

The Effects of Hot Tear Segregations on the Rolled Product Quality of Continuously Cast Steel

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Abstract

The main objective of this project was to investigate the behavior and the damaging effects of hot tear segregations in the continuously cast steel blooms on the final product quality. To achieve this aim, plant data from three different types of steels were used. Investigations using the scanning electron microscope (SEM) equipped with energy dispersive x-ray spectroscopy (EDS) probe and metallographic techniques showed that during the subsequent stages of the cast products, the hot tear segregations were transformed into spherical shapes, joined to each other and moved toward the surface. Also, it was observed that hot tear segregations affected the final product quality in two ways: (1) they could cause uneven surfaces in the final products, and (2) if they reached the surface in a line oriented pattern, they could make a surface crack. The hot tear segregations located near the surface could be crushed to the smaller ones during the rolling. This phenomenon made hot tear segregations less destructive.

Keywords: Microanalysis, Steel, Continuous casting, Hot tear, Surface crack.

1. Introduction

Nowadays, many semi-finished steel products are produced through the continuous casting process¹. The quality of the final products depends on the quality of the continuously cast products². Therefore, the steel industry tried to improve the quality and reduce the costs in a single continuous casting machine. On the other hand, the amount of production is also considered by the researchers. These can be achieved by increasing both casting speed and cross section area³ as this can lead to a high solidification velocity and more stress generation in the continuous casting machine. As a result, the continuously cast products may include any internal defects such as solidification cracks or hot tears which can exhibit the main effect on the quality of the final products⁴⁻⁶.

Hot tear is related to the interaction between the reduced ductility in the root of dendrites (the cracking zone near the solidus temperature) and the tensile stresses⁷⁻⁹. Hot tear is mainly found in two types: ¹ open hot tear and ² hot tear segregation¹⁰. It has been stated that ductility is decreased because of the liquid

film between the dendritic arms¹¹. The tensile stresses in the cracking zone can pull away the dendritic arms, thereby leading to the generation of a crack called open hot tear⁴. Hot tear segregation is mainly a segregated region formed in the mushy zone. In the continuously cast steels, hot tear segregation clearly consists of high concentrations of segregating elements, especially manganese and sulfur^{12, 13}.

For several decades, open hot tear has been considered as a major defect in comparison with hot tear segregation¹⁴, whereas both open hot tear and hot tear segregation have considerable damaging effects on the final quality of the continuously cast steel products^{10, 15}. The term "hot tear segregation" was first introduced and investigated by Bernhard¹⁴. Pierer and Bernhard only recounted the following reasons to show the harmful aspects of hot tear segregation on the final products¹⁴.

(1) Because of the high concentration of the segregating elements in hot tear segregations, they cannot be reduced by the subsequent preheating and rolling process.

(2) Hot tear segregations show a modified transformation behavior which results in the formation of the undesirable phases such as martensite.

(3) Due to the high degrees of deformation, hot tear segregations can reach the surface and thus, degrade the quality of the surface.

Few researches have focused on the mechanism of hot tear effect on the surface quality of the final products. Therefore, the main aim of this work was to investigate how hot tear segregations could cause

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the mentioned damages on the final quality of the continuously cast steel products.

More specifically, the aim of this study was to investigate the behavior of hot tear segregations during the processes after continuous casting (reheating and rolling) and the impacts of hot tear segregations on the quality of the final product surface. In fact, in the present study, the hot tear segregations throughout different stages of cast production (from the continuous cast blooms up to the final round products) were traced in order to compare the effect of reheating and rolling on the shape, size and location of hot tear segregation. Finally, the ways in which the hot tear segregations could influence the final product surface were studied. The research was performed based on metallographic techniques, SEM and EDS analyses using the steel plant samples.

2. Experimental procedure

To investigate the behavior of hot tear segregations during reheating and rolling (the following stages of the cast products), three types of steel (type A, B and C) were solidified during the continuous casting process. The continuously cast steels were blooms with the dimensions of 0.23 m × 0.25 m. The chemical composition and the casting operational parameters of the samples are shown in Tables 1 and 2, respectively. As can be seen from the Table 1, various steels of A, B and C differed in Sulfur (S) content and the ratio

of Manganese (Mn) to Sulfur was a very important parameter in hot tear formation.

After continuous casting, the blooms were cooled to ambient temperature in the usual atmosphere. Then, the blooms were heavily hot rolled to form steel billets with the dimensions of 0.13 m × 0.13 m and then cooled to the room temperature. In following, the billets were lightly hot rolled to generate the final products of round billets with a diameter of 0.02 m. The samples used for hot tearing investigation were provided from the as cast, semi-final and final products. The samples were cut from the bloom and the billet surface in which the studied surface was perpendicular to the casting direction and the bloom/billet surface. Table 3 depicts the operational conditions of the steels used in the present work.

In order to investigate the hot tear, the test samples were polished and used under non-etched, hot etched and cold etched conditions. The hot etching process was done using a solution of hydrochloric acid (50%) for eight minutes at the temperature of 70 °C. In order to cold etch, the desired test samples were etched using a solution of Nital (4%) at room temperature. The hot tears size, shape and location were investigated during changing the bloom to the final products using a high resolution scanning electron microscopy (SEM) VEGA/TESCAN equipped with energy dispersive x-ray spectroscopy (EDS) probe and an optical microscope.

Table 1. The chemical compositions of blooms types A, B and C (%).

Type	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Ti	Fe	Mn/S
A	0.44	0.24	0.6	0.01	0.03	0.14	0.01	0.03	0.23	0.003	Base	20
B	0.56	0.3	0.75	0.007	0.004	0.75	0.08	0.03	0.15	0.003	Base	187
C	0.32	0.54	1.51	0.008	0.078	0.22	0.08	0.02	0.2	0.02	Base	19

Table 2. The casting operational parameters of blooms types A, B and C.

Type	Casting Speed (m/min)	Pouring Tem. (°C)
A	0.71	1530
B	0.75	1528
C	0.69	1535

Mold Dimension: 0.25m×0.23m
Mold Length: 0.78m

Table 3. The operational conditions of the used steels

Steel	Cross Section	Operational Condition
A0	Square 0.23m×0.25m	As-cast bloom
A1	Square 0.13m×0.13m	Heavily hot rolled billet
A2	Square 0.1m×0.1m	Lightly hot rolled billet
A3	Round =0.02 φ m	Lightly hot rolled billet
B3	Round=0.02 φ m	Lightly hot rolled billet
C3	Round=0.02 φ m	Lightly hot rolled billet

The symbol φ represents the diameter of the round

3. Results and discussion

3.1. Hot tear segregations in the continuously cast bloom

Fig. 1 depicts the SEM image of the polished sample A0 which exhibited a series of segregated regions between the surface and the bloom center. In order to investigate the chemical composition of these segregation regions, the concentration mapping of Fig. 1 is illustrated in Fig. 2 (a) and (b) shows S and Mn concentration mappings, respectively). According to this figure, the concentration of Mn and S in the segregation zone was more than that in the matrix. Therefore, these segregation zones consisted of high concentrations of the segregating elements (Mn and S). So, it can be deduced that this segregation zone was a kind of hot tear segregation^{10, 14)}. As can be seen from Fig. 1, the hot tear segregations length was limited between about 2 to 10 μm and they were formed in spherical and longitudinal shapes. Besides, the hot tear segregations in the continuously cast bloom were surrounded partially or fully with pores.

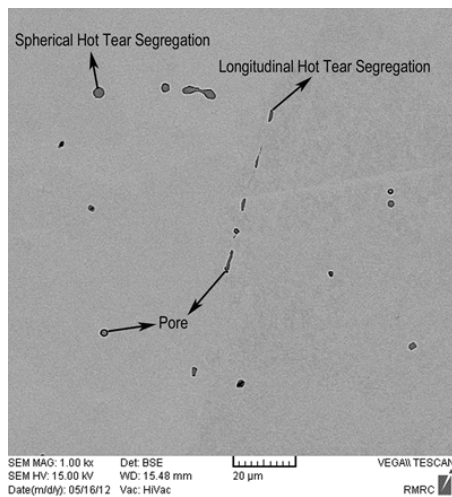


Fig 1. The SEM image of the polished sample A0 which exhibited a series of hot tear segregations.

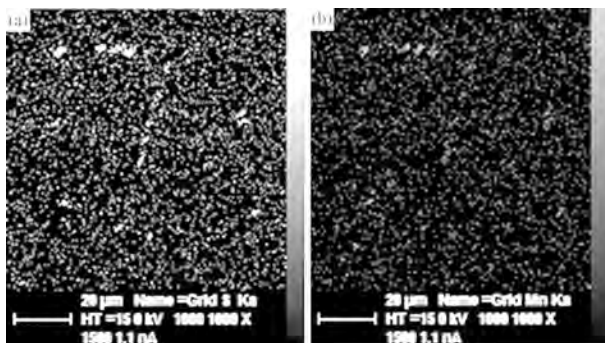


Fig 2. Concentration mapping of Fig. 1. (a) S concentration mapping, and (b) Mn concentration mapping.

3.2. Hot tear segregations during reheating and rolling

Fig. 3 depicts the SEM image of the non-etched polished sample A2 which was attached to S and Mn concentration mapping. Similar to Fig. 1, this image also shows some segregation regions. As can be seen, like the hot tear segregations in the bloom, they were composed of high concentrations of the segregating elements. Therefore, it must be emphasized that hot tear segregations were maintained after the final hot rolling process. In other words, hot tear segregations could not be reduced or eliminated by reheating and hot forming. This conclusion has also been reached before^{10, 14)}. Likewise, during reheating, due to decreasing the interfacial free energy¹⁶⁾, the longitudinal hot tear segregations (in the bloom) were converted to the spherical ones.

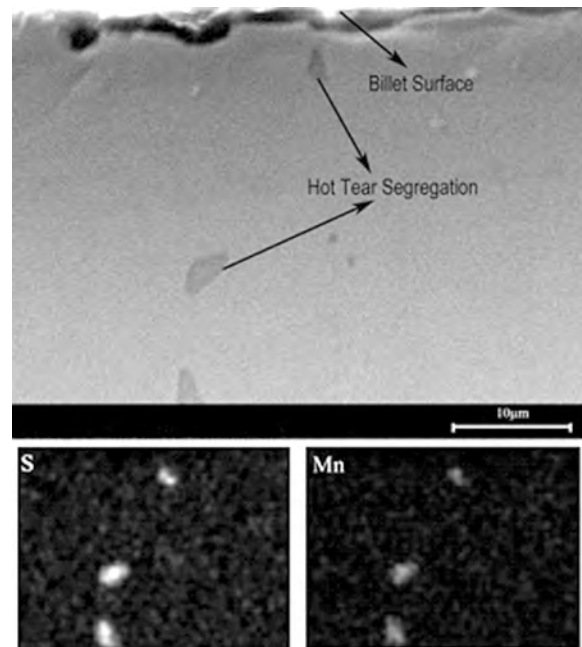


Fig 3. The SEM image of non-etched polished sample A2 attached with S and Mn concentration mapping.

In order to better understand the hot tear segregations behavior during the following stages of continuous casting, the steel samples A1 and A2 were hot etched and studied by SEM as shown in Fig. 4. Figs. 4a and 4c depict the SEM microstructures of the samples A1 and A2, respectively. They are related to the area near the surface while Figs. 4b and 4d are related to the regions between the surface and the billet center of the samples A1 and A2, respectively. Because of the higher free energy of hot tear segregations in comparison with the matrix, they were etched to make some holes (black spots) which represented the shape, location and size of hot tear segregations.

As can be found from Fig. 4, the size of the hot tear segregations in the heavy rolled steel exhibited a considerable gradient from the billet surface toward the billet center (see Figs. 4a and 4b) while the lightly rolled steel did not show a significant hot tear size gradient (see Figs. 4c and 4d). This behavior may be related to the fact that the heavy rolled steel experienced a strain of about 122% whereas the strain applied to the light rolled one was about 52%. It is well known that the surface of the rolled material experiences a higher deformation with respect to the core layers of the material¹⁷⁾. This could cause further crushing of hot tear segregations located near the billet surface. For this reason, the hot tear segregations near the surface of the heavy rolled steel were smaller than those in the billet center. As mentioned, the hot tear segregation is a concentrated zone. In fact, this zone is more brittle with respect to the matrix (however, in the high temperature, the matrix is austenite). Therefore, obviously, the crushing mechanism may be a sequential fracture during the rolling. Fig. 4 divulges that the hot tear segregations in the light rolled steel were considerably more than those in the heavily rolled steel in terms of size. In fact, during the reheating of the billet, the hot tear segregations were joined to each other in order to decrease their interfacial free energy¹⁶⁾.

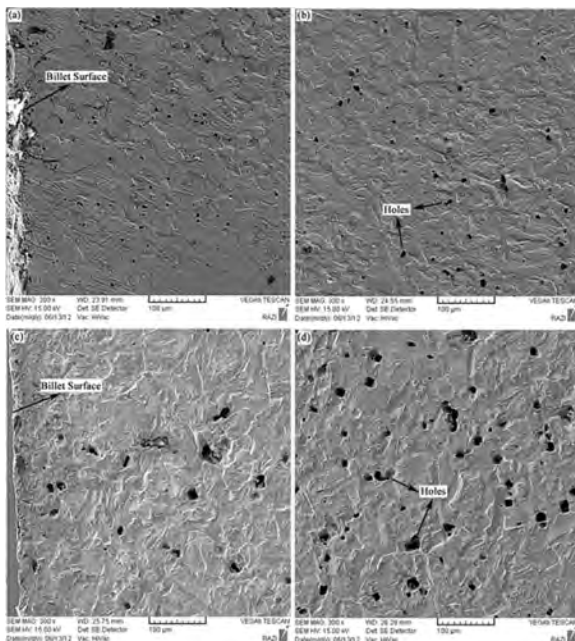


Fig 4. The SEM images of hot etched samples A1 and A2 with the same magnifications. Images (a) and (c) depict the SEM microstructures of samples A1 and A2, respectively. They are related to the region near the surface while images (b) and (d) are related to the regions between the surface and the billet center of samples A1 and A2, respectively.

3.3. The effect of hot tear segregation on the surface cracks

It has been reported that due to the high degrees of deformation during the subsequent stages of the cast products, defects such as hot tear segregations can be transported toward the surface^{15, 18)}. Fig. 5 depicts the SEM image of the near surface region of the non-etched polished light rolled steel (sample A2). It shows a line of hot tear segregation which reached the product surface during the heavy and then light rolling. Since hot tear segregations were formed at the primary grain boundaries^{19, 20)}, it can be concluded that the stretched primary grain boundaries caused the linear morphology of these hot tear segregations. The billet surface experienced a high tensile stress during the rolling process. On the other hand, the hot tear segregation line behaved as a brittle region. So, the hot tear segregation line could be opened on the billet surface during rolling and as a result, the surface crack would be generated. In order to investigate the effect of the hot tear segregation on the formation of the surface crack in more details, the final products (A3, B3 and C3) were investigated in the following way.

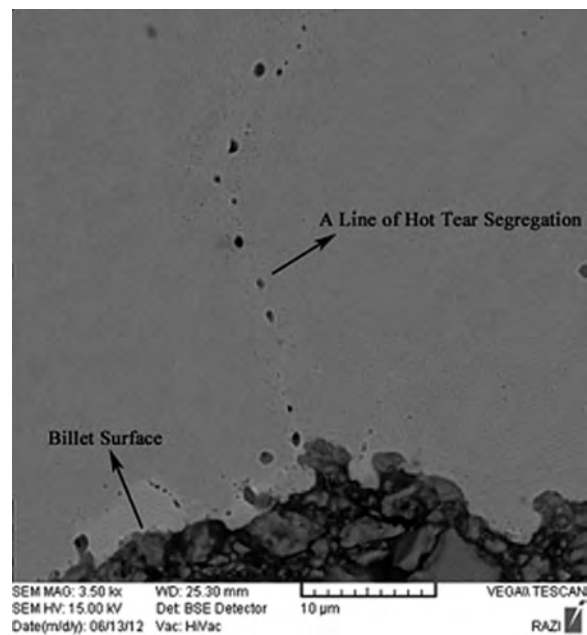


Fig 5. The SEM image from the near surface region of the non-etched polished sample A2.

Fig. 6a shows the cold etched optical microscopy micrograph of the sample A3. Also, this figure is accompanied with the SEM images of the inner parts of the surface crack (detail A, as shown in Fig. 6b) and along the crack tip (detail B, as shown in Fig. 6c) at the higher magnifications. As can be seen from the SEM images, some segregation regions were around the crack wall (zone P) and also, some line oriented

segregations (like point Q) were seen at the tip of the crack (Fig. 6b and 6c). Therefore, it can be concluded that the surface crack was initiated from the segregation line.

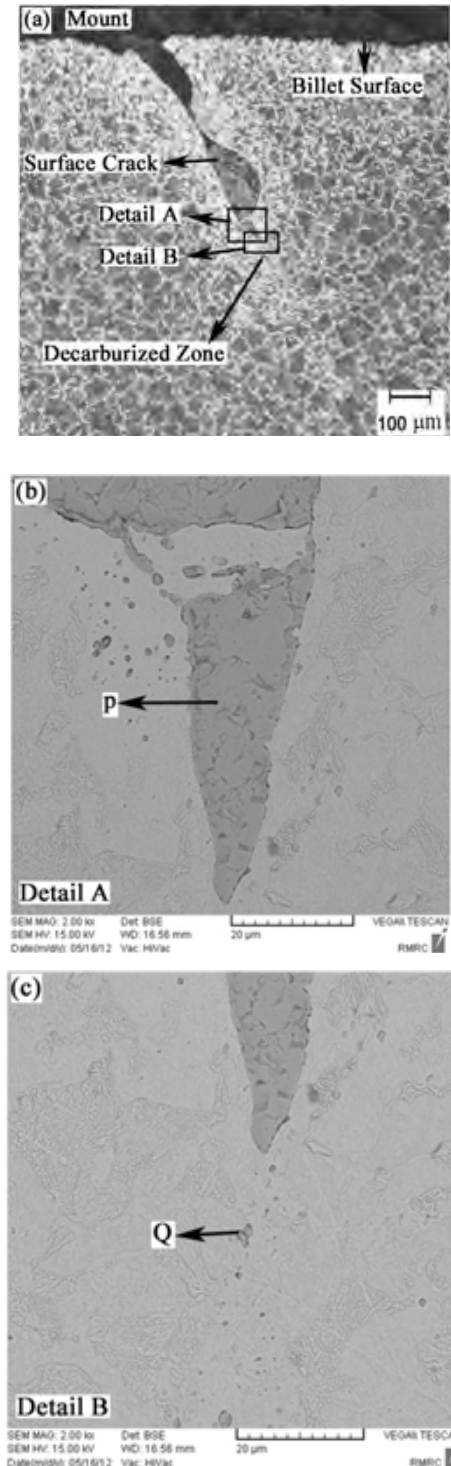


Fig 6. Images of the cold etched sample A3. Fig. 6a: The optical microscopy micrograph. Fig. 6b: The SEM image of the inner parts of the surface crack (detail A). Fig. 6c: The SEM image along the crack tip (detail B).

Fig. 7 depicts the optical microscopic image of the cold etched steel sample B3 which was attached to the SEM image of the crack at the higher magnification. This crack was entirely surrounded by some zones of segregations. Consequently, the surface crack in the steel B3 was also formed due to the segregations which reached the billet surface and were completely opened by the rolling stresses.

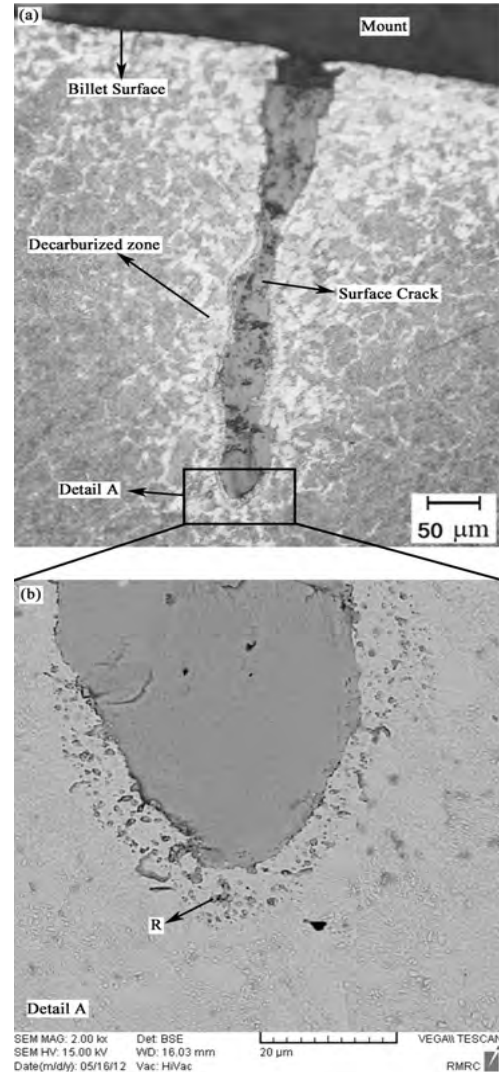


Fig 7. Images of the cold etched sample B3. Fig. 7a: The optical microscopy micrograph. Fig. 7b: The SEM image along the crack tip (detail A).

Fig. 8 shows the optical microscopy micrograph of the cold etched C3. Also, it was added to a higher magnification image of the tip of the surface crack which revealed a continuous hot tear segregation line. This figure also confirms well that the surface crack was due to opening the hot tear segregations which reached the billet surface.

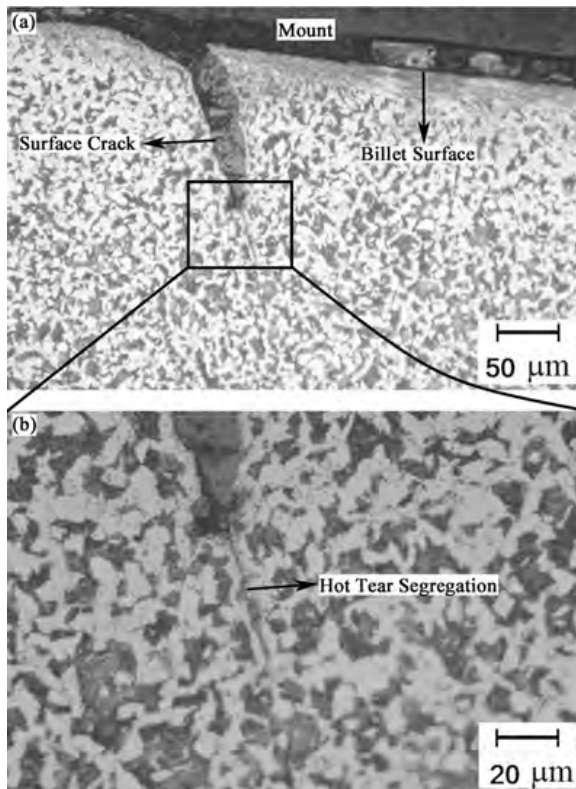


Fig 8. Images of the cold etched sample C3. Fig. 8a: The optical microscopy micrograph. Fig. 8b: The optical microscopy micrograph along the crack tip.

3.4. The effect of the hot tear segregations on the surface roughness

To study the roughness of the final product surface, the non-etched steel samples A3, B3 and C3 were used. Fig. 9 shows the optical microscopy images of them at the same magnifications. As can be seen, the quality of the surface was distinctively variable in these round billets. It has been reported that the steels with lower Mn/S ratios¹²⁾ and higher sulfur and carbon contents²¹⁾ are specifically more sensitive to the hot tearing formation. It has also been said that increasing sulfur contents extends the solidification range (especially the brittle temperature range), thereby causing higher hot tear susceptibility²¹⁾. Also, it should be noted that increasing the carbon contents increases the solidification shrinkage (especially between 0.1 up to 0.2 Wt% carbon contents due to δ/γ transformation), helping hot tear formation²¹⁾. Thus, the possibility of the hot tear formation in the steel types C, A and B was decreased, respectively. Consequently, given the fact that the defects are transported toward the surface during reheating and rolling, in the steel sample C3, in comparison with the steel samples A3 and B3, further hot tear segregations reached the surface and caused more uneven surfaces. It must be noted that the steel type B had much higher Mn/S ratio and less S content, so the steel sample B3 had the best surface quality.

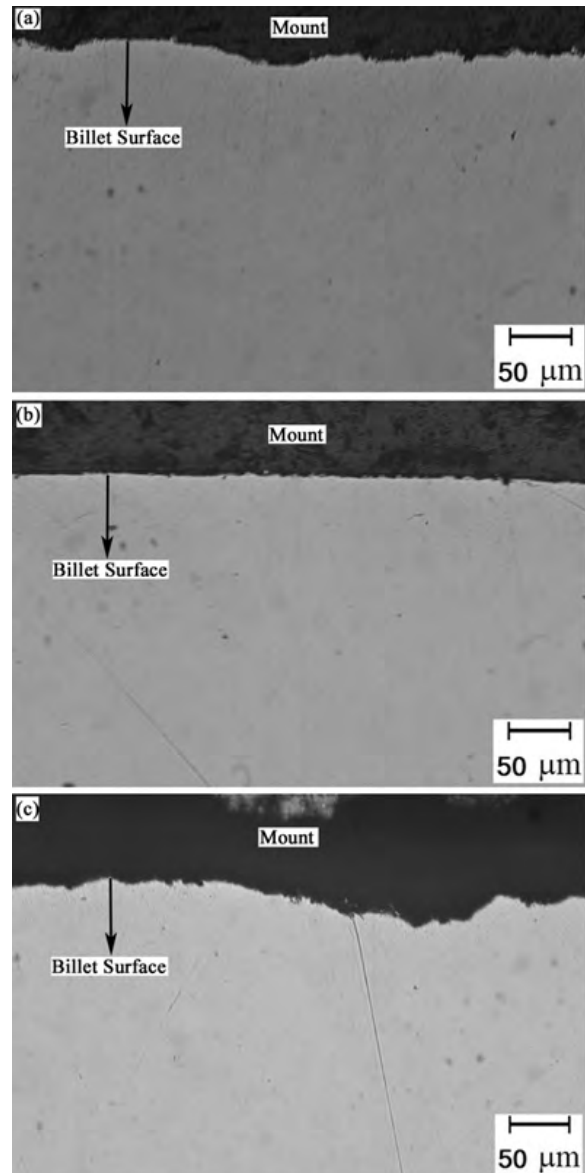


Fig 9. The optical microscopy micrographs of the polished non-etched samples. Fig. 9a: Sample A3. Fig. 9b: Sample B3. Fig. 9c: Sample C3.

4. Conclusions

According to plant data, the behavior of hot tear segregations during the following stages of the cast products and the effects of hot tear segregation on the final product were studied for three chemical compositions. The most important results of the present study can be summarized as follows:

1. During reheating and rolling, the longitudinal hot tear segregations in the blooms were converted to the spherical ones.
2. During reheating and hot rolling of the cast products, hot tear segregations could join each other and make larger ones. This phenomenon was more obvious when the product experienced less strain.
3. The effect of sulfur content on the hot tear segregation

behavior was more significant with respect to the Mn/S ration effect.

4. The hot tear segregations which were located near the surface could be crushed to the smaller ones during the rolling.

5. During the following stages of the cast product, hot tear segregations could affect the quality of the surface in two ways: (1) they could cause uneven surfaces on the final products, and (2) if they reached the surface in a line oriented pattern, they could make a surface crack.

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References

- [1] N. Cheung and A. Garcia: *Eng. Appl. Artif. Intel.*, 14(2001), 229.
- [2] K. Schwerdtfeger and K. H. Spitzer: *ISIJ. Int.*, 49(2009), 512.
- [3] C. Li and B. G. Thomas: 85th Steelmaking Conf. Proc, Warrendale, (2002), 109.
- [4] M. Rappaz, J. M. Drezet and M. Gremaud: *Metall. Mater. Trans. A.*, 30B(1999), 449.
- [5] Y. M. Won, T. J. Yeo, D. J. Seol and K. H. Oh: *Metall. Mater. Trans. B.*, 31B(2000), 779.
- [6] C. Monroe and C. Beckerman: *Mat. Sci. Eng. A.*, 413(2005), 30.
- [7] D. G. Eskin and L. Katgerm: *Metall. Mater. Trans. A.*, 38A(2007), 1511.
- [8] A. B. Phillion, S. L. Cockcroft and P. D. Lee: *Mat. Sci. Eng. A.*, 491(2008), 237.
- [9] H. K. Kamga, D. Larouche, M. Bournane and A. Rahem: *Mat. Sci. Eng. A.*, 527(2010), 7413.
- [10] R. Pierer, C. Bernhard and C. Chimani: *Rev. Metall.*, 72 (2007).
- [11] A. Chojecki, I. Telejko and T. Bogacz: *Theor. Appl. Fract. Mech.*, 27(1997), 99.
- [12] J. K. Brimacombe and K. Sorimachi: *Metall. Trans. B.*, 813(1977), 489.
- [13] R. Pierer and C. Bernhard: *Iron & Steel Technology Conference and Exposition, USA*, (2007), 193.
- [14] R. Pierer and C. Bernhard: *Iron & Steel Technology Conference and Exposition, USA*, (2010), 193.
- [15] C. Bernhard, R. Pierer and C. Chimani: 5th Decennial International Conference on Solidification Processing, UK, (2007), 525.
- [16] D. A. Porter and K. E. Easterling: *Phase transformations in metals and alloys*, 2nd ed., Chapman L Hall, London, (1992), 110-181.
- [17] P. S. Nalawade, A. J. Puranik, G. Balachandran, K. N. Mahadik and V. Balasubramanian: *Int. J. Mech. Sci.*, 77(2013), 8.
- [18] A. B. Sychkov, M. A. Zhigarev, A. V. Perchatkin, S. N. Mazanov and V. S. Zenin: *Metallurgist.*, 50(2006), 83.
- [19] D. J. Lahaieand and M. Bouchard: *Metall. Mater. Trans. B.*, 32B(2001), 697.
- [20] R. Pierer, W. Rauter and C. Bernhard: *TMS Annual meeting & exhibition, USA*, (2012), 251.
- [21] K. H. Kim, T. J. Yeo, K. H. Oh and D. N. Lee: *ISIJ. Int.*, 36(1996), 284.