The Evolution of Heterogeneous Microstructure During Reheating of Strip-Cast Medium-Manganese Duplex Steel

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Keywords: Medium Manganese steel, strip casting, Mn segregation, microstructure evolution

INTRODUCTION

In recent years, advanced high strength steel (AHSS) has attracted the wide attention of many researchers to meet the requirements for vehicle lightweight and crashworthiness in the automotive industry.1 The first generation AHSS such as transformation-induced plasticity (TRIP) steels, dual phase (DP) steels have a lower plasticity when the strength is higher than 600Mpa. The second generation AHSS like twinning induced plasticity (TWIP) steels faced with the problem of high alloying cost.2 As the representative of the third generation AHSS, the medium manganese steel shows good comprehensive mechanical properties and have the lower alloying cost due to the its unique two-phase (austenite + ferrite or austenite + martensite) microstructure. Particular in the (austenite + martensite) duplex phase steels, austenite in the steel can coordinate the deformation process and prevent the initiation of cracks due to the TRIP mechanism, while the martensite can provide the strength as a harder phase.3-5 Therefore, the mechanical properties of medium manganese steel can be controlled by adjusting the phase proportion of complex microstructure. However, the medium manganese steel still has some difficult to deal with in production, such as serious Mn macro-segregation, difficult hot rolling process and complex procedure on manufacturing at present.

Strip casting technology can directly cast the molten steel into the steel strip with thickness of several millimeters followed by single pass hot rolling (rolling reduction below 30 %) to obtain final strip product, which can effectively solve the problem of difficult hot rolling in the high strength steels production.5,7 Meanwhile, due to the rapid solidification process of molten steel, the Mn elements in the steel is impossible to carry out long-distance diffusion during solidification, and the macrosegregation behavior is inhibited. It has been reported that the segregation behavior of Mn in steel produced by strip casting changes from macroscopic scale to microscopic.8-10 Different from the Mn macrosegregation, the manganese microsegregation can further improve the mechanical properties of medium manganese steel by inducing austenite formation during reheating treatment.3 Therefore, strip casting is considered to be an ideal way to produce medium manganese steel. However, the research on the development of new steel grade in strip casting production is mainly focused on plain carbon steel strips, microalloyed high-strength steel strips, silicon steel strips at present.11,12,13 The research of industrial production of medium manganese steel strips
through strip-casting technology is not sufficient yet. Reheating process is one of the most important processes in the production of medium manganese steel. According the prior study, during the reheating process, Mn and C elements is tend to partition into the austenite. So, the reheating process is easily to be affected by Mn segregation behavior. However, the studies on the evolution of Mn segregation in medium manganese steel during the reheating process mainly focus on the microsegregation caused by hot rolling or heat treatment process, and there are no reports on the evolution of microsegregation formed by strip casting process. Considering strip casting can be used to avoid the problems in the traditional production of medium manganese steel, it is of great significance to study the evolution of microstructure and Mn segregation behavior in the strip casting production of medium manganese on the laboratory scale.

Table 1. The Chemical Composition of Studied Medium Manganese Steel, wt.-%

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>V</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>6.04</td>
<td>2.24</td>
<td>0.29</td>
<td>0.53</td>
<td>0.05</td>
<td>Bal</td>
</tr>
</tbody>
</table>

The chemical composition of the self-designed medium manganese duplex steel was shown in Table 1. The simulation striping casting production of the investigated steel was carried out by strip-casting simulator in Steel Research Center at Central South University, China, as shown in Figure 1. Through this simulator, molten steel can solidify in to strip cast directly on the surface of the copper substrate and air-cooled to room temperature. In our previous study, this simulator has been demonstrated that this strip-casting simulator can simulate the strip casting of steel well. In order to in situ observe the austenite transformation during the reheating process, confocal laser scanning microscope (CLSM, VL2000DX-SVF18SP) was employed for the observation of reheating process. The strip casts produced by strip casting simulation were machined into cuboid samples and the cross section of cuboid sample was selected as the observation surface after being polished. During the CLSM experiment, samples were heated to 600°C with the heating rate of 15°C/s. After isothermal hold for 900 s, the samples were continuously cooled to room temperature at the rate of 30°C/s. Then, the samples from strip cast and the samples after the reheating process were ground and polished before further etched by 4 pct Nital. The microstructure of samples was observed by optical microscope (OM) and scanning electron microscope (SEM, JSM-7900F). And the electron probe microanalysis (EPMA) was also used to observe the evolution of Mn microsegregation behavior in the medium manganese steel cast strip during reheating process.
DISCUSSION

Microstructure and segregation of the as-cast strip.

Figure 2. (a) OM image and (b) EPMA quantitative Mn mapping of as-cast strip.

Due to the high Mn content in the study steel, the precipitation of ferrite is inhibited, the microstructure of air-cooled cast strip was mainly martensite as shown in Figure 2(a). The distribution of the martensite in the as-cast strip is uniformed, which is similar to most of the medium manganese steel cast strip produced by traditional methods. However, there is obvious banded manganese segregation in the quantitative Mn mapping from EPMA as shown in Figure 2(b). The distance between each two Mn enrichment bands is about 12.5 μm, which indicating that dendritic segregation occurred during the sub-rapid solidification of the steel. Through the characterization of the microstructure and composition of the cast strip, it is easy to see that the Mn segregation in the cast strip is mainly microsegregation, and there is no obvious macrosegregation in the as-cast strip, which is difficult to solve in the traditional continuous casting production of medium manganese steel without homogenizing annealing process.

Figure 3. The formation of Mn dendritic segregation in the as-cast strip.

The formation of dendrite segregation can be deduced to be related to the solidification. At first, the solidification and growth of the dendrite trunk leads to the enrichment of Mn element in the surrounding interdendritic molten steel during solidification (Figure 3(a-c)). Then, with the further decrease of temperature, the interdendritic molten steel solidified, which resulting in the composition heterogeneity in the cast strip (Figure 3(d)). Due to the faster cooling rate of the cast strip after solidification, the diffusion of Mn element is inhibited, so the composition heterogeneity can be retained in the room temperature. However, it is worth noting that although Mn elements enrichment can improve the stability of austenite and reduce the martensite transformation temperature ($M_t$) to a certain extent, martensite transformation still occurs in the Mn enrichment band due to the faster cooling rate after the casting. In other word, the dendritic segregation has little effect in the microstructure of as-strip cast.
In-situ observation of phase transformation during reheating process.

The reheating process of cast strip through CSLM is shown in Figure 4. It can be seen that the austenite phase transformation mainly occurs in the process of holding process, and no obvious phase transformation phenomenon occurs in the heating process (Figure 4(a)). The process of sub-rapid solidification tends to enrich manganese in the interdendritic region of the steel produced by strip casting as shown in Figure 2(b). As austenite stabilizers, Mn can significantly reduce the temperature of the austenite transformation initiating temperature (Ac1). Therefore, the austenite transformation occurs in the interdendritic Mn enriched areas. The change of crystal structure used to lead to the change of the volume in the phase transformation region, which lead to the sinking of the interdendritic region during the holding process as shown in Figure 4(b-d). Besides, until the end of the holding process, phase transformation still did not occur in the interior of dendrite (Figure 4(d)). It is found that the austenite transformation mainly occurs in the interdendritic region with Mn enrichment band by in-situ observation during reheating process. These results indicate that the Mn enrichment bands formed in the process of strip casting can reduce the Ac1 temperature in the local region to a certain extent, and thus induce the austenite transformation. These results suggested that the Mn dendritic segregation would result in the inhomogeneity of the phase transformation during reheating process, which would lead to heterogeneous microstructure of the cast strip after reheating process: austenite is distributed in the interdendritic areas, and martensite is distributed in the dendrite.

The evolution of microstructure and chemical composition during the reheating process.

Figure 4. In-situ observation of the strip cast samples held at 600°C for (a) 1s, (b) 150s, (c) 500s, (d) 900s.

Figure 5. (a-c) OM (The brown areas surrounded by white dotted lines corresponds to austenite and white areas corresponds to martensite) and (d) SEM images (The brown areas surrounded by white dotted lines corresponds to austenite and the other white areas corresponds to martensite) of microstructure in the samples which was reheated to 600°C for 900s.
The examinations suggested that the microstructure in the reheated samples consists of two components: martensite and austenite as shown in Figure 5. Under lower magnification, it can be seen that the austenite mainly distributed in the interdendritic areas which is consistent with the in-situ observation (Figure 5(a-b)). Under higher magnification OM, it can be found that the white area around austenite has obvious lath martensite characteristics (Figure 5(c)). SEM images showed that the boundary of martensite lathes was not obvious after reheating process. It indicates that the martensite without transformation to austenite during the reheating process transformed into tempered martensite. Besides, martensite lath appeared in austenite, which indicated that part of retained austenite transformed to martensite again during the cooling process after reheating process (Figure 5(c)).

![Figure 6. EPMA quantitative Mn mapping of cast strip after reheating process.](image)

Figure 6 shows the Mn distribution in the samples after reheating process. It can be seen that the Mn microsegregation was still retained and the distance between enrich bands almost remains unchanged after reheating process. That is to say, the temperature of 600°C is insufficient to cause the Mn in the sample to carry out the long-distance diffusion and homogenize in the samples. However, compared to the strip cast, the content of Mn increased in part of the Mn enrich band with the formation the austenite and reduced in the Mn enrich band without austenite transformed, which induced that the Mn elements can carry out short-distance diffusion in the 600°C.

Through the OM images and SEM images, the samples which was reheated to 600°C for 900s have austenite-martensite heterogeneous microstructure. It is indicated that the main phase transformation during the reheating process is mainly $\alpha' \rightarrow \gamma$ in the interdendritic Mn enriched areas. And the tempering process of martensite mainly occurs in the interior of dendrite with Mn depleted bands. Compared with the prior austenite formed in the solidification process, the austenite formed in the reheating process has the finer grain size, which improve the stability of the retain austenite. So, most of austenite transformed during the reheating process is retained during the cooling process. According to Figure 6, the reheating process involves not only the transformation of austenite, but also the enrichment of Mn element. The formation of austenite during the reheating process would promote the partitioning of the surrounding Mn elements. Due to the austenite directly formed at the interdendritic Mn enrich areas, austenite has the higher Mn content. Therefore, compared to homogenization samples, the Mn in the strip cast with Mn dendritic segregation was easier to enrich in the austenite, which result the higher stability of the austenite. Besides, medium manganese duplex steel produced by strip casting have the unique heterogeneous microstructure after the reheating process. The more dispersed and finer austenite grains can effectively prevent crack initiation in the process of deformation.

**CONCLUSIONS**

The strip-casting simulator has been used to simulate the strip casting of medium manganese duplex steel. And the evolution of the structure and Mn microsegregation behavior in the medium manganese steel cast strip during reheating process were studied. The following conclusions were drawn:

1. The structure of the strip cast was found to be mainly martensite and have uniformed distribution. But the obvious Mn enrichment was found in interdendritic areas of the strip cast. It is shown that the process of strip casting can avoid Mn macrosegregation and promote the Mn microsegregation in the medium manganese steel.
2. The phase transformation of the cast strip during the reheating process was in-situ observed by CSLM. It can be seen that the austenite transformation mainly occurred in the interdendritic Mn enriched band areas and the martensite in the dendrite remained unchanged during the reheating process.
3. The medium manganese duplex steel produced by strip casting was found to have the unique heterogeneous austenite-martensite microstructure after the reheating process. The partition of Mn elements during the reheating process was

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found to increase the content of Mn elements in part of the Mn enrich band with the formation the austenite. It is induced that the short-distance Mn diffusion had taken place during the reheating process.

REFERENCES


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