GENERATION BEHAVIOR OF THERMAL AND RESIDUAL STRESSES DUE TO PHASE TRANSFORMATION DURING WELDING HEAT CYCLES

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ABSTRACT
Weld residual stress is possible to be controlled by considering and changing mechanical properties of the materials. History of thermal stress due to phase transformation and residual stress during welding heat cycles is studied in order to investigate the generating mechanism of residual stress and the effects of material properties on stress generation. Two materials of high-tensile strength steels are used in the numerical simulation and experiment. Material property of each microstructural phase is used and the time- and temperature-dependant proportion of microstructure are considered by using CCT-diagram in the analysis. Thermal stress history obtained by the simulation agrees well with the experimental result during welding heat cycles.

INTRODUCTION
Thermal distortion and residual stress are essentially generated by welding and it is well known that they affect the performance of welded structures such as brittle fracture, fatigue, buckling deformation, and stress-corrosion cracking. Welding distortions and residual stresses can be possible controlled and reduced by using some countermeasures. Considering and changing material properties of the metals are also effective to reduce residual stress and distortion.

High strength steels are used in a lot of industries and the effect of phase transformation on mechanical behavior during welding in high strength steels becomes much larger than that of mild steels. The Satoh test is one of the most popular methods for evaluating the effect of phase transformation on generating thermal stress [1], [2]. Welding-simulated thermal stress cycles are produced in a round-bar specimen with both ends fixed. Temperature and thermal stress histories are then measured in the Satoh test. Production mechanism of thermal and residual stresses can be evaluated by using the Satoh test [3]-[11]. Not only thermal stress behavior but also prediction of microstructural phase during weld heat cycles are very important [12]-[15], and a simultaneous evaluation between thermal stress and microstructure during welding should be necessary in a precise evaluation.

The history of thermal stress due to phase transformation and residual stress during welding heat cycles are studied in this paper. The generating mechanism of residual stress and the effects of material properties on stress generation are investigated by using thermal elastic-plastic analysis with CCT-diagram and the Satoh test experiment. The time- and temperature-dependant material properties of each microstructural phase are used in the analysis. The thermal stress history is compared between results of the experiment and numerical simulation.

EXPERIMENTAL METHOD
Two kinds of high strength steels were used in the experiments and numerical analyses. Chemical composition of materials used in the evaluation is shown in Table 1, and mechanical properties of materials are also shown in Table 2. Both steels have high tensile strength near 1000 MPa, and Steel-F has a lower yield-to-tensile ratio than Steel-T. The initial proportion of microstructural phase is 85 % martensite and 15 % bainite for Steel-T, and 100 % bainite for Steel-F.

Figure 1 shows a configuration of a round-bar specimen for simulated welding heat cycle tests. Both ends of the specimen were fixed to the constraint box. The center of the specimen received a simulated welding heat cycle by induction heating and cooling processes, as shown in Fig. 2 (a). The equivalent rigid modulus of the fixing jig K was 118 kN/mm.

Temperature and stress histories were measured during the experiment by thermocouples and a loading-cell. Figure 2 (b) shows the apparatus of welding heat cycle test during experiment.
Table 1 Chemical composition of materials used (wt. %).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>N</th>
<th>T</th>
<th>B</th>
<th>P_cm</th>
</tr>
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<tbody>
<tr>
<td>Steel-T</td>
<td>0.16</td>
<td>0.24</td>
<td>0.9</td>
<td>0.012</td>
<td>0.001</td>
<td>0.081</td>
<td>0.31</td>
<td>0.4</td>
<td>0.27</td>
<td>0.033</td>
<td>0.004</td>
<td>0.017</td>
<td>0.263</td>
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<tr>
<td>Steel-F</td>
<td>0.043</td>
<td>0.312</td>
<td>1.03</td>
<td>0.006</td>
<td>0.0008</td>
<td>0.032</td>
<td>0.474</td>
<td>0.333</td>
<td>0.022</td>
<td>1.024</td>
<td>0.013</td>
<td>1.543</td>
<td>0.228</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of materials used.

<table>
<thead>
<tr>
<th></th>
<th>σ_y [MPa]</th>
<th>σ_T [MPa]</th>
<th>EL(%)</th>
<th>YR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel-T</td>
<td>890</td>
<td>1020</td>
<td>18</td>
<td>0.87</td>
</tr>
<tr>
<td>Steel-F</td>
<td>780</td>
<td>950</td>
<td>33</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Fig. 1 Configuration of a round-bar specimen for simulated welding heat cycle tests.

ANALYTICAL METHOD

The maximum temperature of the center of specimen was set to 800, 1000, 1200, and 1400 °C. The cooling rate was defined by using an elapsed time from 800 to 500 °C, t_{8/5}, which is often used to evaluate hardness or fracture toughness. The elapsed time t_{8/5} was measured at thirty seconds for normal free-cooling and at five seconds for rapid-cooling. Rapid cooling was done by air shower near the specimen surface.

Analytical method

Temperature, microstructural phase, and stress-strain histories were simulated by numerical analysis. The commercial code SYSWELD was used in the numerical analysis [16]. Mesh division of a round-bar specimen for the finite-element analysis is shown in Fig. 3. An axisymmetric model was produced with two-dimensional four-node isoparametric elements.

Physical properties for the heat conduction analysis with temperature- and microstructure-dependant material properties were determined from material data books, references, and some experimental data. Figures 4 (a) and (b) express the physical properties of austenite phase and the others for thermal conductivity and specific heat, respectively. The value of each temperature at each time in the analysis was defined from the proportion of each microstructural phase by using the mixed law.

Figure 5 shows the CCT diagram for the temperature-

Fig. 2 Apparatus of welding heat cycle test (Satoh test).

(a) Schematic illustration
(b) During experiment
APPENDIX

The phase transformation of cource affects the thermal stress history during welding heat cycles and it is important to understand the effects of consideration of phase transformation on the results of the numerical analysis.

Thermal stress history in one-dimensional bar with both-ends fixed was studied during welding heat cycles. Material property was set to that of Steel-T, except thermal strain. Three types of the thermal strain was used in the analysis:

1. Thermal strain without any phase transformation effect. Dilatometric curve during heating and cooling is averaged by one monotonic curve. Phase transformation is not considered in the analysis.

2. Thermal strain with simplified phase transformation effect. Dilatometric curve during heating and cooling is smoothed averaged by one monotonic curve. Phase transformation is considered only as the change of the dilatometric curve in the analysis.

3. Thermal strain is determined as the results of the phase transformation and the law of the mixture by the proportion of each phase. This method was done in this paper.

Figure A shows the comparison of the thermal stress histories by using the three different dilatometric curves of the thermal strain. The stress behaviors during heating and cooling processes are completely different, particularly during martensitic transformation. Consideration of phase transformation is important to predict the accurate thermal stress history.

Fig. A  Comparison of constraint stress history between the consideration of phase transformation effect during welding heat cycles.
microstructure coupling analysis of Steel-T. The number near the cooling curve shows the percentage proportion of each phase. The cooling history along the left-side curve in the figure for example shows that 13% of bainite is distributed until 400 °C (the rest of 87% is still austenite) and then 82% of martensite deposited until 150 °C, finally the residual of 5% is remained as austenite. The phenomena in the CCT-diagram was formulated by the Leblond model in the analysis [17], [18].

For mechanical calculation, the results of temperature and microstructure histories were used as an input data for the external load and for determining mechanical properties by the law of mixtures,
respectively. Mechanical properties for thermal elastic-plastic stress analysis with the dependency of temperature and microstructure are shown in Fig. 6. Yield stress has four kinds of phase-dependant, but Young’s modulus has no dependency on microstructure in the analysis. Stress-strain curves were determined from the experimental data.

Examples of dilatometric curves during welding heat cycles are shown in Fig. 7. Thermal strain is different between austenite and the others. History of thermal strain without any constraint moves between two lines during phase transformation process. The other detailed conditions of the thermal elastic-plastic analysis have already been described in the authors’ reference [19]-[21].

RESULTS AND DISCUSSION

History of Temperature and Microstructure

Comparison of temperature history between the results of the experiment and thermal elastic-plastic analysis during welding heat cycles in the round-bar specimen of Steel-T at a free-cooling condition is shown.
in Fig. 8. Histories were compared on the center in the heating zone and a point of 10 mm apart from the center along the axis direction in the round-bar specimen. The analytical result agrees well with the measurement. There is a little difference at the latent heat zone during cooling, which was not considered in the simulation.

Figure 9 shows the transformation history of microstructure during welding heat cycles by using Steel-T. The initial proportion of microstructural phase is 85% martensite and 15% bainite for Steel-T. At the free-cooling condition with maximum temperature of 1400 °C, the proportion of the microstructural phase became 100% austenite after heating process, and then martensite and bainite were transformed from austenite during cooling process, and finally the proportion became 55% martensite and 45% bainite, as shown in Fig. 9 (a). Figure 9 (b) shows that the phase proportion is 93% martensite and 7% bainite at rapid-cooling condition with maximum temperature of 1400 °C. At free-cooling condition with maximum temperature of 800 °C, the austenitic transformation was not completely done during heating process, and finally 80% martensite and 20% bainite remained after welding heat cycle. These results were validated by comparing the CCT-diagram.

**Thermal Elastic-Plastic Stress Behavior**

Thermal elastic-plastic analysis was performed by using temperature distribution and microstructural proportion at each time with temperature- and microstructure-dependant properties. Comparison of axial stress history in Steel-T between free- and rapid-cooling conditions during welding heat cycles is shown in Fig. 10. The maximum heating temperature was 1400 °C for both cooling conditions and the temperature at the center of the specimen was plotted in the figure. Compressive axial stress was first generated and became larger after heating process due to the expansion of the specimen and its constraint. Yield stress became lower according to temperature rise, and the compressive stress in the specimen gradually decreased after 285 °C, at which the specimen yielded the first time. The axial stress became zero during high temperature region from around 900 °C to 1400 °C. During cooling process, tensile axial stress was generated after the recovery of the stiffness around 1000 °C, and it became larger as the temperature decreased. Martensitic transformation was observed near 500 °C at the center of the specimen, and tensile stress decreased due to the expansion by the generation of martensite. Thermal stress increased after the end of the martensitic transformation and the final residual stress distributed. Residual stress at free-cooling condition becomes larger than that at rapid-cooling condition. This is because the martensitic transformation at rapid-cooling generates larger stress reduction due to specimen expansion and it becomes larger than that at the free-cooling condition.

The comparison of axial thermal stress history in the specimen of Steel-T between the results of experiment and numerical simulation during welding heat cycles is shown in Fig. 11. The analytical behavior agrees well with the measured values during all cooling cycles including Fig. 12  **Relation between maximum heating temperature and residual stress.**
phase transformation process both for the free-cooling and rapid-cooling conditions.

The relation between the maximum heating temperature and residual stress is shown in Fig. 12. The residual stress in Steel-T descends at the free-cooling condition due to the decrease of the proportion of martensitic phase when the maximum temperature becomes higher. Residual stresses in Steel-T at the rapid-cooling condition are nearly constant for the maximum heating temperature greater than 1000 °C, and the maximum stress is smaller than that of the free-cooling condition, whereas the stress at 800 °C is higher. This is because the proportion of bainitic phase became larger at the maximum temperature of 800 °C for the rapid-cooling process than the higher maximum temperature. There is no difference in Steel-F as the characteristics of the phase transformation is completely disparate from Steel-T.

CONCLUSIONS

The history of thermal stress due to phase transformation and residual stress during welding heat cycles was studied in order to investigate the generating mechanism of residual stress and the effects of material properties on stress generation. Two materials of high-tensile strength steels were used in the numerical simulation, and material properties of each microstructural phase were used including the time-and temperature-dependence by using the CCT-diagram in the analysis. Thermal stress histories obtained by the simulation agrees well with the experimental result during welding heat cycles and the behavior of microstructural phase was precisely simulated.

REFERENCES


