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COMPARATIVE STUDIES ON A CHAMFER TECHNOLOGY AND A CONVEX ROLL TECHNOLOGY DURING THE SOFT REDUCTION PROCESS

To comprehensively investigate the diversity of a chamfer technology and a convex roll technology under the same soft reduction process (i.e., section size, reduction amount, casting speed and solid fraction), a three-dimensional mechanical model was developed to investigate the effect of the chamfer profile and roll surface profile on the deformation behavior, cracking risk, stress concentration and reduction force of as-cast bloom during the soft reduction process. It was found that a chamfer bloom and a convex roll can both avoid the thicker corner of the as-cast bloom solidified shell, and significantly reduce reduction force of the withdrawal and straightening units. The convex profile of roll limits lateral spread along bloom width direction, therefore it forms a greater deformation to the mushy zone of as-cast bloom along the casting direction, the tensile strain in the brittleness temperature range (BTR) can obviously increase to form internal cracks. The chamfer bloom is much more effective in compensating the solidification shrinkage of mushy zone. In addition, chamfer bloom has a significant decrease of tensile strain in the brittleness temperature range (BTR) areas, which is expected to greatly reduce the risk of internal cracks.

Keywords: convex roll technology, chamfer technology, deformation behavior, cracking risk

1. Introduction

High carbon steel, has been widely used in the mechanical industry of automobile and rail transportation, which requires the quality of uniform hardness, high contact fatigue strength and good wearability [1]. Since high carbon content and long solidification time in the solidification process, carbon segregation, central porosity, and crack usually occur in as-cast blooms. Those internal defects bring many adverse effects on the quality of the final products, and should not be effectively eliminated by the subsequent forging or rolling process [2].

Eliminating those internal defects is a key subject of as-cast bloom for ensuring a high quality in various industries. Soft Reduction (SR) technology is an effective method to reduce bloom center segregation and porosity in many industrial practices [3-4]. However, minimizing center segregation and porosity often result in internal crack induced by the soft reduction technique [5]. Therefore, it is of vital importance in the development of new technologies in the soft reduction process by improving internal quality of as-cast bloom steel.

A large amount of researches [6-8] showed the convex roll technology can avoid the low temperature part of bloom side, and reduction deformation concentrates at the bloom centre zone. Ogibayashi [6] demonstrated that center segregation grade of as-cast bloom was improved efficiently by the convex roll compared with that of the flat roll. Chang et al. [7] calculated deformation behavior for as-cast bloom (400 mm×500 mm) during the soft reduction process, the tensile stress in the middle of the bloom was eliminated to reduce the risk of internal cracks. In addition, the present authors [9-10] investigated the chamfer technology of the bloom during the soft reduction process, the stress concentration decreased gradually by adjusting the chamfer design of the bloom. The application of chamfer bloom (280 mm×325 mm) can effectively alleviate the internal defects of as-cast bloom compared with the right-angle bloom, a chamfer technology can decrease the deformation resistance and improve the internal quality of as-cast bloom with both finite element method and performing actual experiment, which can meet deformation resistance requirements without upgrading the hydraulic and mechanical system of withdrawal and straightening machine.

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Although a chamfer technology and a convex roll technology is in favour of improvement of internal defects in as-cast bloom, few researchers have comprehensively studied of a chamfer technology and a convex roll technology during the same soft reduction process (i.e., section size, reduction amount, casting speed and solid fraction). In the present work, the effect of the bloom chamfer profile and the roll surface profile on deformation behavior, cracking risk and reduction force of as-cast bloom during the soft reduction process was investigated with numerical simulation method for the first time, which aims to provide theoretical basis for designing SR and thus effectively improving the internal defects.

2. Model description

2.1. Development of the 3D bloom mechanical model

The temperature distribution of the bloom at the optimum reduction position has been calculated firstly, which was introduced in detail elsewhere [11], then the initial temperature fields were transferred to the 3D mechanical model. If the the optimum reduction position is valid in the 3D mechanical model, the other reduction positions are also valid due to its effectiveness in the end location of solidification stage. Reduction rolls were regarded as discrete rigid bodies without deformation, and the bloom with a cross section of 280 mm×325 mm was regarded as deformable bodies, the casting speed of the bloom was 0.7 m/min during the soft reduction process. In addition, the 3D bloom mechanical models have been developed using the software ABAQUS® under soft reduction conditions (Fig. 1). During the mechanical reduction between the reduction rolls and bloom surface, the friction coefficient was set as 0.3 [12], and the conversion factor of plastic heat generation was adopted as 0.9 [12].

The average chemical composition of the high carbon steel is shown in Table 1, and the melting point of the steel studied is 1425°C. The properties of as-cast bloom, such as density, thermal conductivity, specific heat capacity and thermal expansion coefficient, were taken from our previous papers [9]. In addition, a constitutive equation of high carbon steel [10] was adopted to describe the metal deformation behavior of the as-cast bloom. The applied constitutive equations is suitable to obtain accuracy of mechanical properties based on high temperature intervals in the 3D mechanical model.

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

2.2. Bloom and roll configuration in the soft reduction process

The solidified shell of the as-cast bloom is thicker in the reduction zone, especially for a large section size bloom. Therefore, the withdraw and straightener units of a continuous caster

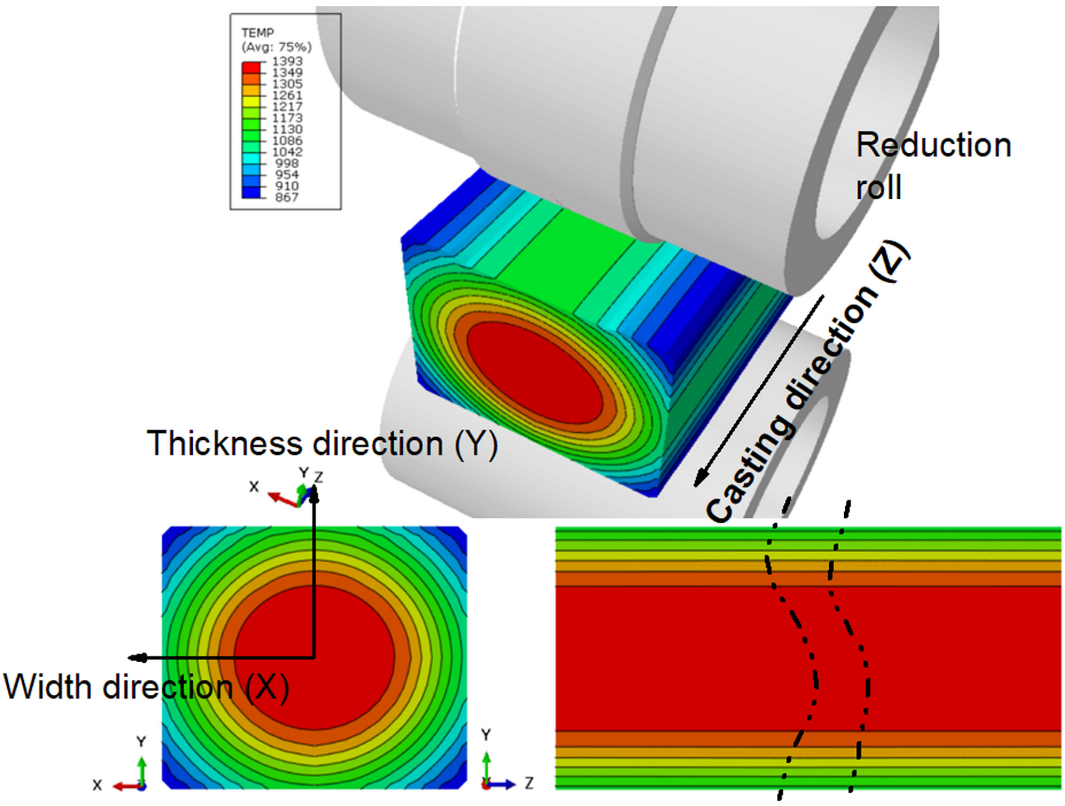

Fig. 1. 3D finite element model and temperature distribution for deformation analysis

required higher reduction capability to conquer the large reduction deformation resistance. The temperature field of the bloom corners can be drastically increased by optimizing the chamfer geometries, and the chamfer bloom has more influence on the deformation and the reduction force. The chamfer geometries of as-cast bloom were performed with different geometric features like the chamfer angle and the chamfer length as illustrated in Fig. 2.

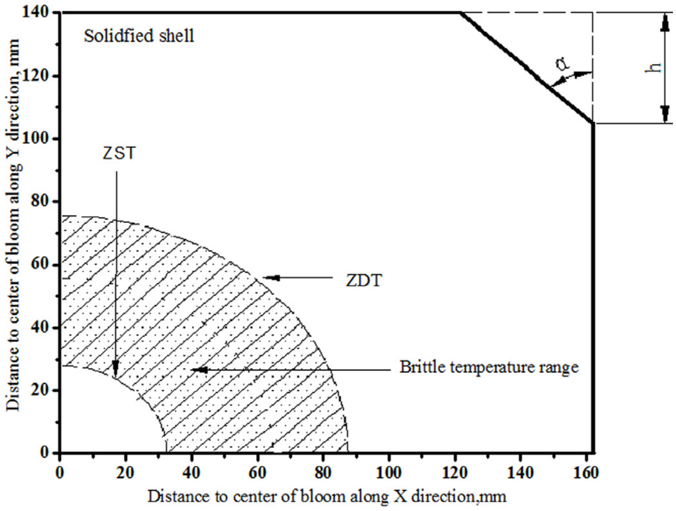

Fig. 2. Section of chamfer bloom during soft reduction

The design approach of convex roll was proposed by Chang et al. with two curved shoulders [7]. The radius of the convex roll and flat roll was both 225 mm, the convex platform region of the convex roll was 192 mm, and the edge region diameter of the convex roll was 420 mm. Right-angle bloom was implemented by flat rolls in case 1 and convex rolls (SR was implemented by one convex roll on the bloom inner side and one flat roll on the outer side) in case 2 as shown in Fig. 3, and chamfer bloom (the chamfer angle (α) is 50°, and the chamfer lengths (h) is 50 mm) was implemented by flat rolls in case 3.

3. Observed internal defects in as-cast bloom

Typical internal defects in a longitudinal cross section of as-cast bloom are shown in Figure 4, which were taken from 280 mm×325 mm rectangular section bloom in the industrial trials. The observed result indicates that a substantial number of large voids and internal cracks were mainly distributed around the bloom internal regions.

In addition, these internal cracks are mainly located midway between the surface and centreline of as-cast bloom, and they are always in close proximity to each other, as shown in Figure 4(a). The substantial number of large size eutectoid carbides around cracks also could be observed in this regions. Carbide distribution of network and banded carbides in hot-rolled rod, which is almost clear relationship of heredity in carbon segregation from as-cast bloom [13-14]. Fig. 5 shows the distribution of eutectoid carbides is consistent with the shape of internal cracks, which could not be easily eliminated in the subsequent hot working process. Therefore, the eutectic carbide has a serious effect on the final product in the subsequent process and the mechanical properties of the products. The internal defects in as-cast bloom are preferred to effectively reduce with meeting the requirement of high-quality final product.

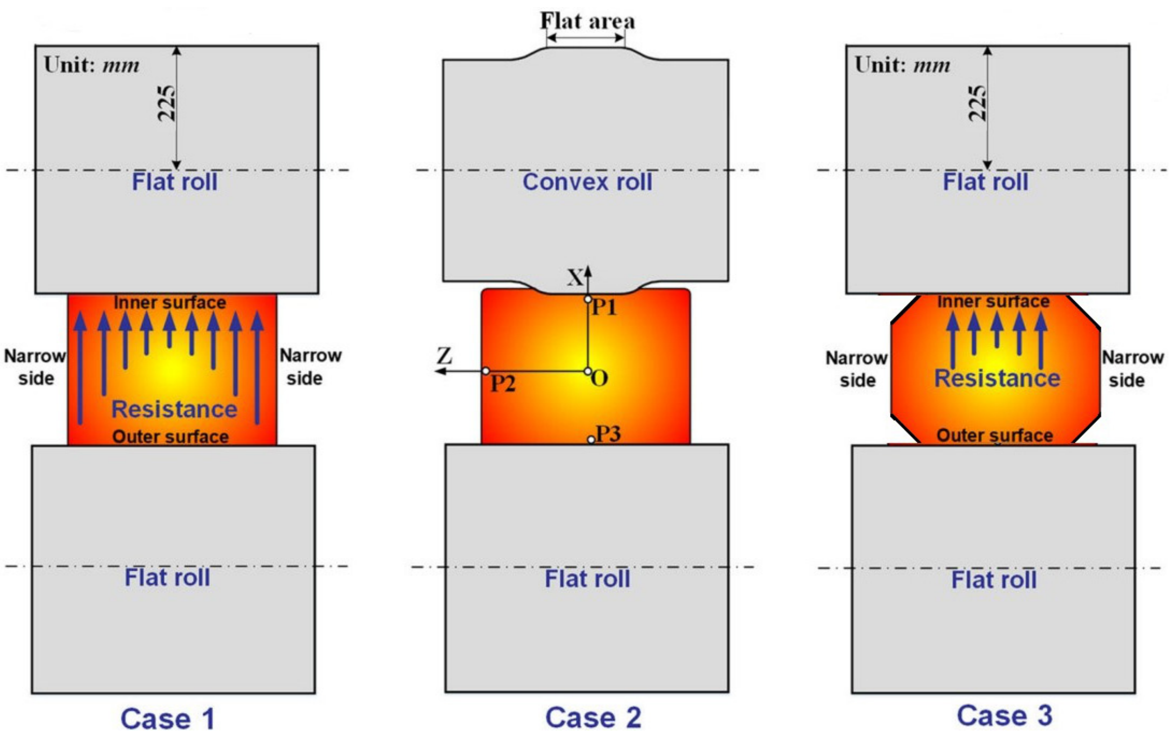

Fig. 3. Schematic of the bloom and roll configuration in three cases

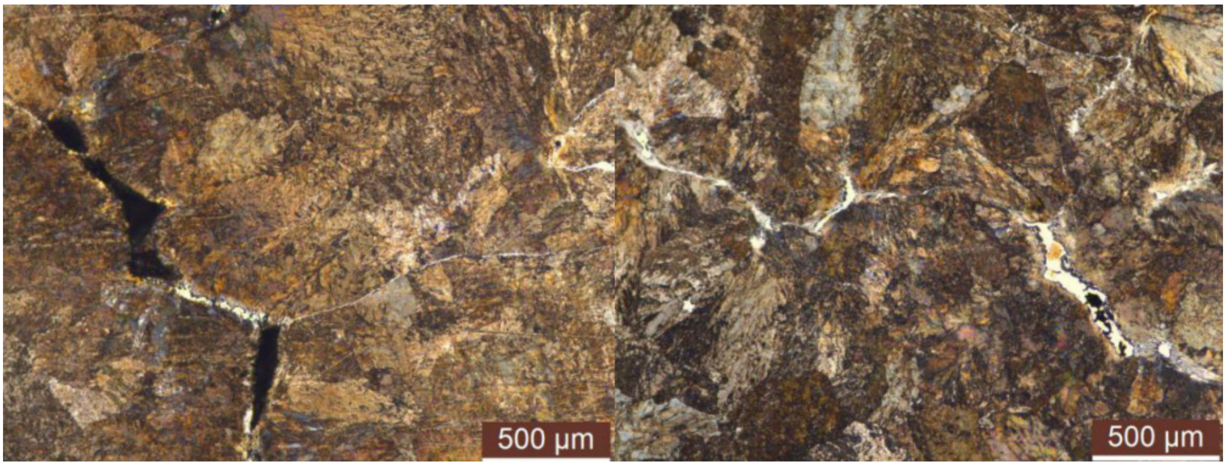

Fig. 4. Macrographs of internal defects in bloom longitudinal section

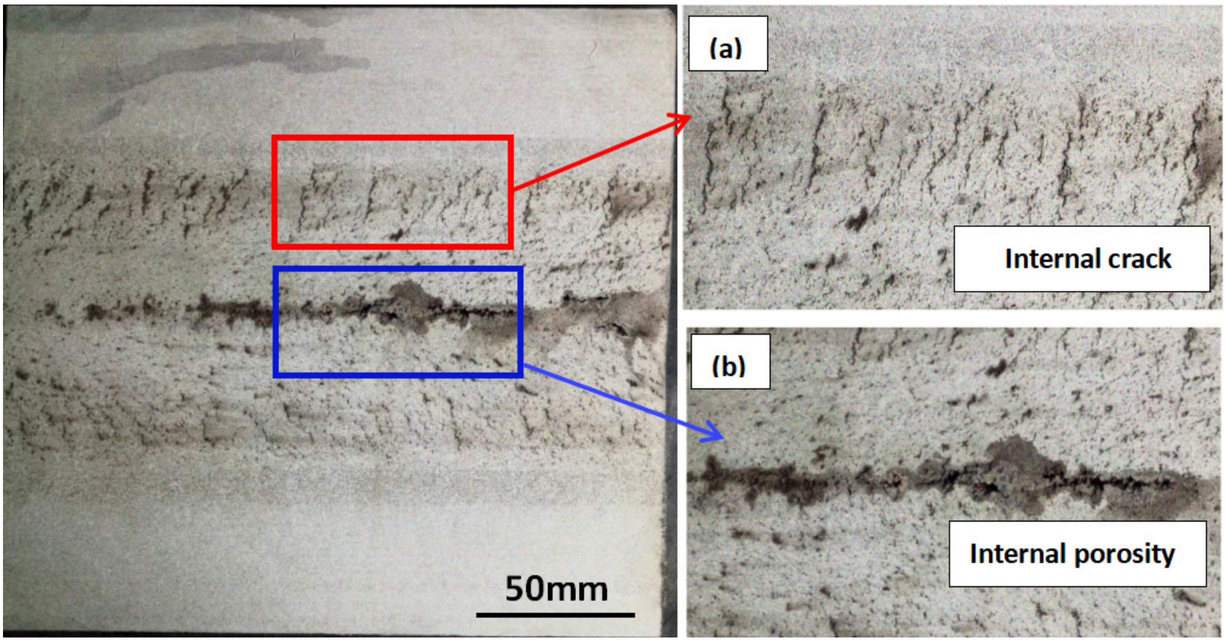

Fig. 5. Morphologies of eutectoid carbides around cracks in as-cast bloom

4. Results and discussion

4.1. Comparison of stress concentration and reduction force under different reduction cases

The corner of the as-cast bloom is solidified completely in the soft reduction region, which provides the large resistance to deformation. The comparison of the temperature distributions on the bloom transverse section is shown in Fig. 6, the lowest temperature is located at the bloom corner for it is cooled both by the wide face and the narrow face, which is more likely to cause stress concentration during the soft reduction.

A chamfer technology can increase the temperature field of the bloom corner significantly. Therefore, a chamfer bloom and a convex roll can both avoid the thicker corner of the as-cast bloom solidified shell, the configurations of the bloom and the roll can affect the contribution of reduction amount.

To clarify the influence of the bloom and roll configuration on the stress concentration in the bloom transverse section, the temperature distribution along the bloom width direction was extracted and compared in Figure 7. In the present work, the three cases (Fig. 3) were calculated under the same operation conditions. The comparison of the stress concentration in the bloom transverse section, as schematically shown in Figure 8, the stress concentration mainly comes from the inner region of the bloom corner sides because of the lower temperature field.

Figure 9 compares the equivalent stress along the bloom inner surface under different reduction conditions, compared with the use of flat rolls and a right angle bloom in case 1, the equivalent stress along the bloom inner surface was both decreased markedly after convex roll and chamfer bloom were used in cases 2 and 3. During the application of SR, the actual reduction force of the withdrawal and straightening units dur-

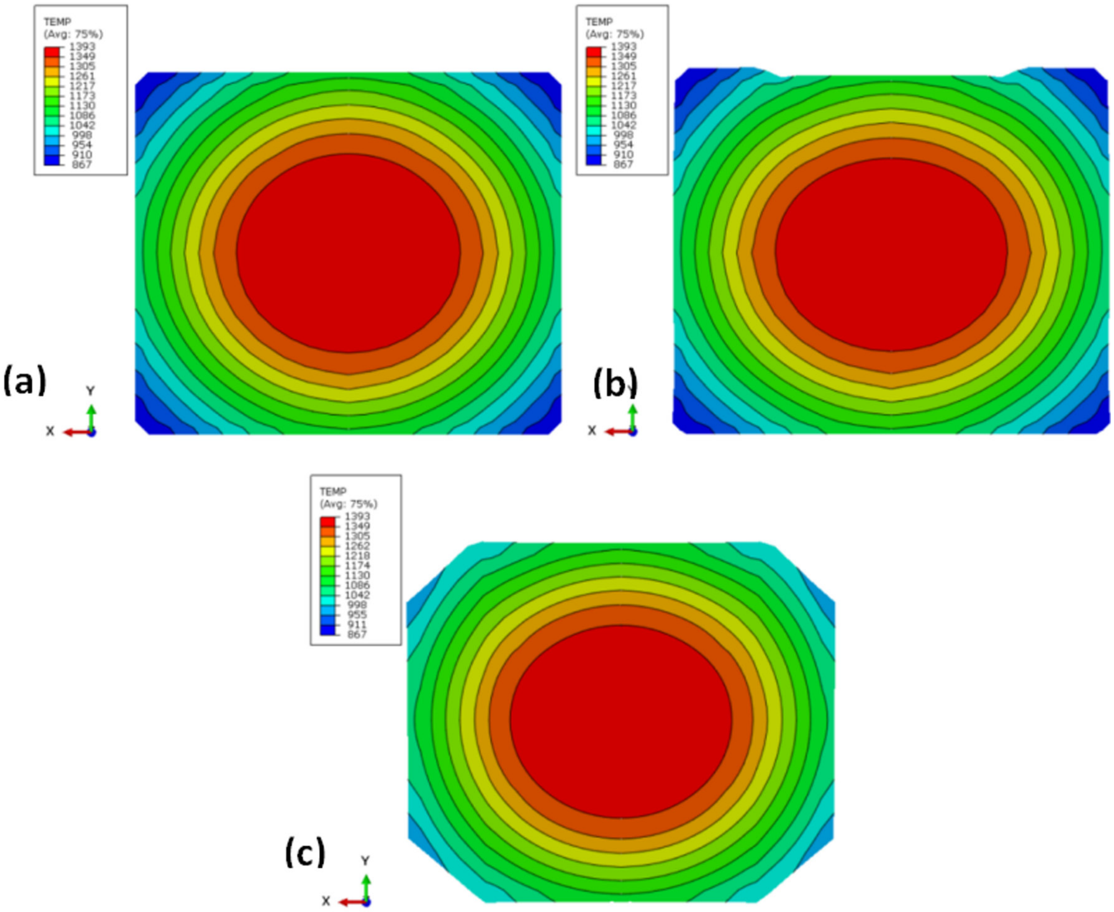

Fig. 6. The comparison of the temperature distributions on the bloom transverse section. (a) Case 1, (b) Case 2 and (c) Case 3

ing soft reduction condition was compared with the calculated reduction force in Figure 10.

The results indicate that the calculated reduction force of the case 1 agrees well with the corresponding measured values. However, reduction forces of the cases 2 and 3 are significantly reduced because of the deformation occurs in the middle high temperature area of the as-cast bloom.

4.2. Comparison of deformation in as-cast bloom under different reduction cases

The deformation behavior of as-cast bloom was systematically studied under different reduction cases. The centerline segregation and central porosity are easily formed by improper deformation in mushy zone, because of main reduction amount is consumed on the deformation of as-cast bloom. The deformation of the as-cast bloom along two axis direction (X and Y axes denote the bloom width direction and bloom thickness direction), was described in Figs. 11 and 14, respectively. To clarify the influence of the different reduction cases on the deformation behavior, the displacement distributions along the bloom thickness direction [from point O to point P1 in Figure 12] and [from point O to point P3 in Figure 13] after the 4 mm reduction amount that were extracted and compared.

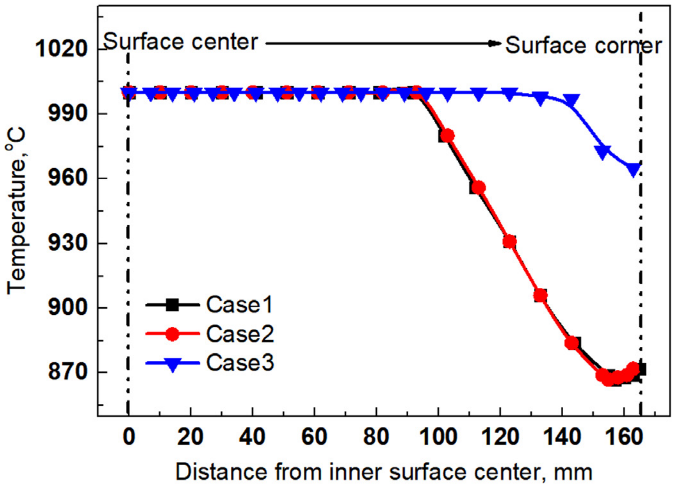

Fig. 7. Distribution of temperature along the bloom inner surface during different reduction conditions

Figs. 12 and 13 show the variation of the solidus line (fs = 1) along the bloom thickness direction (y-axis) under different reduction cases. The displacement of solidus line in the bloom cross section is a negative value, this indicates that the mushy zone is under compression and becomes smaller toward the bloom thickness direction (from point O to point P1). However, the mushy zone becomes larger toward the bloom thickness direction (from

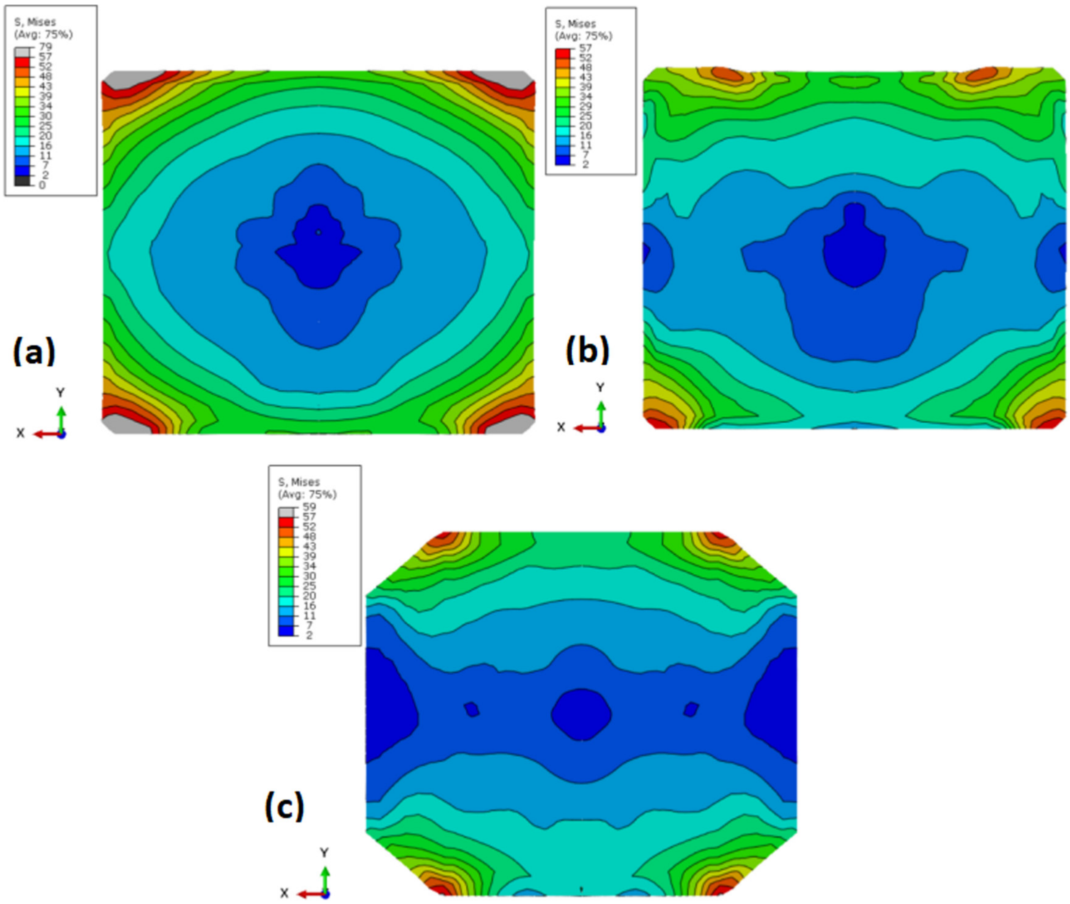

Fig. 8. The comparison of the stress concentration on the bloom transverse section. (a) Case 1, (b) Case 2 and (c) Case 3

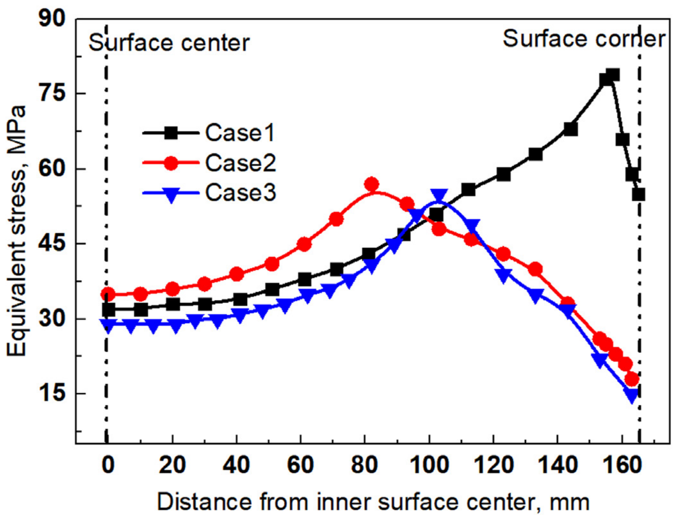

Fig. 9. Distribution of equivalent stress along the bloom inner surface during different reduction conditions

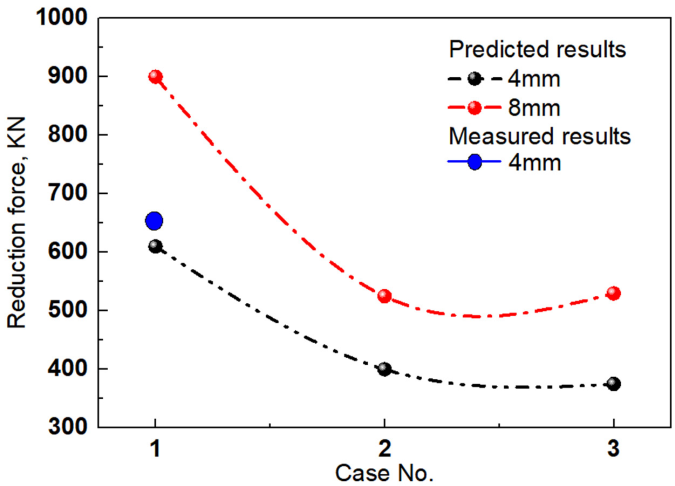

Fig. 10. Comparison of the reduction force during different reduction conditions

point O to point P3) when the displacement of solidus line in as-cast bloom cross section is a negative value. This implies that the convex roll is effective in compensating the solidification shrinkage than the flat roll and chamfer bloom even though its magnitude difference is small in the bloom thickness direction (from point O to point P1), and the chamfer bloom is much more effective than the flat roll and convex roll in compensating the solidification shrinkage in the bloom thickness direction (from point O to point P3).

The displacement of solidus line toward the bloom width direction (x-axis) is a positive value, this indicates that the mushy zone of as-cast bloom is elongated simultaneously. The chamfer bloom is more effective in consequently decreasing the mushy zone size and the solidus line moves toward bloom center.

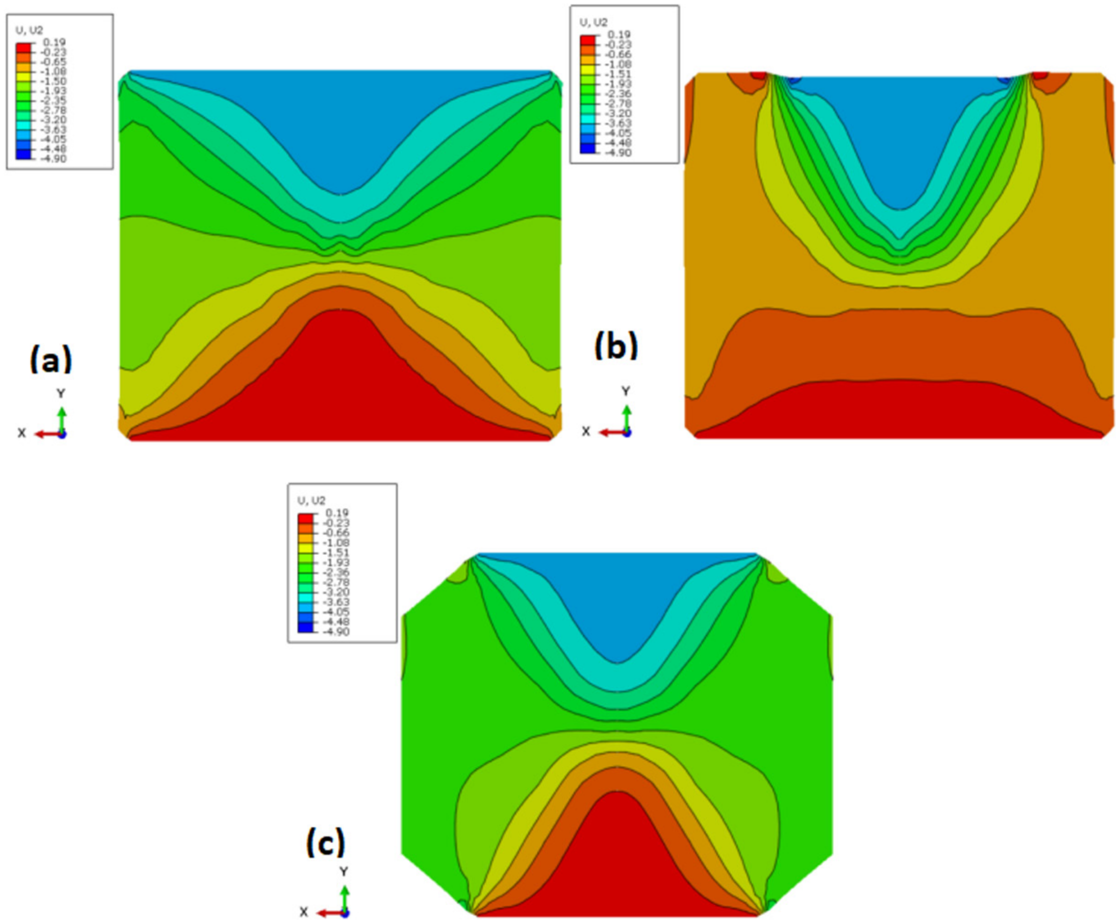

Fig. 11. Distribution of displacement along the bloom thickness direction Case 1, (b) Case 2 and (c) Case 3

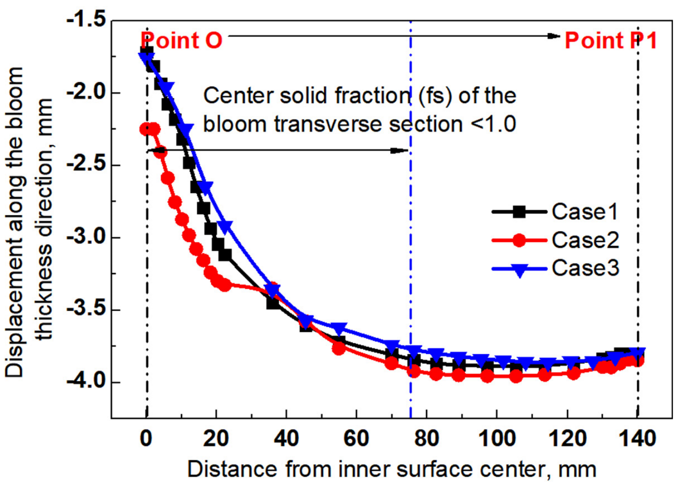

Fig. 12. Displacement along the bloom thickness direction (from point O to point P1)

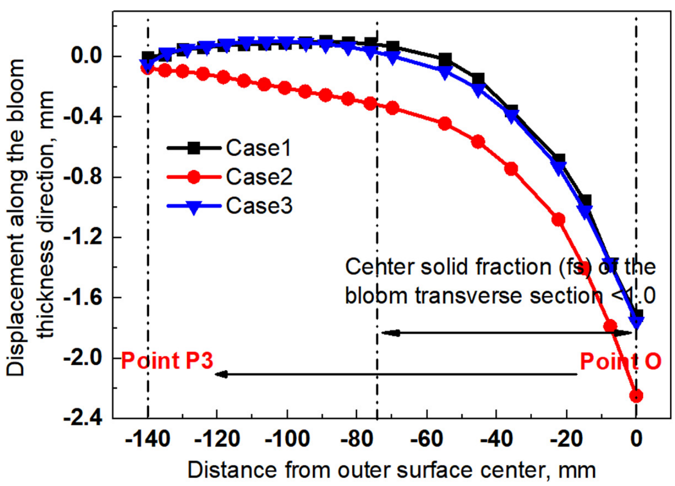

Fig. 13. Displacement along the bloom thickness direction (from point O to point P3)

Figure 16 demonstrates a schematic of the deformation of the mushy zone at the bloom transverse section under different reduction cases, the mushy zone before and after deformation can be described by the change of the solidus line. Consequently, mushy zone of the chamfer bloom could be shrunk in its transverse section even though width-spreading is taken into account.

4.3. Comparison of cracking risk in as-cast bloom under different reduction cases

The cracking risk of as-cast bloom can be evaluated by the corresponding equivalent strain during the soft reduction process. Figure 17 shows the distributions of equivalent strain when the as-cast bloom is deformed under different reduction cases,

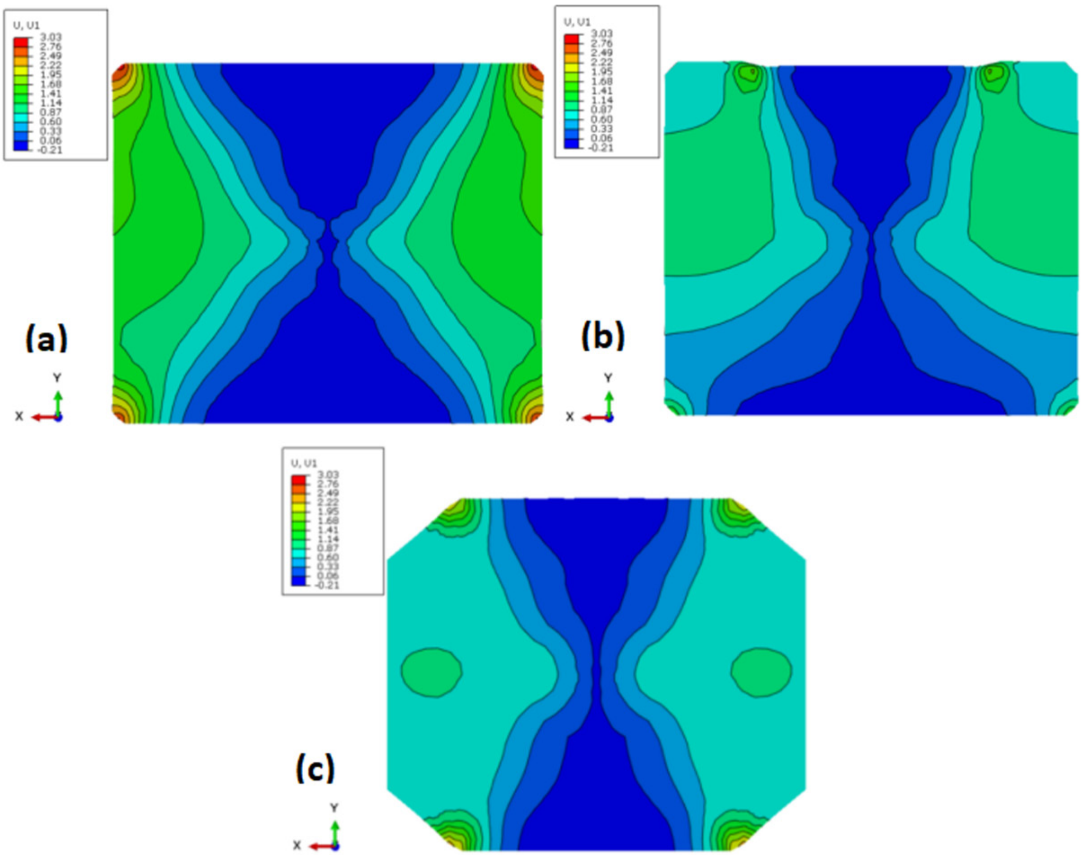

Fig. 14. Distribution of displacement along the bloom width direction (a) Case 1, (b) Case 2 and (c) Case 3

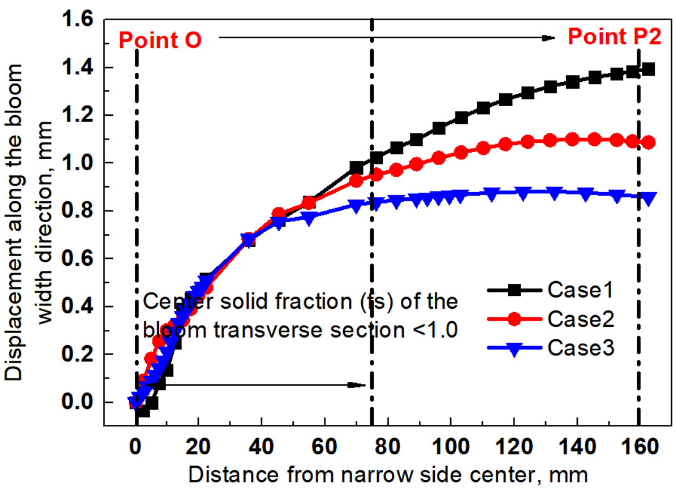

Fig. 15. Displacement along the bloom width direction (from point O to point P2)

the greatest equivalent strain was at the bloom corner when the bloom was deformed by the flat rolls (Case 1). The equivalent strain was the greatest at the contact area between the convex roll shoulder and the bloom (Case 2). Compared with the cases 1, the application of chamfer bloom (Case 3) significantly reduced the equivalent strain value. However, the greatest equivalent strain was also generated at the bloom corner.

Schematic of internal crack along the continuous casting direction is described in Fig. 18. The inclination angle of initial cracks observed in the as-cast bloom commonly ranges from 30 degree to 60 degree towards the continuous casting direction. Internal cracks are commonly generated and concentrated on the bloom outer region, this subsequently causes crack formation. To clarify the effect of different reduction cases on the cracking risk of as-cast bloom, the equivalent strain distribution along the bloom thickness direction [from point O to point P2] was compared in Fig. 19. The variation of the equivalent strain (Case 3) along the bloom thickness direction was obviously smaller than that of Cases 1 and 2.

For a chamfer bloom with a flat roll (case 3), the equivalent strain in the bloom outer region was smaller than that in the cases 1 and 2. Since this strain distribution in the casting direction (CD) is independent of the coordinate transformation in as-cast bloom perpendicular to that direction, only the strain status in CD in the default coordinate system is demonstrated as shown in Fig. 20. The strain of the deformation zone is tensile on the bloom cross section, which transitions gradually from the bloom inner surface to the bloom outer surface, and the bloom lower part was not deformed since the bloom thickness is much larger than the thickness during deformation by soft reduction roll.

Tensile strain is mostly found in the area of the brittleness temperature range (BTR), thus the internal cracks are easily formed in the soft reduction process. In addition, the tensile strain in the bloom inner region was more larger than that in the bloom outer region, which can accumulate greater deformation

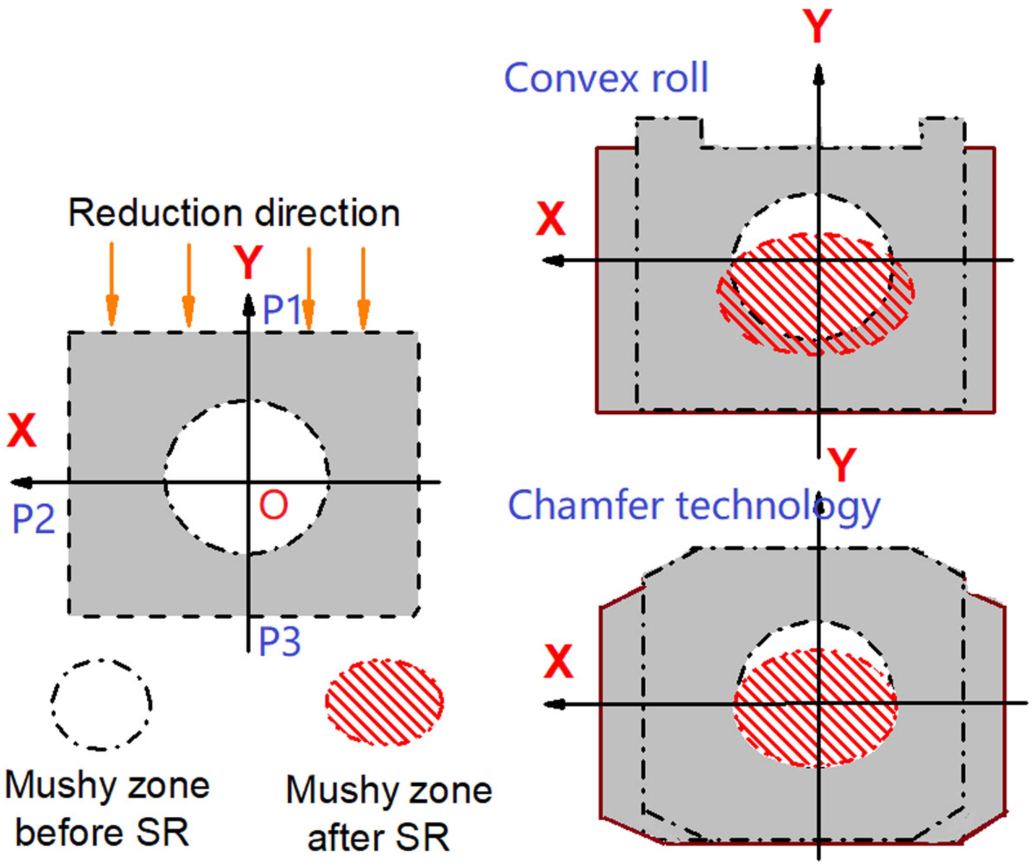

Fig. 16. Schematic of the deformation of the mushy zone at the bloom transverse section under different reduction cases

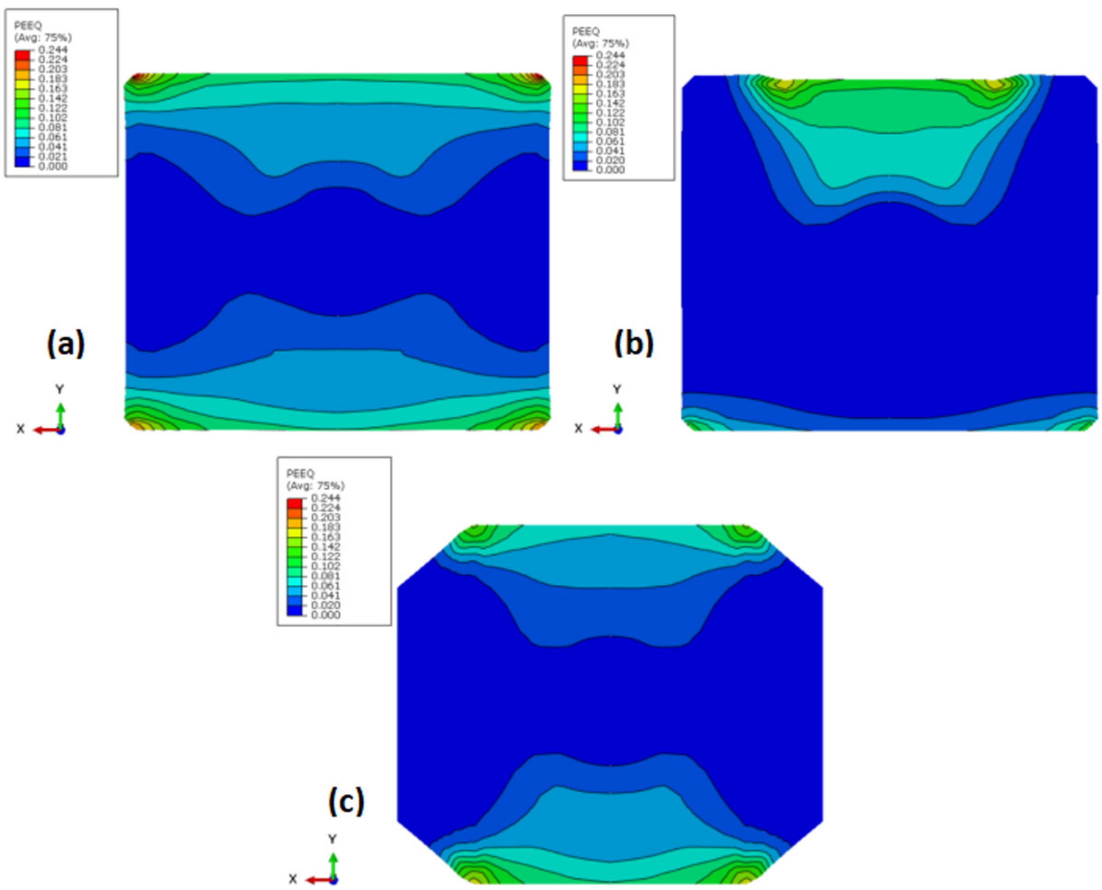

Fig. 17. Distributions of equivalent strain when the bloom is deformed under different reduction cases. (a) Case 1, (b) Case 2 and (c) Case 3

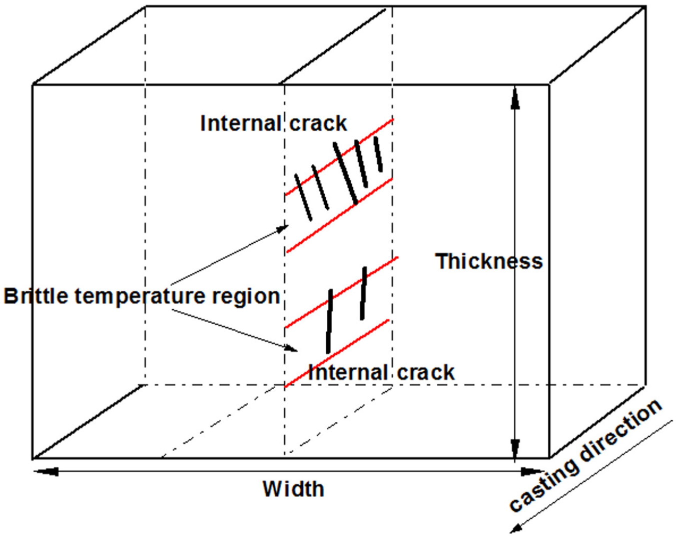

Fig. 18. Schematic of internal crack along the continuous casting direction

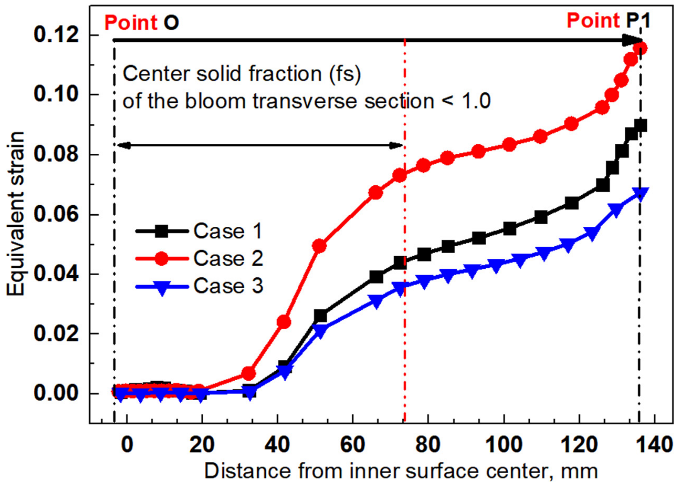

Fig. 19. Distribution of equivalent strain along the bloom thickness direction (from point O to point P2)

of BTR to form internal cracks in the as-cast bloom. The simulation results were in agreement with the actual casting experiment results. Chamfer bloom has a significant decrease of tensile strain in the BTR areas, which is expected to greatly reduce the risk of internal cracks. When the convex roll works on the as-cast bloom, the middle zone of blooms had the greatest effective strain, which promotes mushy zone deformation. And the convex profile of roll limits lateral spread during SR, and it forms a greater deformation to the mushy zone of bloom along the casting direction, so the tensile strain obviously increased to form internal cracks.

The tensile stress in the bloom continuous casting direction makes it easier for the as-cast bloom to extend longitudinally. Distribution of PE33 along the bloom thickness direction has a similar trend under different reduction cases as shown in Fig. 21. The tensile strain toward the bloom continuous casting

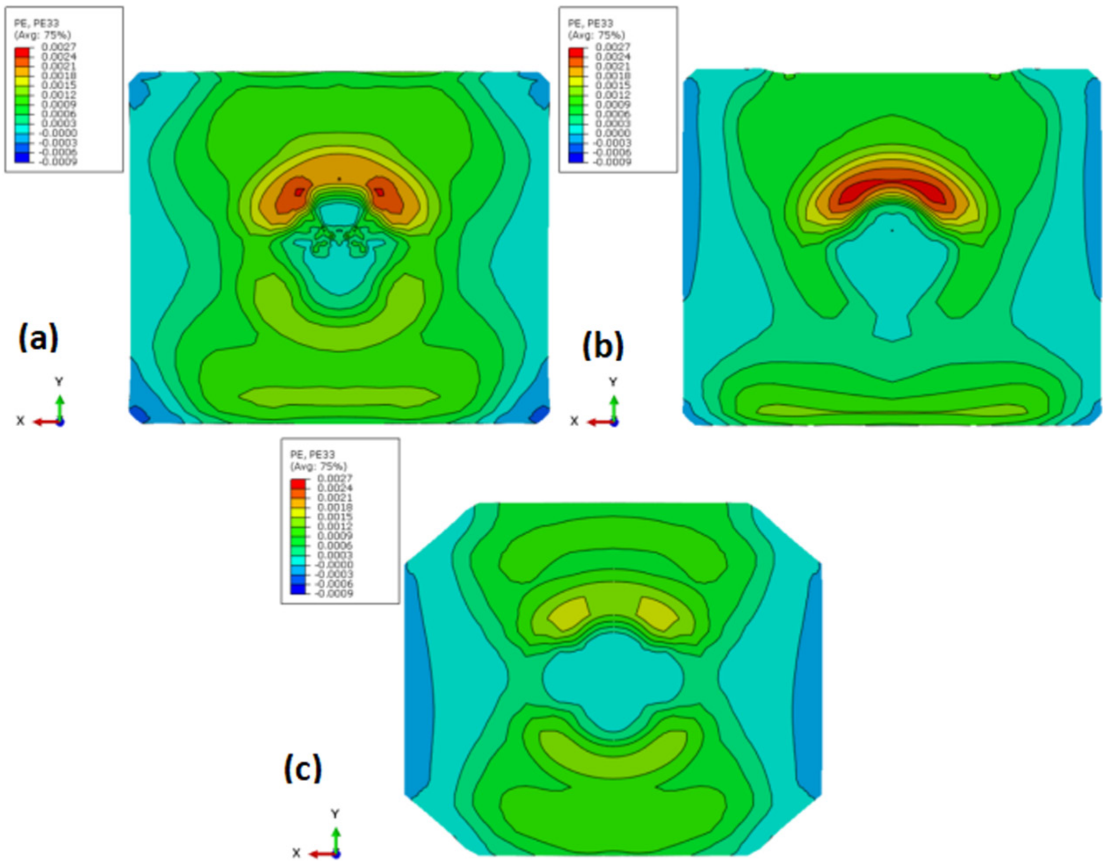

Fig. 20. Distributions of PE33 when the bloom is deformed under different reduction cases. (a) Case 1, (b) Case 2 and (c) Case 3

direction (z-axis) was simulated and compared to analysis the risk of internal cracks. Compared with the convex roll in case 2 and flat roll in case 1, this is an obvious decrease in tensile strain with the application of chamfer bloom in case 3. The chamfer geometry of the as-cast bloom can increase the temperature distribution on the bloom corner, which largely reduces the deformation resistance of the soft reduction rolls.

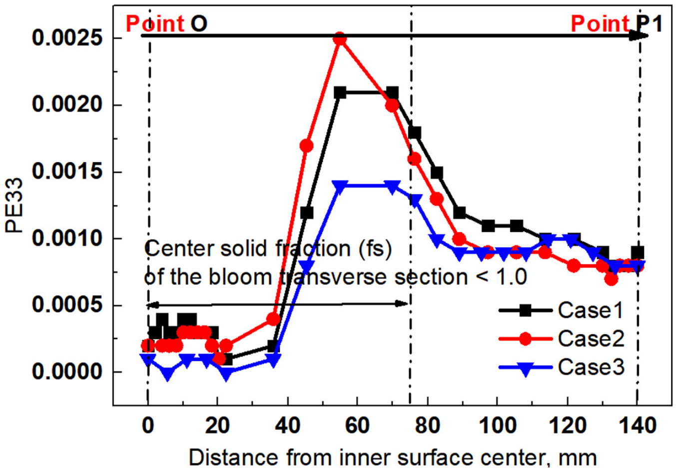

Fig. 21. Distribution of PE33 along the bloom thickness direction (from point O to point P1)

4. Conclusions

A three-dimensional mechanical model was developed to investigate the effect of the bloom chamfer profile and roll surface profile on deformation behavior, cracking risk, stress concentration and reduction force of as-cast bloom during the soft reduction process. Some conclusions are summarized from the simulated results as follows:

(1) Compared with a conventional flat roll, the application of a convex roll and a chamfer bloom can both avoid the thicker corner of the as-cast bloom solidified shell, and significantly reduce reduction force of the withdrawal and straightening units under the same soft reduction process (i.e., section size, reduction amount, casting speed and solid fraction). The equivalent stress along the bloom inner surface was both decreased markedly after convex roll and chamfer bloom were used.

(2) The cross-section of mushy zone decreased along the bloom thickness direction while simultaneously increasing along the bloom casting direction and the bloom width direction. The convex roll limits lateral spread along bloom width direction, deformation degree of the mushy zone was significantly larger along the bloom casting direction, therefore the tensile strain in the brittleness temperature range (BTR) can obviously increase to form internal cracks.

(3) The chamfer bloom is much more effective in compensating the solidification shrinkage of mushy zone to minimize the center segregation and the porosity more effectively. In addition, chamfer bloom has a significant decrease of tensile strain in the brittleness temperature range (BTR) areas, which is expected to greatly reduce the risk of internal crack.

Acknowledgments

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