Postprint: High-Temperature Mechanical Properties of P-Containing High-Strength IF Steel

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Abstract

The high-temperature mechanical properties of P-containing high-strength IF steel were investigated by determining the zero ductility temperature (ZDT), zero strength temperature (ZST), and temperature dependence of maximum tensile strength using a Gleeble3500 thermal simulator, observing and analyzing the fracture morphology at different tensile temperatures via scanning electron microscopy, and calculating phase transformations and precipitated phases during cooling using THERMO-CALC software. The results indicate that the ZDT and ZST of this steel grade are 1420°C and 1445°C, respectively; the Type I brittle temperature range is 1400°C to melting point; no Type III brittle temperature range exists; and slab surface cracks are not formed during straightening. The maximum tensile strength of the slab decreases with increasing tensile temperature, remaining below 5.3 MPa at temperatures above 1300°C. Large amounts of Fe3P precipitate when the high-strength IF steel continuous casting slab is cooled to 500°C-200°C, potentially causing cold brittleness cracking. Adopting a hot charging process can reduce the probability of transverse crack occurrence on the surface of high-strength IF steel slabs.

Full Text

High Temperature Mechanical Properties of P-Containing High Strength IF Steel

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Abstract

The high-temperature mechanical properties of P-containing high-strength interstitial-free (IF) steel were investigated using a Gleeble3500 thermal simulation testing machine to determine the zero ductility temperature (ZDT), zero strength temperature (ZST), and the relationship between maximum tensile strength and temperature. Fracture morphologies at different tensile temperatures were characterized using scanning electron microscopy, and phase transformations and precipitates during cooling were calculated using THERMO-CALC software. The results show that the ZDT and ZST of this steel are 1420℃ and 1445℃, respectively. The brittleness temperature interval I is from 1400℃ to the melting point, and there is no brittleness temperature interval III, indicating that surface transverse cracks on the casting blank did not form during the straightening process. The maximum tensile strength of the casting blank decreases with increasing temperature, with all values below 5.3 MPa above 1300℃. When the high-strength IF steel continuous casting blank cools to 500℃-200℃, a large amount of Fe3P precipitates, which may cause cold brittleness cracking. Adopting hot charging technology can reduce the probability of surface transverse cracks on high-strength IF steel casting blanks.

KEY WORDS: metallic materials, high temperature mechanical properties, high-temperature tension test, P-containing high strength IF steel, THERMO-CALC, phase transition

Introduction

The development of the automotive industry urgently demands vehicle weight reduction and improved impact resistance, leading to rapid advancement in high-strength steel production. Among these, high-strength IF steel developed based on interstitial-free steel has been widely applied in automotive manufacturing. In its matrix, C and N atoms are completely fixed by Ti and Nb, which benefits texture development during annealing. Consequently, high-strength IF steel exhibits excellent deep-drawing properties, and solid solution strengthening is achieved by adding elements such as P, Mn, and Si, improving strength without compromising ductility and the plastic strain ratio r-value [1-4]. A steel plant discovered surface transverse cracks during offline inspection of P-containing high-strength IF steel continuous casting blanks, seriously affecting product qualification rates. This study uses a Gleeble3500 thermal simulation testing machine to investigate the high-temperature mechanical properties of this steel's casting blanks and applies THERMO-CALC to calculate phase transformations and precipitates during cooling, providing a theoretical basis for controlling continuous casting and hot rolling parameters.

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1. Experimental Methods

The high-strength IF steel used in the experiments was produced via the 210t BOF—210t RH—CC process, with main chemical compositions listed in Table 1 . Normal continuous casting blanks with cross-section dimensions of 1300 mm × 230 mm were used for high-temperature thermoplasticity studies. Tensile specimens were taken between 1/2 to 1/4 of the blank width, near the inner arc side, with the specimen length direction aligned with the casting direction. The tensile specimens had a diameter of 10 mm, length of 121.5 mm, threaded ends of 15 mm length, and thread pitch of 1.5 mm.

A Gleeble3500 thermal simulation testing machine was used to investigate the high-temperature mechanical properties of high-strength IF steel, obtaining the variation of reduction of area ( ) and maximum tensile strength (σmax) with temperature, thereby determining the ZDT and ZST values—defined as the temperatures at which equals zero and σmax equals zero, respectively [5, 6].

To simulate actual production conditions of continuous casting blanks, specimens were first heated to 1375℃ at 10℃/s and held for 3 minutes to eliminate internal stresses, then cooled to the tensile temperature at 3℃/s, held again for 3 minutes, and finally stretched at a strain rate of 1$×10^{-3}$ s^{-1}. Argon gas was used for protection during the tests. The temperature schedule for high-temperature tensile experiments is shown in Figure 1 [Figure 1: see original paper].

The temperature range for high-temperature tensile experiments was 650℃-1430℃. The temperature interval was 25℃ in the 800℃-1000℃ range, 10℃ above 1400℃, and 50℃ in other temperature ranges. After fracture, specimens were immediately cooled by blowing large amounts of compressed air on the fracture surfaces to preserve the high-temperature microstructure morphology. The macroscopic fracture morphology was observed under scanning electron microscopy to analyze the fracture mode.

The Fe-based alloy database in Thermo-Calc software was used for thermodynamic simulation calculations to obtain the precipitation temperatures and amounts of equilibrium phases precipitated in the experimental steel casting blanks during cooling.

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2. Results and Discussion

2.1 High-Temperature Tensile Strength The maximum tensile strength of steel refers to the maximum stress resisting uniform plastic deformation. During continuous casting, when stress at any point on the blank exceeds σmax, cracks form. The relationship between σmax and temperature for high-strength IF steel casting blanks is shown in Figure 2 [Figure 2: see original paper]. It can be seen that σmax gradually decreases with increasing tensile temperature. In the 650℃-800℃ range, σmax drops sharply; in the 800℃-1250℃ range, σmax slowly decreases with increasing temperature, dropping to 24.2 MPa at 1250℃. In the 1250℃-1300℃ range, σmax decreases significantly, reaching 5.3 MPa at 1300℃. At 1430℃, σmax is 2.4 MPa, and linear fitting yields a zero strength temperature (ZST) of 1445℃ for high-strength IF steel.

When the tensile temperature exceeds 1300℃, σmax of high-strength IF steel is below 5.3 MPa. This result indicates that the steel has low tensile strength above 1300℃. If continuous casting blanks are subjected to large stresses above 1300℃, they are prone to crack defects. Therefore, during production, the precision of the continuous casting machine should be ensured to avoid non-uniform stresses on the blank in the high-temperature zone that could generate cracks.

2.2 High-Temperature Thermoplasticity Reduction of area is the percentage of cross-sectional area reduction at the fracture surface after tensile fracture relative to the original cross-sectional area of the specimen, and is an important indicator for measuring the plasticity of casting blanks. The larger the value, the greater the possibility that the blank can resist external forces without generating cracks.

The variation trend of values with tensile temperature for high-strength IF steel casting blank high-temperature tensile specimens is shown in Figure 3 [Figure 3: see original paper]. Literature [7, 8] proposes that when is greater than 60%, steel is not prone to cracking. Other studies [9, 10] indicate that when is less than 40%, the crack sensitivity of casting blanks increases significantly. Using = 40% as the critical point for judging plasticity, this study obtained brittleness temperature interval I of 1400℃ to melting point for this steel. In the 900℃-1000℃ range, plasticity decreases somewhat, with reaching a minimum value of 61.7% at 950℃, which is still far greater than 40%. This demonstrates that this steel has no brittleness temperature interval III, and surface transverse cracks on casting blanks did not form during the straightening process.

In the 1000℃-1250℃ range, the blank exhibits very good ductility, with values around 80%. After the tensile temperature exceeds 1250℃, the hot plasticity of the blank gradually decreases, with dropping from 79% at 1250℃ to 58.8% at 1400℃. At 1410℃, the value is only 4.5%. Therefore, during continuous casting, the blank should avoid prolonged residence above 1400℃ to reduce the probability of hot cracking. At 1420℃ and 1430℃, values are both zero, indicating that the zero ductility temperature of this steel is 1420℃. The difference between zero strength temperature and zero ductility temperature is 25℃, and the brittle temperature interval at the solidification front is relatively small, indicating that casting blanks of this steel have good resistance to high-temperature cracking.

2.3 Fracture Morphology Analysis Tensile fracture morphology can intuitively reflect the fracture type. The fracture morphologies of specimens at tensile temperatures of 650℃, 800℃, 900℃, 950℃, 1000℃, and 1150℃ were observed using scanning electron microscopy, with results shown in Figure 4 [Figure 4: see original paper].

The fracture at 650℃, shown in Figure 4a, exhibits numerous fine dimples, characteristic of typical ductile fracture. At 800℃, the dimples are larger and fewer in number but much deeper, with reaching 92.4%. The fracture at 950℃, shown in Figures 4d and 4h, consists of numerous particles exhibiting smooth "rock candy" morphology, typical of brittle intergranular fracture, yet the value reaches 61.7%. The fracture morphologies at 900℃ and 1000℃ are similar, as shown in Figures 4c and 4e. The number of dimples is less than that at 650℃, but the dimples are larger and shallower, with values around 77%. At 1150℃, the fracture morphology is similar to that at 800℃, with reaching 88%. Analysis of fracture morphology indicates that in the 650℃-1050℃ range, the tensile fracture mode of specimens is primarily ductile fracture, with only the fracture at 950℃ exhibiting brittle fracture morphology.

2.4 THERMO-CALC Calculation Results Thermo-Calc software was used to calculate the equilibrium phase diagram of high-strength IF steel (multicomponent system property diagram) and plot the element distribution curves in each phase to identify the composition of phases in the diagram, as shown in Figure 5 [Figure 5: see original paper]. At approximately 1350℃, the crystal structure of this steel transforms from body-centered cubic to face-centered cubic, i.e., from δ-ferrite to austenite. In the 1000℃-900℃ range, the crystal structure transforms from face-centered cubic back to body-centered cubic, i.e., from austenite to α-ferrite. This result indicates that the poor plasticity of this steel in the 900℃-1000℃ range is due to the transformation from austenite to α-ferrite in the matrix.

As shown in Figure 5, TiN begins to precipitate in the matrix at approximately 1420℃, with precipitation essentially completed at 1200℃ and an amount of about 2\$$\times10^{\{-4\}.NbNbeginstoprecipitateinthematrixataround900℃, andtransformsfromface-centeredcubicNbNtoclose-packe}$ 4}\$. According to the equilibrium solubility product formulas for NbN and NbC in α-ferrite, lg{[Nb]×[N]}α = 4.96 - 12230/T and lg{[Nb]×[C]}α = 5.43 - 10960/T [11], the estimated equilibrium solution temperatures are 658℃ and 532℃, respectively, indicating that NbC is more stable than NbN in this steel, thus the transformation from NbN to NbC occurs. The precipitation of TiN and NbC demonstrates that Ti and Nb can effectively fix interstitial atoms C and N, thereby improving casting blank plasticity, with most N atoms being fixed by Ti at high temperatures, while C atoms are fixed around 500℃.

When the casting blank cools to about 500℃, the matrix begins to precipitate the P-containing phase Fe3P, with calculations showing that the Fe3P precipitation amount reaches 0.63% at 200℃. When phosphorus segregation concentration at grain boundaries is low, phosphorus exists as a solid solution at grain boundaries [12]; when the segregation concentration is high, structures similar to Fe3P form at grain boundaries. The P content in the experimental steel used in this study is as high as 0.089%, and the M3P precipitated in the matrix at 500℃-200℃ should be Fe3P, which is also identified as Fe3P by the element distribution curves in this phase. Fe3P has high hardness and distributes along grain boundaries, creating significant stress with the α-Fe matrix and producing notable strengthening effects, which markedly reduces steel toughness and ductility [13, 14]. In the experimental steel used in this study, the Fe3P precipitation amount reaches 0.63% when cooled to 200℃. Large amounts of Fe3P precipitation in the matrix may cause cold brittleness and surface cracking in casting blanks. Therefore, when adopting hot charging technology, the temperature of high-strength IF steel casting blanks during hot charging should be above 500℃ to prevent Fe3P precipitation in casting blanks.

Conclusions

1. The zero ductility temperature of high-strength IF steel is 1420℃, and the zero strength temperature is 1445℃. The brittle temperature interval at the solidification front is relatively small, and casting blanks have good resistance to high-temperature cracking.
2. At a strain rate of 1$×10^{-3}$ s^{-1}, the brittleness temperature interval I of high-strength IF steel is 1400℃ to melting point. Plasticity decreases in the 900℃-1000℃ range, with a minimum value of 61.7%; therefore, there is no brittleness temperature interval III, and transverse cracks on casting blanks did not form during the straightening process. The reason for reduced plasticity of high-strength IF steel in the 900℃-1000℃ range is the transformation from austenite to α-ferrite in the matrix.
3. High-strength IF steel casting blanks have poor tensile strength at high temperatures, with maximum tensile strength below 5.3 MPa when tensile temperature exceeds 1300℃. Casting blanks should avoid bearing large stresses above 1300℃.
4. When high-strength IF steel casting blanks cool to 500℃-200℃, large amounts of Fe3P precipitate, with precipitation amount reaching 0.63%, causing cold brittleness cracking in casting blanks.

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Note: Figure translations are in progress. See original paper for figures.