Study on high temperature plasticity of Q390 microalloyed steel

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Abstract: In this paper, the effect of Al and Ti on the high temperature plasticity of Q390 microalloyed steel was studied. The high temperature tensile tests of two Q390 steels with different contents of aluminum and titanium (0.02%Al-0.01%Ti and 0%Al-0.02%Ti) were carried out on Gleeble 3800 thermal simulation test machine. The high temperature plasticity of the two steels was compared and analyzed by calculation of shrinkage ratio, fracture morphology and energy spectrum of the precipitates. The study indicated: The toughness of 0%Al-0.02%Ti steel is 12%-35% higher than that of 0.02%Al-0.01%Ti steel in the III brittleness temperature zone. Aluminum has a negative effect on the high temperature plasticity of microalloyed steel, while titanium has a positive effect on the high temperature plasticity of microalloyed steel. Therefore, the surface quality of Q390 microalloyed steel is improved when Q390 is adopted the composition of 0%Al-0.02%Ti steel.

1. Introduction
Micro-alloy high-strength steel has been widely used in various fields with its high strength, high toughness and excellent weldability. It has been used especially in the construction industry, bridge construction and shipbuilding [1]. The addition of Nb, V, Ti micro alloy elements can improve the strength and toughness of the steel with refined grain strengthening and precipitation strengthening. However, these elements increase the crack sensitivity of steel slab, which makes it more prone to crack and other surface defects during continuous casting production [2, 3], and seriously affects the surface quality of continuous casting slab.

Due to the large size and difficult control of production process parameters, the surface quality of microalloyed steel wide and thick continuous casting slab is worse. However, the demand for wide and thick plates is increasing with the rapid development of modern industry, which has great economic benefits. Therefore, it is of great significance to reduce and prevent surface defects of microalloyed steel continuous casting slab by studying the high temperature plasticity of microalloyed steel. In particular, the Q390 microalloyed steel wide and thick continuous casting slab of SGIS Songshan Co., Ltd has...
some surface defects, which affect the overall economic benefit. Aluminum and titanium have a greater impact on these surface defects. In this study, the influence of Al and Ti on the high temperature plasticity of the Q390 microalloyed steel is studied.

2. Materials and methods

2.1. Materials
The experimental material was Q390 microalloying steel produced by SGIS Songshan Co., Ltd. During production, the composition was adjusted as shown in Table 1, which form two groups of Q390 microalloying steel with different composition.

Table 1 Chemical composition of the experimental steels (mass%)

| Steel | C   | Si | Mn   | P   | S   | N   | Nb | Ti | Al |
|-------|-----|----|------|-----|-----|-----|----|----|----|
| I     | 0.16| 0.30| 1.45 | 0.020| 0.006| 0.005| 0.030| 0.020| —  |
| II    | 0.16| 0.30| 1.45 | 0.020| 0.006| 0.005| 0.030| 0.010| 0.020|

In order to ensure uniform composition and microstructure of the sample, the steel was cut from the part of the continuous casting billet with better quality, and then the 40mm epidermis around it is removed, as shown in Fig. 1. Finally, the steel was processed to make a Ø10mm diameter and a 120mm length round bar with threads on both ends. The sample size is shown in Fig. 2.

2.2. Methods
The high temperature tensile test was conducted on the Gleeble 3800 thermal simulation machine. A schematic diagram of thermomechanical controlled processing is shown in Fig. 3. After the sample was placed, vacuum was pumped. Then the samples were reheated to 1320℃ at a heating rate of 10℃/s and held for 3min to fully dissolve the precipitates. Next, the samples were cooled to the target temperature (600℃, 650℃, 700℃, 750℃, 800℃, 850℃, 900℃, 950℃, 1000℃, 1050℃, 1100℃, 1150℃, 1200℃,
1250℃, 1300℃) at a rate of 3℃/s and held for 30s eliminate the temperature gradient. The strain rate of $\varepsilon = 1 \times 10^{-3} \text{s}^{-1}$ was applied for tensile experiment. After the fracture, the samples were quickly cooled to room temperature.

![Fig.3 Schematic diagram of high temperature drawing process](image)

After the sample was fractured, the cross-sectional area of the fracture site was measured. The section shrinkage rate $R$ of the sample was calculated according to formula (1), so as to evaluate the high temperature plasticity of the sample. According to the calculated data, the trend diagram of the section shrinkage rate $R$ with the change of temperature was drawn in Fig. 4. The fracture morphology of the two steels at different temperatures was observed and compared by Sigma300 scanning electron microscopy (Gemini, ZEISS, the United Kingdom), and the corresponding positions were analyzed by energy dispersive spectrum.

$$ R = \frac{(A_1 - A_0)}{A_0} $$

In the formula, $A_0$ is the original cross-sectional area of the sample. $A_1$ is the cross-sectional area at the neck contraction of the sample after breaking.

3. Results & Discussion

3.1. Tensile mechanical property

The change of section shrinkage of the two steels at different temperatures is shown in Fig. 4. In general, the section shrinkage rate $R$ is used as an index to characterize the high-temperature plasticity of the material. The higher the section shrinkage rate is, the better the plasticity is, and the lower the probability of cracking of continuous casting slab is. In general, the critical point is the section shrinkage rate $R=60\%$. When the section shrinkage rate is higher than 60\%, it is called the toughness interval. The section shrinkage rate is lower than 60\%, it is called the brittle interval [4].

In Fig. 4, there are some differences in the overall high temperature plasticity of the two steels, especially in the 700-950℃ range, which is the third brittle zone of the steel. In this temperature range, $\gamma$ phase transitions to $\alpha$ phase. Thin-film $\alpha$ phase precipitates at the grain boundary of $\gamma$ phase, which reduces the continuity of $\gamma$ phase and reduces the high temperature plasticity of steel. Moreover, the strength of $\alpha$ phase is much lower than that of $\gamma$ phase, which also reduces the plasticity of steel and is prone to fracture. In addition, the precipitation of the second phase particles in the austenite grain boundary nail the austenite grain boundary, which reduces the ability of grain boundary to coordinate deformation, and also causes the embrittlement of grain boundary to reduce the plasticity. At the same time, there is a thin and soft precipitation-free zone at the grain boundary, which significantly reduces the bonding force of the grain boundary, increases the crack sensitivity. In this temperature range, the
plasticity of steel I is significantly worse, while steel II shows better plasticity.

![Graph showing section shrinkage of two steels at different temperatures](image)

Fig.4 Section shrinkage of two steels at different temperatures

3.2. The fracture morphology
The SEM micrographs of fracture morphology at 600-1000℃ was photographed. The difference between the two samples can be clearly observed. Steel I shows obvious brittle fracture in the third brittle temperature zone, and the macroscopic necking phenomenon is weak. Its fracture form is cleavage fracture. Cleavage fracture is a transgranular fracture that occurs along a certain crystallographic plane at a very fast rate. Its microscopic features become a very flat mirror surface, which is composed of many cleavage surfaces roughly equivalent to the size of the crystal grains. In the III brittleness temperature zone, the toughness of steel II is reduced slightly, and the macroscopic neck shrinkage phenomenon is relatively obvious. The fracture morphology of the sample shows a river pattern which is semi-cleavage fracture. Some areas are microporous aggregation fracture, showing dimples of different depths, and there are obvious tearing edges at grain boundaries, which are ductile fractures.

In Fig. 5, at 600℃ and 650℃, the fracture shrinkage of the two steels is large and basically the same, and there is an obvious necking phenomenon at the fracture, which is a ductile fracture. The fracture morphology of the two steels is not much different, and there are many dimples of different depths, which are microporous aggregation type fractures.
In Fig. 5, comparison of fracture morphology at 600℃ and 650℃:
(a) I, 600℃; (b) I, 650℃; (c) II, 600℃; (d) II, 650℃.

In Fig. 6, below 700℃, the shrinkage ratio of the two steels is not much different, which belongs to the typical cleavage fracture. At 750℃, a huge contrast is formed. The fracture shrinkage of steel II has been significantly increased. Obvious micropore aggregation can be observed from the fracture morphology, showing a certain toughness. While the shrinkage of steel I continues to decline, with great brittleness. The fracture of steel I is still typical cleavage fracture.

In Fig. 7, at 800℃ and 850℃, the difference between steel I and steel II is still obvious. Steel II still shows better toughness. Steel I is still brittle fracture, but its toughness is increased.
As shown in Fig. 7, with the increase of temperature, at 900°C and 950°C, the shrinkage rate of steel I increases. Its plasticity is improved. Shrinkage cavity began to gather in some areas of the fracture. Steel II continues to maintain good plasticity. The places where the micropores gather are more and more even.
In Fig. 9, after the temperature exceeds the III brittle interval, the plasticity of the two steels rebounded rapidly, and the fracture shrinkage rates of the two steels increased significantly. The fracture has a very obvious necking phenomenon, showing strong toughness.

3.3. Energy dispersive spectrum
Due to the large difference in high-temperature plasticity, the relevant areas are especially enlarged to find the differences under the microscopic view and energy dispersive spectrum were performed. Comparing the microstructures in Fig. 10 and Fig. 11, it can be seen that there are more obvious luminescent precipitated particles in steel II, while there are few such precipitated particles in steel I. The energy dispersive spectrum of the corresponding particles was performed. Their elemental composition are obviously different. The main precipitation in steel II are Ti and Nb, while the main precipitation in steel I are Ti and Al.
3.4. Influence of precipitates

Microalloying elements are mainly precipitated in steel grades as second phase particles such as AlN, TiN, TiC, Ti (C, N), Ti2CS, NbC, NbN, and Nb (C, N).

For Al elements, the AlN precipitated phase has obvious edges and corners. It is usually quadrilateral, hexagon, or irregular shape, small size. Under normal circumstances, AlN precipitates at about 900℃, which greatly reduces the ductility of the austenite region, which causes the third brittleness to widen and the wave trough to deepen. It has a certain negative effect on the fracture toughness of the steel [5,6].

The carbon and nitride of Nb will not precipitate until the temperature is lower than 1000℃. This precipitation will reduce the binding energy of the grain boundary interface. Under stress concentration, it will easily deform into pores and aggregate to form cracks when the grain boundary slips. This deteriorates the high temperature plasticity of cast slab [7].

For Ti element, it has a stronger binding capacity with carbon and nitrogen than niobium, vanadium, and aluminum. At high temperatures, TiN phase will be precipitated, which reduces the nitrogen content of steel grades, plays a role in nitrogen fixation. This reduces the precipitation of Nb (C, N) and AlN at the austenite grain boundary, and reduces the influence of the second phase precipitation in the third brittle zone. At the same time, TiN has a pinning effect on the austenite grain boundary, which prevents the growth of the austenite grain boundary, refines the austenite grains, reduces the prerequisites for cracks, and improves the high-temperature ductility of the cast slab. When the temperature is relatively low, the titanium precipitated particles are large and scattered, which can be used as nucleation points for niobium, vanadium and other precipitates to form composite carbonitrides. This reduces the adverse effects of niobium and vanadium on the high-temperature plasticity of steel [8].

When Ti content exceeds 3.4w(N), Ti4C2S2 begins to form. When the Ti content exceeds 3.4w(N) + 3w(S), excess Ti is precipitated in the ferrite to form fine dispersed TiC particles, which play a role of
precipitation strengthening \[9\]. Steel I, due to the lower Ti content, less TiN formed with N, which cannot form an effective nitrogen fixation effect. This cause AlN and Nb carbonitrides to normally precipitate in the austenite grain boundaries in the III temperature zone, which weaken the bonding energy between the grain boundaries, and easily cause stress concentration, deteriorates the high temperature plasticity of the slab. Therefore the fracture shrinkage rate is greatly reduced. The second phase precipitates of Al and Nb in this temperature range are relatively small and deform and break under the action of external force, so it is difficult to find complete second phase precipitates. Steel II, the increase of Ti content increases the precipitation of TiN which inhibits the growth of prior austenite grains and makes the austenites finer. The nitrogen fixation effect of Ti is obvious. The precipitation of Nb nitride is inhibited. The precipitation temperature of Nb nitride is reduced. At the same time, aluminum element is removed, so that there is no AlN phase at high temperature to deteriorate the high temperature plasticity of the slab.

4. Conclusions
(1) There is a significant difference in the high-temperature plasticity of the two-component steel in the third brittle temperature range of 700-950℃. The toughness of steel II is 12%-35% higher than that of steel I. The fracture forms of steel II are mainly quasi-cleavage fracture and microporous aggregation fracture. The fracture shrinkage rate of steel I is low, and its fracture form is basically cleavage fracture.

(2) The Al element has an adverse effect on the high-temperature plasticity of the steel. The precipitation of the Al deteriorates the high-temperature toughness of the steel. Increasing the content of Ti element refines the austenite grains and suppress the precipitation of Nb (C, N) and AlN, which is beneficial to the high-temperature plasticity of the steel.

(3) In actual production, the Q390 microalloyed steel increases Ti content and removes Al element, which improves the overall plasticity of the III brittle zone and reduces the crack sensitivity of the niobium-containing microalloyed steel. The surface quality of Q390 microalloyed steel wide and thick continuous casting slab is improved.

In the future, it is necessary to further study the precipitation relationship of Al, Ti, Nb, V and other microalloying elements at high temperature of steel. By comparing the high-temperature performance of different types and quantities of precipitates, the effect of microalloying elements on the high-temperature performance of steel can be further clarified. These provide guidance and theoretical basis for further optimizing the alloy composition of steel grades. As a result, the high-temperature performance of steel can be continuously improved, and the surface defects of the continuous casting slab can be further reduced.

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