Original Article

Hot ductility of Cr15Mn7Ni4N austenitic stainless steel slab

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1. Introduction

Stainless steel has been widely used in various fields, including daily necessities, decoration, and other fields. The industrial application of continuous casting has improved the productivity and quality of steels [1,2]. However, the crack in continuous casting slab has been one of the main problems during the continuous casting process, which has attracted much attention of many researchers [1–5]. The hot tensile test has been developed to be the main research method to simulate the slab condition in continuous casting, which has also proven to be very useful in designing secondary cooling patterns to avoid the formation of crack [6,7]. According to the conditions during continuous casting, the strain rates of hot tensile tests were usually taken to be \(10^{-4} - 10^{-2} \text{ s}^{-1}\). The reduction of area (RA) determined by the hot tensile tests can be used to evaluate the susceptibility to crack formation of the slab during the continuous casting process.

The effect of grain refinement by the addition of nitrogen on the hot ductility of 316N stainless steel was investigated by Kim [8]. The grain size was reduced from 100 \(\mu\text{m}\) to 47 \(\mu\text{m}\)
as nitrogen concentration was increased from 0.04% to 0.1%; meanwhile, there was an 8% increase in yield stress. Zhang et al. [9] studied the effects of steel composition and cooling rate on the hot ductility of steel. They found that the hot ductility improved with the increase of the strain rate, while the increase of the holding temperature performed a negative effect on the hot ductility of steel. The effect of aluminum contents on hot ductility of steel was investigated by Wang et al. [10]. They found that the hot ductility was very poor in the steel containing 0.54 wt pct aluminum, which was lower than 20 pct in the temperature range from 873 K to 1473 K. For the steels containing 0.002 and 2.10 wt pct aluminum, the ductility was higher than 40 pct in the same temperature range. Lan et al. [11] investigated the solidification microstructure and hot ductility of Fe-22Mn-0.7C steel. They reported that the intragranular MnS inclusions and grain boundaries sliding led to the drop of the hot ductility with the temperature range from 1073 to 1223 K. These studies indicated that the hot ductility of steels was affected by many factors.

Some studies have investigated the effects of phase structure on the hot ductility of stainless steels. Mintz et al. [12] have investigated the hot ductility of an austenitic and a ferritic stainless steel. They found that ductility was excellent at fine grain size throughout the temperature range (700–1000 °C) and strain rates examined (10\(^{-1}\)–10\(^{-4}\) s\(^{-1}\)). The poor ductility in coarse grain size stainless steel was due to the presence of precipitation, mainly at the grain boundaries. The effect of strain rate on the deformation behavior of the slab shell and slab core in Cr15Mn9Cu2NiN slab was studied through hot tensile tests by Hou et al. [13]. They pointed out that too many ferrite/austenite interfaces in the microstructure of the slab shell led to a high decrease (20%) of RA. However, Bilmes et al. [14] have reported that the ferrite plates had high coherence with the austenitic matrix, and the separation in the ferrite/austenite interface was barely reproduced, which would be beneficial to the ductility of austenitic stainless steel. It can be found that the effect of ferrite on the hot ductility of austenitic stainless steel is still controversial [15–18]. Thus, this work is aim to get a further understanding of the effect of ferrite on the hot ductility of Cr15Mn7Ni4N austenitic stainless steel, which is important for optimizing the control of continuous casting.

2. Method

2.1. Materials

The steel sample for hot tensile experiments was taken from the columnar zone of the continuous cast slab to investigate the hot ductility of Cr15Mn7Ni4N austenitic stainless steel slab. The sampling positions of the tensile specimens are shown in Fig. 1. The tensile specimens were machined to 10 × 120 mm with 10 mm thread zone. The sketch of tensile specimens is shown in Fig. 2. The steel specimen taken at the sampling position was cleaned by machining off the surface for chemical analysis. Cylinders (5 × 5 mm) were machined for the measurement of the nitrogen contents which were analyzed by the inert gas fusion-infrared absorptiometry method. The contents of C and S were analyzed by high-frequency infrared carbon and sulfur analyzer. The contents of Si, Mn, P, Cr, and Ni were determined by the inductively coupled plasma optical emission spectrometry method (ICP-OES). The chemical compositions of the steel specimen are shown in Table 1.

2.2. Experimental methods

Hot tensile experiments were carried out on the Gleeble-3500 thermomechanical simulator. Thermal histories for the hot tensile experiment are shown in Fig. 3. Tensile specimens were heated up to 1250 °C with a heating rate of 10° C s\(^{-1}\), kept for 5 min to homogenize, and then heated up or cooled down with
Chemical composition of the steel sample (mass percent).

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>0.031</td>
<td>0.50</td>
<td>7.38</td>
<td>0.01</td>
<td>0.0027</td>
<td>14.76</td>
<td>4.00</td>
<td>0.11</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature/°C</th>
<th>The reduction of area/%</th>
<th>Tensile strength/Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>0.00</td>
<td>2.19</td>
</tr>
<tr>
<td>1350</td>
<td>23.96</td>
<td>9.58</td>
</tr>
<tr>
<td>1300</td>
<td>48.45</td>
<td>16.83</td>
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<tr>
<td>1250</td>
<td>65.19</td>
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<td>67.28</td>
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<tr>
<td>1150</td>
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<td>25.02</td>
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<td>32.09</td>
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<tr>
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<tr>
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<td>800</td>
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<td>39.68</td>
<td>205.89</td>
</tr>
<tr>
<td>650</td>
<td>41.73</td>
<td>256.34</td>
</tr>
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</table>

The reduction of area and tensile strength of all samples.

Equilibrium phases of stainless steel at different temperatures.

3. Results and discussion

The equilibrium phase diagram of the Cr15Mn7Ni4N stainless steel is shown in Fig. 4, which was calculated by Thermocalc software. It can be seen that the liquid steel began to solidify at 1446 °C in conjunction with the formation of δ-ferrite (BCC_A2). At 1426 °C, δ-ferrite reaches a maximum mass fraction of 55.42%. Meanwhile, the γ-austenite (FCC_A1) was formed with the peritectic reaction (L → δ → γ). As the temperature decreased to lower than 1407 °C, MnS was formed. Liquid steel completely disappeared at 1407 °C. When the temperature was lower than 1321 °C, the δ-ferrite (BCC_A2) phase was completely transferred into γ-austenite (FCC_A1) phase. When the temperature was lower than 708 °C, the γ-austenite (FCC_A1) phase began to transform into the α-ferrite (BCC_A2) phase. Meanwhile, the amount of α-ferrite (BCC_A2) phase increased with the decrease of temperature. The optical micrograph of the stainless steel slab is shown in Fig. 5. It can be found that the network ferrite filled in the slab microstructure. The volume fraction of ferrite of the sample was 14.7%.

The true stress-strain curves obtained from hot tensile experiments at different temperatures are shown in Fig. 6. It can be seen that the flow curves gradually increased to a peak point by strain hardening at temperatures ranging from 650 °C to 800 °C. At temperatures ranging from 825 °C to 1300 °C, the flow curves reached a plateau after the initial strain hardening, and followed by a decrease of the flow stress (softening). The difference in these curves might be due to the dynamic recrystallization (DRX) behavior [19,20]. Generally, the occurrence of dynamic recrystallization can be known from the abrupt decrease or oscillation of flow curves [21]. The increase of deformation temperature could promote DRX, which would...
lead to the DRX performance at the temperature above 825 °C [19]. When the temperature increased to 1350 °C, the curve decreased dramatically, which was due to the temperature approaching the solidus of the steel (1407 °C). According to the stress-strain curves, the tensile strengths of samples at different temperatures are shown in Fig. 7. It can be found that the tensile strength was almost 0 MPa at 1400 °C close to solidus. As the temperature decreased, the tensile strength gradually increased. When the temperature was lower than 850 °C, the tensile strength increased at a higher rate. The highest tensile strength was 256.34 MPa at 650 °C.

The hot ductility curves of Cr15Mn7Ni4N stainless steel are shown in Fig. 8. The experiment results of austenitic stainless steel from other researchers are also plotted for comparison. It can be found that the reduction of area was lower than 40% with the temperature higher than 1300 °C. When the temperature was higher than 1300 °C, it was close to the solidus. Therefore, the liquid film would exist in the grain boundary, which could become the crack nucleation on the grain boundary during the hot deformation process. The fracture morphology of tensile samples is shown in Fig. 9. As can be seen in Fig. 9(a) and (b), parts of the grain boundary in tensile samples at the temperature higher than 1300 °C were in a liquefied state, which would deteriorate the hot ductility of steel and reduce the reduction of area. At 1200 °C and 1250 °C, the reduction of area was higher than 60%. The specimens performed a ductile fracture with some dimples, as shown in Fig. 9(c) and (d), indicating a better hot ductility at these temperatures. With temperatures ranging from 750 °C to 1300 °C, the reduction of area of tensile samples was basically at 50%–60%. Hou et al. [13] have experimentally investigated the hot ductility at 0.1 s⁻¹ strain rate from similar stainless steel slab (Cr15Mn9Cu2NiN), which is also shown in Fig. 8. In Hou’s study, much higher reduction of area was obtained at 1000–1250 °C, which might be related to the strain rate being much higher than 1 × 10⁻³ s⁻¹ strain rate in the present work. Meanwhile, Mintz et al. [12] have investigated the hot ductility of austenitic
stainless steel (Fe-0.014C-0.40Si-1.7Mn-0.013P-0.006S-25.5Cr-2.16Mo-22.4Ni-0.130N-0.11V-0.002O) with 600μm grain size at $10^{-3}$ s$^{-1}$ strain rate, as shown in Fig. 8. It can be found that the RA in Minz’s study was higher than that of Cr15Mn7Ni4N stainless steel. They pointed out that the poor ductility at 850°C was due to the precipitation of coarse chromium carbides at the grain boundaries. The 14.76 mass% Cr content in the Cr15Mn7Ni4N steel was much lower than 25.5 mass% Cr content in their stainless steel. Therefore, coarse chromium carbides were not observed at the grain boundary in this experiment. The third brittle zone for Cr15Mn7Ni4N stainless steel was around 650°C–750°C, in which the RA decreased sharply from 51.56% at 750°C to 39.68% at 700°C.

The ferrite structure of the tensile samples taken after tensile test ranging from 650°C to 775°C are shown in Fig. 10. The volume fraction of ferrite of samples was analyzed by using ImageJ software, as shown in Table 3. The volume frac-

Fig. 9 – Fracture morphology of tensile samples: (a) 1350°C, (b) 1400°C, (c) 1200°C, (d) 1250°C, (e) 700°C, (f) 750°C.
tion of ferrite in the sample at 750 °C was 5.8%, which was higher than 4.3% of the sample at 775 °C. As the temperature decreased, the ferrite of samples increased rapidly from 5.8% at 750 °C to 10% at 700 °C. Meanwhile, the reduction in area of stainless steel also decreased from 51.56% at 750 °C to 39.68% at 700 °C. As the temperature decreased to 650 °C, the ferrite increased to 12.7%. The calculation results of the equilibrium phase in Fig. 4 also indicated that the ferrite began to form at 708 °C, and the amount of ferrite gradually increased with the decrease of temperature. During the high-temperature deformation process, the deformation induced ferrite (DIF) could begin to form at the temperature above 708 °C, which would cause the amount of ferrite to rapidly increase to 10% at 700 °C [22–24]. As the ferrite increased, strain concentration imposed on the ferrite within austenite would increase rapidly, which was due to the strength difference between ferrite and austenite [13,25]. The strain concentration could lead to the uncoordinated deformation in ferrite and austenite, which would cause the decrease of hot ductility of stainless steel. This indicated that the increase of ferrite from 5.8% at 750 °C to 10% at 700 °C would lead to the decrease of hot ductility of stainless steel at the temperature lower than 750 °C.

Table 3 – The volume fraction of ferrite of the tensile sample at different temperatures.

<table>
<thead>
<tr>
<th>The temperature of tensile sample/ °C</th>
<th>The volume fraction of ferrite/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>12.7</td>
</tr>
<tr>
<td>700</td>
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<td>750</td>
<td>5.8</td>
</tr>
<tr>
<td>775</td>
<td>4.3</td>
</tr>
</tbody>
</table>

4. Conclusions

The hot ductility of Cr15Mn7Ni4N austenitic stainless steel slab was investigated from 650 °C to 1400 °C. The dynamic recrystallization performance of the stainless steel occurred at the temperature higher than 825 °C. As the temperature decreased, the tensile strength gradually increased to 256.34 MPa at 650 °C. The reduction of area was 50% to 60% at the temperature of 750 °C–1300 °C. The third brittle zone for Cr15Mn7Ni4N stainless steel was around 650 °C–750 °C, in which the reduction of area was lower than 50%. The volume fraction of ferrite in the tensile sample at 700 °C (10%) was higher than the sample at 750 °C (5.8%). The equilibrium phase diagram also indicated that ferrite began to form at 708 °C and increased with the decrease of temperature. The reduction of area of the tensile sample decreased from 51.56% at 750 °C to 39.68% at 700 °C, which indicated that the formation of ferrite could lead to the decrease of the hot ductility.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES


