Welding procedure qualification of Q345 grade fire-resistant steel based on Jmat-pro calculation

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Abstract: The welding process of two Q345 grade low Mo (about 0.25 wt.%) fire-resistant steels will be calculated and evaluated in this paper. The continuous cooling transformation (CCT) curve and isothermal transformation (TTT) curve of test steel were calculated by Jmat-pro software. The welding processes of steels were evaluated by measuring the continuous cooling transition (SH-CCT) curves of welding heat affected zone. The test results show that when the actual cooling time of Q1 steel is t8/5>43s, cracking does not occur in the HAZ of welding and near the fusion zone, while when t8/5<43s, cracking may occur in the HAZ or fusion zone; When the actual cooling time of Q2 steel is t8/5>44s, cracking does not occur in the welding heat affected zone and the vicinity of the fusion zone, while when t8/5<44s, cracking may occur in the heat affected zone or the fusion zone. In addition, Jmat-pro software has a certain accuracy for the calculation of Ac3, but has a large error for the continuous cooling transformation (CCT) curve, especially the difference between the calculated value and the measured value of Q2 steel is larger, which only has reference value.

1. Introduction

With the development of economy and society, steel structures have been widely used in the construction field because of their high strength, environmental protection and other advantages, such as Beijing’s Bird’s Nest, World Trade Center and other high-rise and large-span buildings. However, due to the poor fire resistance of steel structure, it is usually necessary to brush the fire-resistant layer on its surface, which will inevitably increase its construction cost and cause pollution to the environment. Fire-resistant steel is characterized by its ability to maintain two-thirds of the room
temperature yield strength at 600°C, while ordinary building steel can only maintain one-half of the room temperature yield strength at 600°C [2-4]. Due to its properties, fire-resistant steel has been widely used in high-rise buildings and other places with high fire safety requirements, especially after the "9.11" incident in the United States [4-6]. As a building steel, the welding process performance of fire-resistant steel has attracted much attention, so it is of great significance to calculate and evaluate its welding process.

The welding process of two Q345 grade low Mo (about 0.25 wt.%) fire-resistant steels will be calculated and evaluated in this paper. The continuous cooling transformation (CCT) curve and isothermal transformation (TTT) curve of test steel were calculated by Jmat-pro software. The continuous cooling transformation curves (SH-CCT) of Q1 and Q2 steel welding heat affected zone were drawn by welding thermal simulation method, through SH-CCT curve and the cooling rate $t_{8/5}$ of the actual welding process, the microstructure and properties of coarse grain zone under different welding processes were predicted, which provided a certain reference for the application of Q345 grade low Mo fire-resistant steel.

2. Test materials and methods
The test material is two Q345 grade, hot rolled 20mm thick, fire-resistant steel, Q1 and Q2. The specific chemical compositions of the Q1 and Q2 steels are presented in Table 1. The chemical compositions of the two tested steels are basically similar, Q2 steel is added with about 0.03 wt. % more than Q1 steel of Nb, V, and Ti microalloy elements.

| Steels | C  | Mn | Si  | Mo | Nb+V+Ti | Fe   |
|--------|----|----|-----|----|---------|------|
| Q1     | 0.10 | 1.00 | 0.33 | 0.25 | 0       | Bal. |
| Q2     | 0.11 | 1.00 | 0.32 | 0.25 | <0.03   | Bal. |

Determination of SH-CCT curve of test steel. The test equipment was a thermal expansion rapid phase change instrument from bahrthermo analysis. Experimental conditions: The austenitizing temperature was 1140°C, the holding time was 5min, and the elevating temperature of 200°C/h was used to measure $Ac_1$ and $Ac_3$. Sample size: diameter d=φ4mm, height h = 10 mm. The cooling rates of the samples after incubation were: 100°C/h, 200°C/h, 500°C/h, 1000°C/h, $(Ac_1-RT)/50s$, $(Ac_1-RT)/100s$, $(Ac_1-RT)/500s$, $(Ac_1-RT)/1000s$, respectively, where RT represents room temperature. In addition, the CCT and TTT curves of Q1 and Q2 steel are calculated by Jmat-pro software.

The samples after the determination of SH-CCT curve diagram of test steel were inlaid, ground, polished, etched and dried with 4% nitric acid alcohol, and the structure morphology was observed by using ZEISS inverted microscope Axio Vert A1.

3. Test results and analysis
3.1. Welding process simulation calculation
The CCT and TTT curves calculated by Jmat-pro software according to the chemical composition of Q1 are shown in Fig.1 and Fig.2. It can be seen from Fig.1 that the temperature of Q1 steel $Ac_1$ is 898.37°C. When $t_{8/5}>4500s$, all the pearlite+ferrite structures can be obtained in Welding heat affected zone (HAZ) and near the fusion line of welding; When $150s< t_{8/5}<4500s$ ferrite+pearlite+bainite structure can be completely obtained near the fusion line in HAZ; When $2s< t_{8/5}<150s$, ferrite+bainite structure can be completely obtained near the fusion line in HAZ; When $t_{8/5}<2s$, martensite structure can be completely obtained near the fusion line in HAZ.
Fig.1 The CCT and TTT curves of Q1 steel
(a) CCT; (b) TTT

Calculation of CCT and TTT curves by Jmat-pro software according to the composition of Q2 steel is shown in Fig. 2. The temperature of Q2 steel Ac3 is 896.52 °C. It can be seen from the comparison between Fig. 1 and Fig. 2 that the effect of cooling rate $t_8/5$ in the actual welding process on the microstructure of coarse grain zone under the welding process is not much different from that of Q1 steel. When $t_8/5 \geq 4500s$, all the pearlite+ferrite structures can be obtained near the fusion line in HAZ; When $150s \leq t_8/5 < 4500s$, ferrite+pearlite+bainite structure can be completely obtained near the fusion line in HAZ; When $2s \leq t_8/5 < 150s$, ferrite+bainite structure can be completely obtained near the fusion line in HAZ; When $t_8/5 < 2s$, martensite+ferrite structure can be completely obtained near the fusion line in HAZ.

Fig.2 The CCT and TTT curves of Q2 steel
(a) CCT; (b) TTT

3.2. Comparison of simulated results with measured SH-CCT curves
The critical transition temperature points of the steel can be obtained by measuring the expansion curve of the equilibrium critical temperature as shown in Table 2. It can be seen from the table that the difference between the calculated value and the measured value is less than 3% within 27℃, and the calculated value is still of reference value.

| Steels | Ac1/℃ | Acυ/℃ | Ac3 (calculated) /℃ |
|--------|--------|--------|---------------------|
| Q1     | 721    | 872    | 898.37              |
| Q2     | 703    | 917    | 896.52              |
Table 3 and Table 4 show the relationship of cooling rate, cooling time, microhardness and microstructure of Q1 and Q2 steels, respectively, the microstructure of the tested steels is ferrite (F), pearlite (P), bainite (B) and martensite (M).

Table 3 Relationship among cooling rate, cooling time, microhardness and microstructure of Q1 steel

| Sample number | Cooling rate \(^{\circ}\text{C}/\text{s}\) | Cooling time \(t_{8/5}\) s | Microhardness HV1 | Microstructure |
|---------------|---------------------------------|-----------------|-----------------|----------------|
| 1             | 0.03                            | ten thousand    | 107.6           | F+P            |
| 2             | 0.06                            | 5000            | 108.2           | F+P            |
| 3             | 0.14                            | 2143            | 152.4           | F+P+B          |
| 4             | 0.28                            | 1071            | 166.6           | F+B+P          |
| 5             | 0.70                            | 429             | 181.0           | B+F+P          |
| 6             | 1.40                            | 214             | 195.8           | B+F            |
| 7             | 7.01                            | 43              | 232.2           | M              |
| 8             | 14.02                           | 21              | 268.4           | M              |

Table 4 Relationship among cooling rate, cooling time, microhardness and microstructure of Q2 steel

| Sample number | Cooling rate \(^{\circ}\text{C}/\text{s}\) | Cooling time \(t_{8/5}\), s | Microhardness HV1 | Microstructure |
|---------------|---------------------------------|-----------------|-----------------|----------------|
| 1             | 0.03                            | 10000           | 107.8           | F+P            |
| 2             | 0.06                            | 5000            | 145.0           | F+P+B          |
| 3             | 0.14                            | 2143            | 179.2           | F+P+B          |
| 4             | 0.28                            | 1071            | 199.8           | B+F+P          |
| 5             | 0.68                            | 441             | 210.8           | B+F            |
| 6             | 1.37                            | 219             | 208.2           | B+F            |
| 7             | 6.83                            | 44              | 238.2           | M              |
| 8             | 13.66                           | 22              | 274.8           | M              |

The SH-CCT curves of Q1 and Q2 steels can be plotted using Table 3 and Table 4. As shown in Fig.3, is the SH-CCT curve of Q1 steel, from which it can be seen that the SH-CCT curve mainly has four parts of structures: F, P, B and the part below the start line of martensitic transformation (Ms). When the cooling rate is less than or equal to 0.06\(^{\circ}\text{C}/\text{s}\), the structure is completely F. The structure of Q1 steel is F+P+B when the cooling rate is greater than 0.06\(^{\circ}\text{C}/\text{s}\) and less than 0.7\(^{\circ}\text{C}/\text{s}\). When the cooling rate is 1.4\(^{\circ}\text{C}/\text{s}\), the microstructure of Q1 steel is mainly B+F, and the cooling rate formed to M is greater than 7.01\(^{\circ}\text{C}/\text{s}\). Fig.4 is an SH-CCT curve diagram of Q2 steel, when the cooling rate is less than 0.06\(^{\circ}\text{C}/\text{s}\), the structure is basically F. When the cooling rate is greater than 0.06\(^{\circ}\text{C}/\text{s}\) and less than 0.68\(^{\circ}\text{C}/\text{s}\), the structure is F+P+B. When the cooling rate is greater than 0.68\(^{\circ}\text{C}/\text{s}\), the microstructure is mainly B+F, and the cooling rate formed to M is greater than 6.83\(^{\circ}\text{C}/\text{s}\).
Table 5 and Table 6 show the relationship between measured and calculated values of cooling rate and microstructure of Q1 and Q2 steels, respectively. It can be seen from the table that the measured value of Q1 steel is in good agreement with the calculated value, but the error is still large (> 10%), and the higher the cooling rate, the greater the error. However, the measured value of Q2 steel basically failed to meet the calculated value with the error of at least 50%, which might be due to the fact that the addition of Nb promotes the bainite transformation, which is somewhat difficult for Jmat-pro software to calculate.

### Table 5 Relationship between cooling time and microstructure of Q1 steel

| Cooling time $t_{\%}/s$ | Cooling time (calculated) $t_{\%}/s$ | Microstructure |
|-------------------------|------------------------------------|----------------|
| $\geq 5000$             | $\geq 4500$                         | F+P            |
| $214 \leq t_{\%} < 5000$| $150 \leq t_{\%} < 4500$           | F+P+B          |
| $43 \leq t_{\%} < 214$   | $2 \leq t_{\%} < 150$              | B+F            |
| $< 43$                  | $< 2$                              | M              |

### Table 6 Relationship between cooling time and microstructure of Q2 steel

| Cooling time $t_{\%}/s$ | Cooling time (calculated) $t_{\%}/s$ | Microstructure |
|-------------------------|------------------------------------|----------------|
| $\geq 10000$            | $\geq 4500$                         | F+P            |
| $1071 \leq t_{\%} < 10000$| $150 \leq t_{\%} < 4500$           | F+P+B          |
| $44 \leq t_{\%} < 1071$  | $2 \leq t_{\%} < 150$              | B+F            |
| $\leq 44$               | $< 2$                              | M              |

3.3. Evaluation of cold cracking tendency of steel by SH-CCT curve

The method and application for evaluating cold cracking tendency of steels with SH-CCT curve are shown in Table 7.

Table 7 The method and application of evaluating the cold crack resistance of steel by using SH-CCT graph

| Method for evaluating cold cracking resistance of steel | Evaluation method | Application examples |
|--------------------------------------------------------|-------------------|----------------------|

5
Use critical cooling time

When the actual cooling time $t_{c5}>C_f'$, no crack occurs near the welding heat affected zone and the fusion zone; At $t_{c5}<C_f'$, cracks are likely to occur in the heat affected zone or fusion zone.

According to fig. 3, $C_f'=43s$ for Q1 steel, so when the actual cooling time $t_{c5}>43s$, cracks do not occur near the weld heat affected zone and the fusion zone, while when $t_{c5}<43s$, cracks may occur in the heat affected zone or the fusion zone.

According to fig. 4, $C_f'=44s$ of Q2 steel, so when the actual cooling time $t_{c5}>44s$, cracks do not occur near the weld heat affected zone and the fusion zone, and when $t_{c5}<44s$, cracks may occur in the heat affected zone or the fusion zone.

Use critical tissue content

To avoid root cracking, the following proportions of the tissues near the heat-affected zone and the fusion zone should be ensured:
- For steel with tensile strength $R_m$ of 600MPa, the content of ferrite+intermediate structure shall not be less than 40%;
- For steel with tensile strength $R_m$ of 700MPa, the content of intermediate structure shall not be less than 25%;
- For steel with tensile strength $R_m$ of 800MPa, the content of intermediate structure shall not be less than 10%.

The $R_m$ specification for construction steel Q345 is 490 to 620 MPa, whereas actual measured values are generally close to 600MPa. According to the table 3 different cooling time $t_{c5}$ corresponding to the structure content, to make the ferrite+intermediate structure content is not less than 40%, so as to avoid the root crack, Q1 steel $t_{c5}$ should be greater than 43 s. The $t_{c5}$ of Q2 steel in Table 4 should be greater than 44s.

Use critical hardness values

According to the actual welding conditions, the hardness value of a low alloy high strength steel is found out from the SH-CCT diagram in the heat affected zone and compared with the maximum hardness value in the heat affected zone allowed by the steel, the tendency of welding cold crack is judged.

Low alloy steel 15Mn (Q345 grade) allows the heat affected zone of the highest hardness of 390HV, known from Table 3, Q1 steel $t_{c5}$ for 21s, micro hardness of 268.4HV1, so when the cooling time $t_{c5}<21s$, there may be a tendency to cold crack, welding need to take measures such as preheating before welding, heat treatment after welding.

It can be seen from Table 4 that when $t_{c5}$ of Q2 steel is 22s, the microhardness is 274.8HV1, and when cooling time $t_{c5}<22s$, there may be a tendency of cold cracking. Pre-welding preheating and post-welding heat treatment shall be taken during welding.

4. Conclusion

(1) Jmat-pro software has certain accuracy for the calculation of $A_c3$, but has large error for CCT curve, especially, the difference between the calculated value and the measured value of Q2 steel is larger, which only has reference value.

(2) Cold crack resistance of steel is evaluated by SH-CCT curve. For Q1 steel, when the actual cooling time is $t_{c5}>43s$, no cracks appear in the HAZ and the vicinity of the fusion zone, however, when $t_{c5}<43s$, cracks may appear in the HAZ or the fusion zone. When the actual cooling time of Q2 steel is $t_{c5}>44s$, no crack is generated in the HAZ and the vicinity of the fusion zone, however, when $t_{c5}<44s$, the crack may be generated in the HAZ or the fusion zone.

Author brief introduction

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