Modeling of Phase Transformation in Cooling Process and Verification of Its Validity

KIM You-Chul 1, HIROHATA Mikihito 1 and HAGEYAMA Yusuke 2

1 Joining & Welding Research Institute, Osaka University, 11-1, Mihogaoka, Ibaraki, Osaka 567-0047, Japan
2 Graduate Student of Osaka University

Abstract
Use of high strength steels is required as the steel structures become large. When high strength steels are welded, phase transformation (martensitic transformation) occurs in cooling stage of temperature with welding. Considering the transformation superplasticity, and idealizing the mechanical properties in the range of phase transformation in cooling stage of temperature, the experiments for RRC test and slit welding were simulated by thermal elastic-plastic analysis. From the results of simulation, the validity of modeling phase transformation in mechanics was confirmed. After that, the effect of phase transformation in cooling stage on welding residual stress was investigated. It was confirmed that phase transformation in the cooling stage largely influenced the generation of welding residual stress. It is expedient that phase transformation occurs in the range of comparatively low temperature from a view point of welding residual stress.

Introduction
Use of high strength steels is required as the steel structures become large. When high strength steels are welded, phase transformation (martensitic transformation) occurs in cooling stage of temperature with welding. It is known that phase transformation largely influences production of welding distortion and residual stress. In this paper, considering the transformation superplasticity, and idealizing the mechanical properties in the range of phase transformation, the experiment for RRC test and slit welding was simulated by thermal elastic-plastic analysis. From the results of simulation, the validity of modeling phase transformation in mechanics was confirmed. After that, the effect of phase transformation in cooling stage on welding residual stress was investigated. It was confirmed that phase transformation in the cooling stage largely influenced the generation of welding residual stress. It is expedient that phase transformation occurs in the range of comparatively low temperature from a view point of welding residual stress.

Figure 1: Temperature dependency of mechanical properties.
welding are simulated by 3D thermal elastic-plastic analysis. The validity of mechanical modeling of phase transformation in cooling stage is verified. After that, the effects of phase transformation in cooling stage on welding residual stress are investigated.

**Idealizing of mechanical properties in range of phase transformation**

The temperature ($M_s$) at starting of martensitic transformation generated in cooling stage of high strength steel (HT780) was $480^\circ \text{C}$ and the temperature ($M_f$) at finishing of that was $310^\circ \text{C}$. Symbols in Fig.1 show Young’s modulus $E$, Yield stress $\sigma_Y$ obtained by using reproducing equipment for temperature histories of welding and the thermal expansion coefficient $\alpha$ obtained by Formaster [1]. Figure 2 shows expansion-temperature diagram. The range of phase transformation is expressed by the dotted lines on the cooling stage of temperature in Fig.1(a). In this temperature range, $E$ and $\sigma_Y$ could not be specified. By the way, according to the study about transformation superplasticity, it is known that if tensile stress is applied when phase transformation occurs and progresses, strength is remarkably lowered and extraordinary ductility is observed in the range of phase transformation [2]. Considering this transformation superplasticity, Young’s modulus $E$ in the range of phase transformation was idealized as shown by a dotted line in Fig.1(a). On the other hand, yield stress $\sigma_Y$ was idealized as shown by a dotted line in Fig.1(a). The thermal expansion coefficient $\alpha$ is uniformly used in phase transformation range as shown by a dotted line in Fig.1(a).

In the next section, introducing the idealized $E$ and $\sigma_Y$ to the self-developed program of 3D elastic-plastic analysis, the validity of modeling phase transformation in mechanics is verified.

**Verification of modeling phase transformation**

**RRC test**

Figure 3 shows the size and the shape of the test specimen. Figure 4 shows histories of temperature measured at weld metal on the center of the welding line of the test specimen. Measuring the reaction force in welding, and dividing it by the throat thickness, the average transient stress of weld metal was obtained. Symbols in Fig.4 show the obtained result. And a solid line shows the result of 3D thermal elastic-plastic analysis. Including the transient state, the experiment is accurately simulated. It is indicated that the validity of modeling phase transformation in mechanics is verified.

**Slit-welding**

Figure 5 shows the size, the shape and the coordinate system of the test specimen.
In the experiment, MIG welding was performed with heat input 17,000 (J/cm).
Temperature in welding was measured at two positions of weld metal and the base metal (y=10, z=20mm). Symbols in Fig.6 show the measured result of temperature histories. The solid and dotted line in the figure shows the result of 3D non-steady state thermal conduction analysis. The result of analysis accurately simulates that of the experiment.

After finishing welding, strain gauges were attached on the surfaces (obverse and reverse) of the test specimen (symbols in Fig.5).

Measuring the relaxed strain by the stress relaxation method, residual stress was obtained as the average value on the two surfaces. Symbols in Fig.7 show the obtained results.

Using the above-mentioned temperature histories, 3D thermal elastic-plastic analysis was carried out. The solid line and the dotted line in Fig.7 show the obtained results of residual stress. As the result of the analysis accurately simulates the result of the experiment, the validity of modeling phase transformation in mechanics can be verified.

### Effects of phase transformation on welding residual stress

In order to elucidate the effect of phase transformation on welding residual stress, 3D thermal elastic-plastic analysis was carried out with and without considering phase transformation. In the case without considering phase transformation, it was assumed that the mechanical properties
and thermal expansion coefficient used in the heating process were also used in the cooling process as shown in Fig.1(b). Object of the analysis is a slit specimen and the temperature history which was measured by the former slit-welding is used in thermal stress analysis.

A broken line in Fig.8 shows the result of the analysis without considering phase transformation. A solid line shows the result with considering phase transformation.

It is found that phase transformation in the cooling stage of temperature largely influences the generation of residual stress. By the way, from a view point of residual stress, the result of analysis is indicated that it is desirable that phase transformation occurs in the range of comparatively low temperature.

**Conclusion**

Considering the transformation superplasticity, and idealizing the mechanical properties in the range of phase transformation in cooling stage of temperature with welding, the experiments for RRC test and slit welding were simulated by 3D thermal elastic-plastic analysis. From the results of simulation, the validity of modeling phase transformation in mechanics was confirmed. After that, the effect of phase transformation in cooling stage on welding residual stress was investigated. It was confirmed that phase transformation in the cooling stage of temperature with welding largely influenced the generation of welding residual stress. It is expedient that phase transformation occurs in the range of comparatively low temperature from a view point of welding residual stress.

**References**
