Numerical simulation of the effect of low-temperature transformation expansion on residual stress in cold cracking test specimens of different restraint factors

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Abstract. Ni-Cr based high-strength weld metals have been developed to reduce preheating processes. In the development process of a welding wire, the evaluation of cold cracking resistance is important. In this study, the effect of low-temperature transformation expansion on the residual stress reduction of welds with different restraint factors in cold cracking test specimens was examined by numerical simulation. The results indicated that the weld metal with low-temperature transformation expansion exhibits the effect of residual stress reduction at a high restraint factor. The reduction decreased for a low restraint factor. Even if the restraint factor changes, the distribution of the restraint factor in the Y-groove weld cracking test is different from that in the H-type restrained weld cracking test. Distributions of residual stresses at the weld root in cold cracking in the Y-groove test and the H-type test have different tendencies. Thus, the difference should be considered when conducting the cold cracking test.

1. Introduction

The use of HT980-class high-strength steels is advantageous because thinner steel plate can be used and a reduced amount of steel and welding consumables leads to a more ecologically beneficial fabrication. In general, cold cracking tends to occur in welds of high-strength steels. Therefore, preheating or post-weld heat treatment processes are essential. However, these processes lead to increased fabrication cost, which limits the applications of HT980-class steels. To realize the use of HT980-class high-strength steels without heat treatment processes, Ni-Cr based weld metals have been developed [1], [2]. Because Ni-Cr welding wire exhibits low-temperature transformation expansion, tensile residual stress, which affects the occurrence of cold cracking, is reduced. In the development of a welding wire, the evaluation of its cold cracking resistance is essential. In cold cracking, the effect of transformation expansion on residual stress is dependent on the restraint factor. It is well known that cold cracking tends to occur for a higher restraint factor at a weld joint [3]. An actual steel structure has varying restraint factor at the weld joint and cold cracking behaviors are changed by the restraint factor. Thus, definitions of the relationship between the cold cracking tendency and the restraint factor at the weld metal are important. In this study, a series of numerical analyses of the residual stress distribution was performed with varying transformation start temperatures of the weld metal in cold...
cracking test specimens of different restraint factors. The effect of the restraint factor and transformation temperature on the residual stress in the weld metal of high-strength steel is discussed.

2. **Numerical simulation method of residual stress considering phase transformation**

In this section, a finite element model and material properties are described for the numerical simulation. SYSWELD, the finite element analysis software for heat treatment and welding, was used.

![Diagram of weld cracking tests](image)

**Figure 1.** Specimen and dimensions of weld cracking tests.

**2.1. Numerical analysis models and condition**

In this study, a series of numerical analyses with varying transformation start temperatures of the weld metal in cold cracking test specimens of different restraint factors was performed to clarify the effect of transformation expansion on the residual stress. The y- and Y-groove weld cracking test [4] based on JIS Z 3158 (hereinafter called the “y-groove test” or the “Y-groove test”) and the H-type restrained weld cracking test [5] with Y-groove (hereinafter called the “H-type test”) were used. The shapes and dimensions of these specimens are shown in Figure 1. To change the restraint factor, thickness of the specimens was set to 10, 20, and 25 mm, and in the H-type restrained weld cracking test, the lengths of slits $B_s$ were varied at 30, 50, 140, 300, and 800 mm.

The finite element models used in the simulation are shown in Figure 2. The same finite element mesh divisions around the welds were set for all analysis cases. The Y-groove test and the H-type test are a half model, considering symmetry. The slit in the H-type test was modeled by deactivating finite elements corresponding to the location and size of the slit.

A thermal-elastic-plastic analysis was performed with a moving heat source and consideration of the deposition of the weld metal. The welding speed and heat input were 4.16 mm/s and 1400 J/mm, respectively. The coefficient of heat transfer was $1.5 \times 10^{-5}$ J/mm$^2$·°C·s, and the ambient temperature
was 30°C. In addition, the restraint factor that represents the restraint intensity of the weld metal was also calculated. The calculation of the restraint factor was performed as follows: detection of the load-displacement relationship by giving forced displacement to the groove. The slope of the load-displacement curve was defined as the restraint intensity. When the restraint intensity is high, the restraint to the weld metal is considered high. Restraint factors for each specimen were calculated and the relationship between the specimen geometries was discussed.

2.2. Material properties
In this analysis, the temperature- and microstructure-dependent material properties of HT980 steel, shown in Figure 3 and Figure 4, were used. The material properties were determined based on the material database [6] [7] as well as the experimental results obtained by the high-temperature tensile test and simulated thermal cycle test. The density used in the simulation was considered to be constant at $7.8 \times 10^{-6}$ kg/mm$^3$. The transformation properties were observed at $A_{C1} = 650°C$ and $A_{C3} = 850°C$ for the heating process, where $M_s$ was defined by the Koistinen-Marburger formula [8] at the cooling process. The effect of transformation expansion of the weld metal on the residual stress was evaluated by changing the martensite transformation temperature to 100°C, 218°C, and 418°C. The $M_s$ of the base metal was set to 418°C irrespective of the weld metal.

![Finite element models.](image-url)
(i) three-dimensional view

(ii) cross-sectional view of the test bead part

(iii) cross-sectional view of the restraint weld part

(c) H-type restrained weld cracking test

Figure 2. Continued.

(a) specific heat

(b) thermal conductivity

(c) evaluation of austenite fraction

(d) evaluation of martensite fraction

Figure 3. Material properties used in the thermal analysis.
3. Effect of restraint factor and transformation temperature on restraint stress

The relationship between the restraint stress and the restraint factor is shown in Figure 5. In this study, the restraint stress is defined as the averaged residual stress in the transverse direction $\sigma_y$ along the throat thickness of the weld metal. Generally, the restraint stress increases with increasing restraint factor. The result of $M_s = 418^\circ\text{C}$, of which the $M_s$ temperature is high, is an example of this relationship. On the contrary, when the $M_s$ temperature decreases, the restraint stress at the high restraint factor deviates from a linear relationship: when the restraint factor is high and $M_s$ decreases, the restraint stress becomes constant. The reduction of the restraint stress from $M_s = 418^\circ\text{C}$ to $M_s = 100^\circ\text{C}$ originates from the transformation expansion of the weld metal. The results indicated that the transformation expansion of the weld metal is more effective when the transformation temperature is low and the restraint factor is high.

4. Effect of specimen geometry on local stress distribution

To evaluate the occurrence of cold cracking, the stress at the weld root should be discussed. The distribution of residual stresses in the transverse direction at the root along the weld line is shown in Figure 6 and Figure 7. The results of the Y-groove test are shown in Figure 6 and the results of the H-type test are shown in Figure 7. The horizontal axis represents the restraint factor at each location along the weld line. The arrows in the figures indicate the maximum stresses in each $M_s$ case. The residual stresses are almost the same along the weld line in the Y-groove test, shown in Figure 6, although the local stress drops at the edge of the weld metal. The martensitic transformation start temperature $M_s$ clearly affects the residual stress. In contrast, the residual stress at the weld root is distributed from the compressive to tensile values in the H-type test; the critical stress that leads to the...
occurrence of cold cracking is difficult to determine in such a case. The difference should be taken into consideration when conducting cold cracking tests.

Figure 5. Effect of restraint factor on restraint stress.

Figure 6. Effect of specimen dimensions on residual stresses distribution in the Y-groove test.

Figure 7. Effect of specimen dimensions on residual stresses distribution in the H-type test.
5. Conclusions
In this study, the effect of low-temperature transformation expansion on the residual stress in specimens of different restraint factors was investigated.

1) The weld metal with low-temperature transformation expansion exhibits the effect of residual stress reduction at a high restraint factor.

2) Even if the restraint factor changes, the distribution of the restraint factor in the Y-groove weld cracking test is different from that in the H-type restrained weld cracking test.

3) The following differences should be taken into consideration when conducting cold cracking tests.
   i. In the Y-groove test, the residual stresses are almost the same along the weld line and the $M_s$ temperature clearly affects the residual stress.
   ii. In the H-type test, the residual stresses at the weld root are distributed from the compressive to tensile values. In such a case, the critical stress that leads to the occurrence of cold cracking is difficult to determine.

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