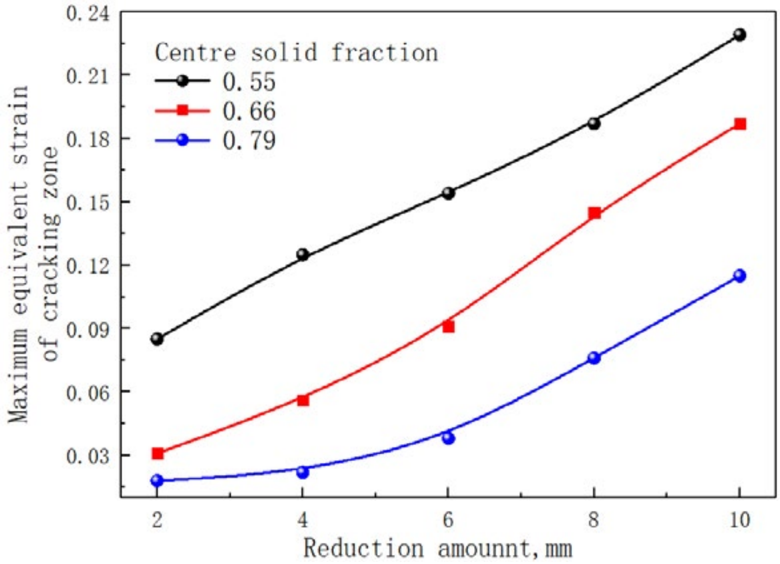

Fig. 8 - Influence of reduction amount and reduction zone on the maximum equivalent strain of cracking zone.

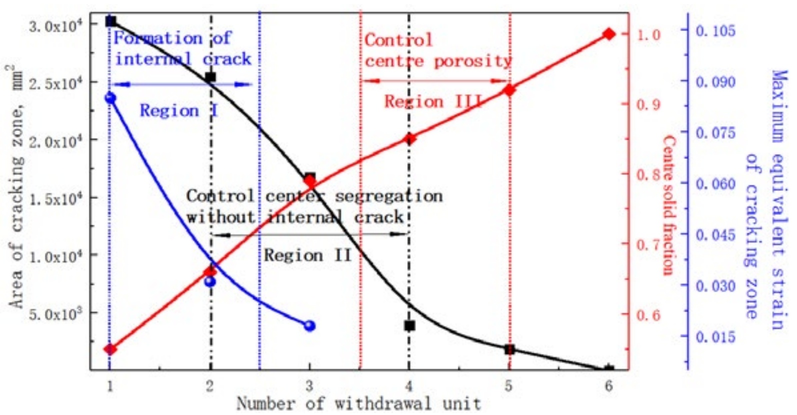

Fig. 9 - Area of cracking zone, centre solid fraction and maximum equivalent strain in cracking zone under a number of withdrawal units.

When the centre solid fraction of as-cast bloom reaches 0.79, internal brittleness temperature range is disappeared and the equivalent strain is smaller than the critical strain when the reduction amount is less then 5mm. The relationship between cracking zone area, centre solid fraction and maximum equivalent strain in cracking zone has been established under a number of withdrawal units, as shown in Figure 9. Although the internal cracks can been effectively alleviated as the increase of centre solid fraction, a deformation implemented in the mushy region for simultaneously improving the center segregation and center shrinkage cavities. In the present work, withdrawal unit was mainly implemented for improving the center shrinkage cavities when center solid fraction of as-cast bloom reached 0.9. Therefore, a novel soft reduction technology for eliminating internal cracks, center shrinkage cavities and center segregation of as-cast bloom has been designed, which aims to provide theoretical basis for improving the internal quality of steel 100Cr6. In the control stage of center segregation, the reduction amount was enhanced to improve the homogeneity of as-cast bloom (withdrawal units 2#, 3# and 4#) without forming of internal crack. In the control stage of center shrinkage cavities, the as-cast bloom was compressed to improve the compactness of as-cast bloom (withdrawal unit 5#).

OPTIMUM DESIGNED EXPERIMENTS OF STEEL 100CR6 INDUCED BY SOFT REDUCTION PROCESS

According to the above simulated results and theoretical analysis, optimum designed experiments of steel 100Cr6 are shown in Table 1. Shrinkage cavities and center segregation are mainly forming at the center position of blooms. Due to the symmetry of the as-cast bloom along its width direction, the longitudinal morphologies of as-cast bloom are taken to validate the designed experiment cases, as shown in Figure 10.

Tab.1 - Optimum designed experiment case.

No.Cases	No. withdrawal machines					
	M1	M2	M3	M4	M5	M6
	Centre solid fraction					
	0.55	0.66	0.79	0.85	0.92	1.00
	Reduction of MSR (mm)					
Case 1	4.0	3.5	3.0	2.0	0.0	0.0
Case 2	1.5	2.0	3.0	2.0	0.0	0.0
Case 3	0.0	2.5	5.0	4.0	2.0	0.0

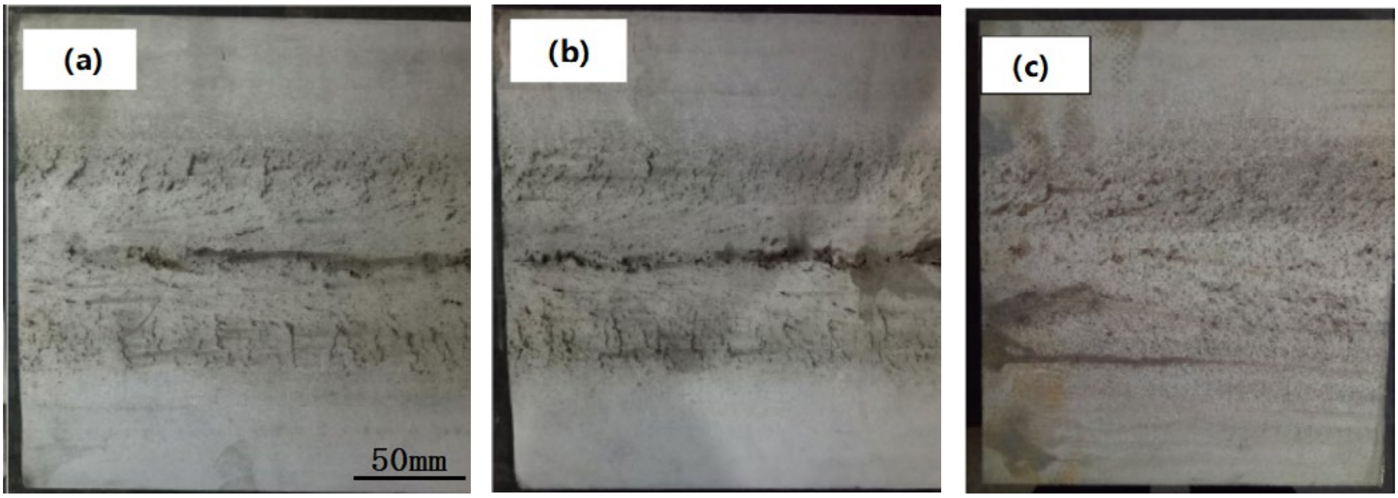

Fig.10 - Longitudinal morphologies of as-cast bloom under designed experiment cases: (a) case 1; (b) case 2; (c) case 3.

A great quantity of internal cracks and large centre shrinkage cavity are obviously observed in the longitudinal section of as-cast bloom for case 1, these internal cracks are located midway between the surface and centreline of the as-cast bloom, and the internal cracks in the inner transverse section are serious and intensive than that in the outer transverse section of as-cast bloom. In order to weaken the internal crack, the reduction amount of reduction roll is both decreased for withdrawal unit 1# and 2#. However, the internal cracks are also clearly observed under the application of case 2, and the center shrinkage cavities are also located in the centerline of as-cast bloom.

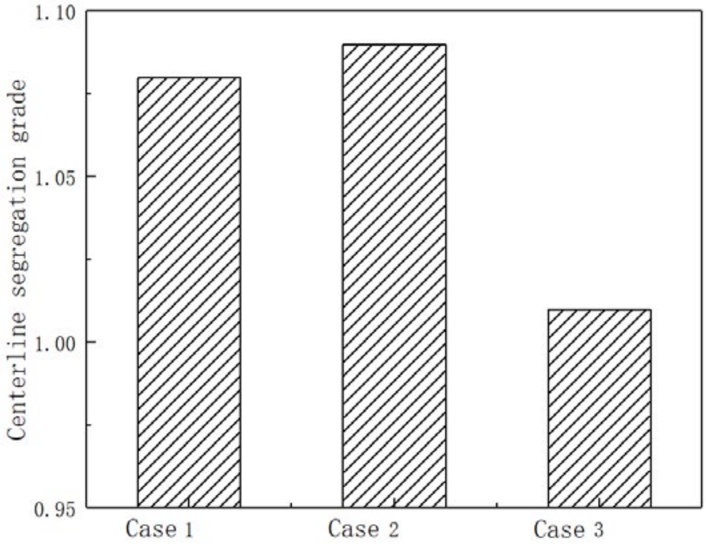

Fig.11 - Effect of designed experiment cases on centerline segregation grade.

The maximum equivalent strain in the cracking zone for withdrawal unit 1# is more larger than the critical strain, therefore withdrawal unit 1# should be avoid to make reduction operation. Case 3 is a novel soft reduction technology, withdrawal units 2#, 3# and 4# are taken to control center segregation without internal crack, and withdrawal unit 5# is added to control center shrinkage cavities. The longitudinal morphologies of as-cast bloom indicated the internal crack and center shrinkage cavities can both be eliminated under case 3 as compared with case 1 and case 2. Figure 8 shows the effect of designed experiment cases on centerline segregation grade. The prepared drill samples were analyzed using the carbon-sulphur analyser, and the solute segregation ratio was calculated by taking the solute content at each location divided by the ladle composition. Although the total reduction amount of case 1 is 4mm larger than that of case 2, the centerline segregation grade difference is small. In addition, the center segregation generated by the optimum designed experiments of case 3 was remarkably improved in comparison with that induced by the conventional soft reduction process. According to the results of optimum designed experiments, the internal cracks were effectively alleviated and center shrinkage cavities were nearly eliminated.

CONCLUSIONS

Comparative analysis of theoretical model and industrial experimental results, the formation mechanism and alleviation technology of internal cracks in steel 100Cr6 have been researched during the soft reduction process, the major conclusions are listed as follows:

(1) To comprehensively investigate the internal cracks in as-cast bloom during the soft reductions, the specific relationship between area of cracking zone, centre solid fraction and maximum equivalent strain of cracking zone has been researched under a number of withdrawal units.

(2) A novel soft reduction technology for eliminating internal cracks, center shrinkage cavities and center segregation of as-cast bloom has been designed, which aims to provide theoretical basis for improving the internal quality of steel 100Cr6. In the control stage of center segregation, the reduction amount was enhanced to improve the homogeneity of as-cast bloom without forming of internal crack. In the control stage of center shrinkage cavities, the as-cast bloom was compressed to improve the compactness of as-cast bloom.

(3) According to the results of optimum designed experiments, the internal cracks were effectively alleviated and center shrinkage cavities were nearly eliminated. In addition, the center segregation generated by the optimum designed experiments of steel 100Cr6 was remarkably improved in comparison with that induced by the conventional soft reduction process.

Acknowledgments

The present work is financially supported by The National Key Research and Development Program of China No. 2017YFB1103700. The authors are also grateful to Dr. Zhifang Lu in Xingtai Iron and Steel Corp., Ltd for discussing on the accuracy of strain analysis in as-cast bloom during soft reduction operation.

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