A Computational Approach on Prediction of Welding Residual Stress with Considering Solid-state Phase Transformations

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KEY WORDS: (Numerical Simulation), (Welding), (Residual Stress), (Phase Transformation), (CCT Diagram)

1. Introduction

It has been recognized that solid-state phase transformation can radically influence the development of residual stress in certain steel welded joints [1-3]. Generally, there are two main factors which have influence on welding residual stress. One is shape deformation including dilatational strain and shear strain; the other is the variation of mechanical properties such as yield strength [4-6]. Some researchers also pointed out that the plasticity induced by phase transformation has effect on formation of welding residual stress [7, 8].

In the past decades, a number of numerical models have been proposed to simulate residual stress in welded joints or heat treated structures with considering the influence of austenitic–martensite transformation. However, researches on how to predict welding residual stress with considering both bainite and martensite transformations using a full 3-D finite element model are very limited.

In this work, based on thermal elastic plastic finite element method (JWRIAN) developed by JWRI Osaka university, we developed a new computational approach which can considers the influence of both reconstructive (or diffusive) phase change and displacive phase transformation on welding residual stress. In the new computational approach, the Johnson-Mehl Avrami-Kolmogrov (JMAK) equation [12] is used to simulate diffusive phase change, and the Koistinen-Marburger (K-M) relationship [13] is employed to trace the displacive phase transformation. Using a signal-pass plate joint model, the effects of volumetric change and yield strength variation due to solid-state phase transformation on the formation of welding residual stress in 2.25Cr-1Mo steel was studied numerically.

2. Computational approach

2.1 Thermo-metallurgical-mechanical finite element method

In the present work, we developed a computational approach based on iterative substructure method [9, 10]. Besides thermo-mechanical behaviors, the effect of solid-state phase transformation on stress and strain was also taken into account. The computational procedure includes two steps. At the first step, the temperature field and thermal cycle of each node is computed according to the heat input, and this step can be called thermal analysis. At the second step, the microstructure, strain and stress are calculated based on the thermal analysis results. In the current work, our emphasis was played on developing a series of subroutines to consider the influence of solid-state phase transformation on the strain/stress formation. In the developed approach, the JMAK equation is used to simulate the diffusive phase change, and the K-M relationship is employed to describe the martensite transformation. As shown in **Fig. 1**, the coupling behaviors among temperature filed, microstructure and stress/strain are very complex. It should be pointed out that we have neglected some factors such as the heat generated by plastic deformation, the latent heat due to solid-state phase change and the effect of stress on phase change.

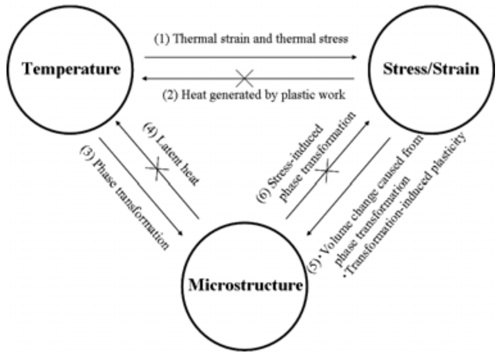


Fig. 1 Coupling effects among temperature, microstructure, and stress/strain [11]

2.2 Phase change during heating and cooling

On heating, the level rule can be used to describe how the original phase changes into austenite. However, because the mechanical properties such as yield strength and Young's modulus are relatively small when the temperature is higher than A_1 or A_3, it can be inferred that the phase transformation during heating maybe insignificantly influences on the stress evolution. Therefore, for the sake of simplicity, a linear relationship is assumed to simulate the formation of austenite in the current study. By using the linear approximation, the austenite volume fraction (f_a) at each step can be calculated using the following equation.

$$f_a = \frac{T - T_1}{A_3 - A_1} \times 100\ \% \qquad (1)$$

where, T is the current temperature. A_1 and A_3 are, cementite and α-ferrite disappearance temperatures, respectively.

In the developed computational approach, the solid-state phase transformation in 2.25Cr-1Mo steel during cooling stage can be schematically described using **Fig. 2**. **Fig. 3** shows how austenite changes into bainite and martensite. In this figure, phase A is bainite, and phase B is martensite.

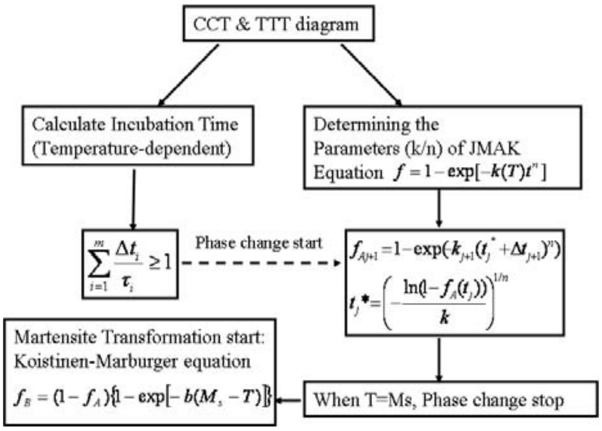
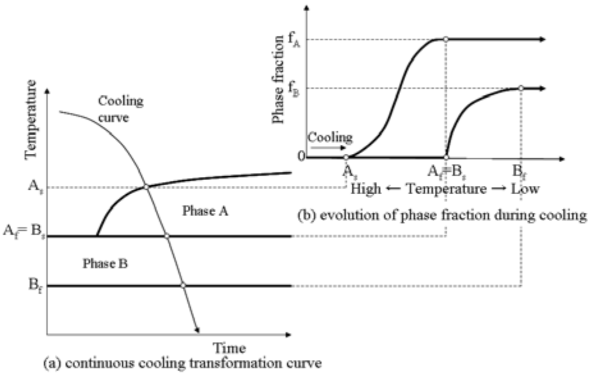


Fig. 2 Phase transformations of 2.25Cr-1Mo steel

Fig. 3 Phase transformations during cooling stage



2.3 Simple mixture rule to consider changes of material properties

During phase transformation, the material properties such as yield strength and thermal expansion coefficient potentially significantly change. In the present study, the yield strength and the thermal expansion coefficient are estimated using a simple (linear) mixture rule. The simple mixture rule is schematically shown in **Fig. 4**.In this figure, only two phases (phase1 and phase 2) are considered.

3. Predicting welding residual stress in a plate joint welded by TIG welding process

In this study, a simple plate welded joint model was used to demonstrate how the residual stresses form with considering solid-state phase transformation. TIG welding process was assumed to perform the 2.25Cr-1Mo steel joint. In the finite element model, the welding conditions were assumed as follows: welding current was 150A; arc voltage was 17V; and welding speed was 5mm/s. The arc coefficient was 0.7. The finite element model is shown in

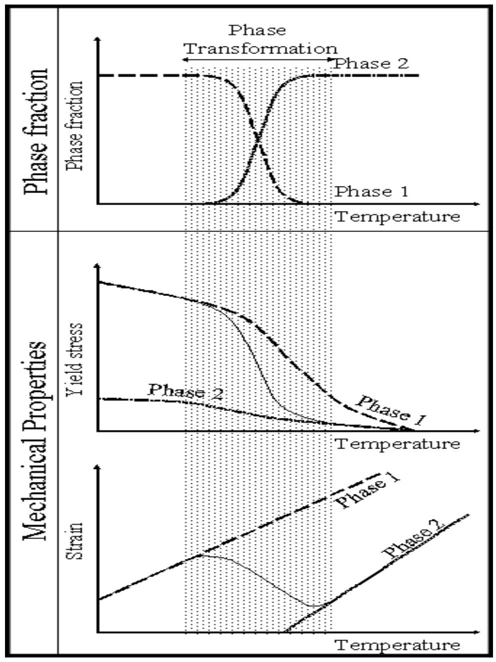


Fig. 4 Simple mixture rule for estimating materials property change during phase transformation

Fig. 5. In this model, the number of element is 12160, and that of node is 15795.

To clarify the influence of solid-state phase transformation on the welding residual stress, two cases (Case-1 and Case-2) were performed. Case-1 considered solid-state phase transformation, while Case-2 neglected this effect.

In the simulations, temperature-dependent thermal and mechanical properties were used. In addition, phase-dependent yield strength and thermal expansion coefficient were also taken into account in Case-1. The yield strength of each phase was shown in **Fig. 6.** A linear mixture rule was used to determine the yield strength (σ_y) according to the fraction of each phase. The simple mixture rule can be expressed using the following formulation.

$$\sigma_y = \sum_{i=1}^{n} \sigma_{yi} f_i \quad (i=1,n) \qquad (2)$$

where, σ_{yi} is the yield strength of phase *i*, and f_i is the fraction of phase *i*.

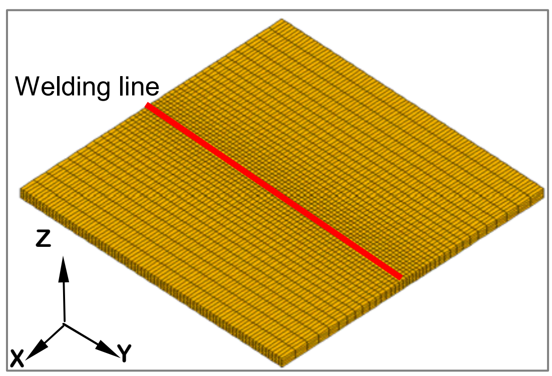
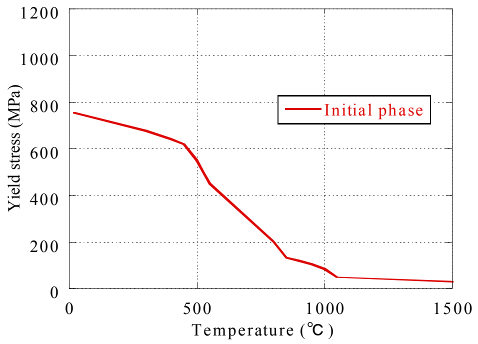
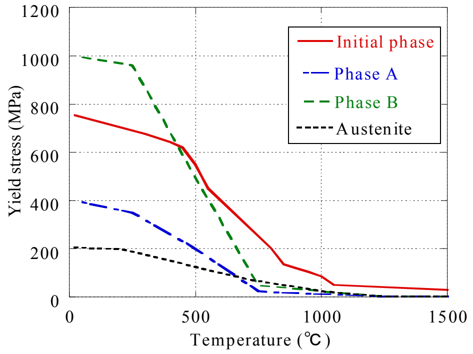


Fig. 5 Finite element model



(a) Yield strength without considering phase change



(b) Yield strengths with considering phase change

Fig. 6 Temperature-dependent yield strengths used in FE model

4. Simulation Results

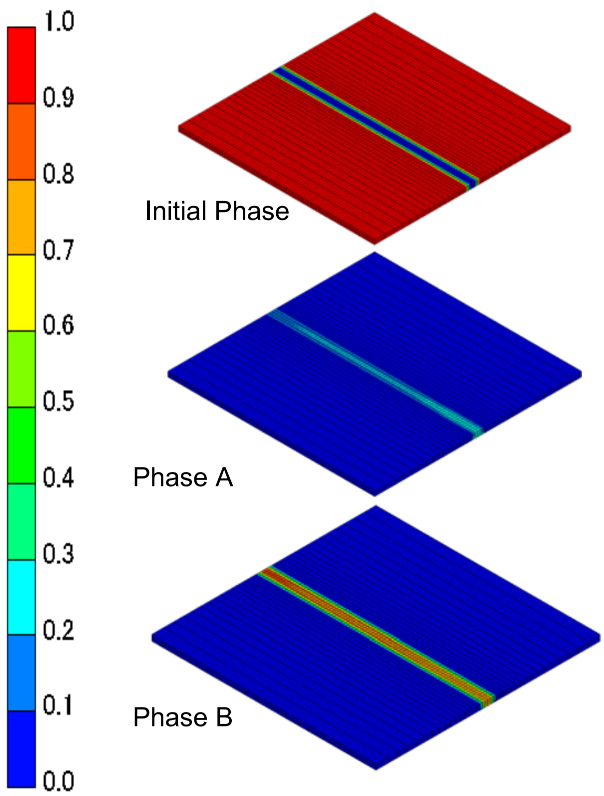


Fig. 7 Fraction of each phase after welding

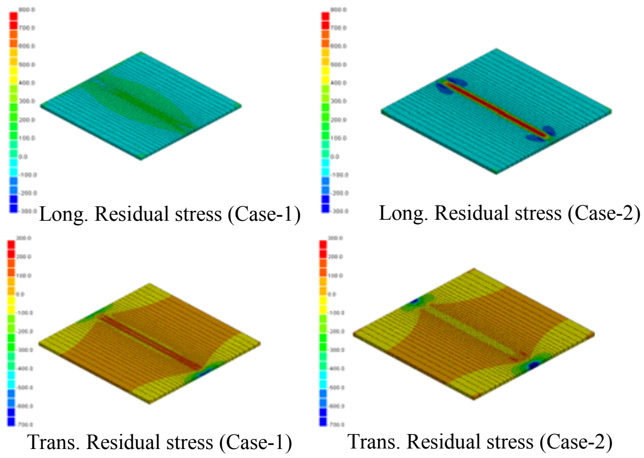


Fig. 8 Comparison between Case-1 and Case-2

Fig. 7 shows the each phase fraction distribution in the finite element model (Case-1). **Fig.8** compares the welding residual stress distributions predicted by Case-1 and Case-2. This figure clearly shows that both longitudinal residual stresses and transverse residual stresses computed by these two cases are much different. This suggests that solid-state phase transformation has significant influence on the final residual stress distribution.

To carefully compare the welding residual stresses predicted by Case-1 and Case-2, we plotted the longitudinal residual stress distributions on the upper and bottom surfaces of the middle section in **Fig. 9** and **Fig. 10**, respectively. From **Fig. 9**, we can know that the longitudinal residual stresses near the weld zone predicted by Case-1 are significantly smaller than those computed by Case-2. In Case-1, because the volumetric change due to phase transformation was taken in account, the cumulated stress was partially cancelled during solid-state phase transformation. In Case-2, the effect of phase transformation was not considered, so it is not strange that very large tensile residual stresses produced near the weld zone after welding. In Case-1, because the maximum temperature of the bottom surface is lower than that of the upper surface, the range experienced solid-state phase transformation is correspondingly smaller than that on the upper surface. This is the reason why relatively tensile residual stresses generated near the weld zone on the bottom surface. However, comparing with Case-2, the peak tensile stress of Case-1 is smaller.

Fig. 11 and **Fig. 12** compare the transverse residual stress distributions of two cases on the upper and bottom surfaces of the middle section, respectively. Contrary to longitudinal stress, the transverse residual stresses near the weld zone in Case-1 are larger than those of Case-2. However, the peak value of tensile transverse residual stress is much smaller than the yield strength at room temperature. From **Fig. 11** and **Fig. 12**, we can find that the solid-state phase transformation not only changed the magnitude of transverse residual stress but also altered its sign from minus to plus near the weld zone.

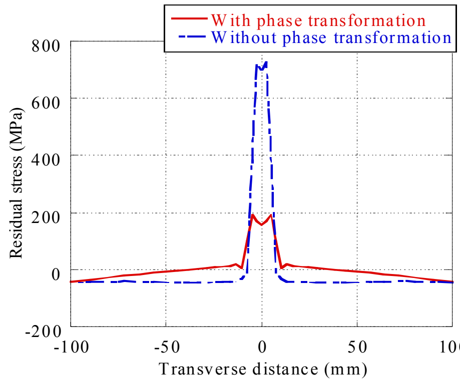


Fig. 9 Longitudinal residual stress distribution on the upper surface

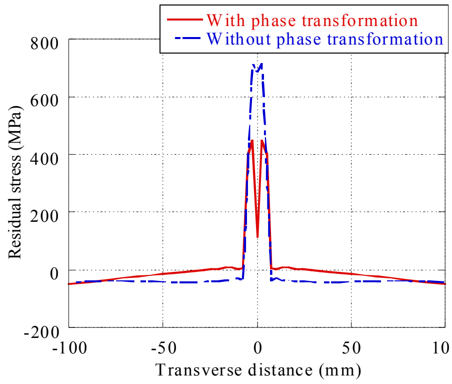


Fig. 10 Longitudinal residual stress distribution on the bottom surface

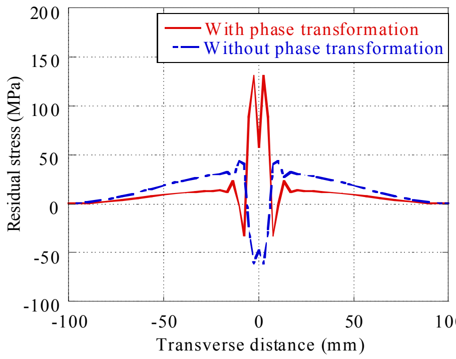


Fig.11 Transverse residual stress distribution on the upper surface

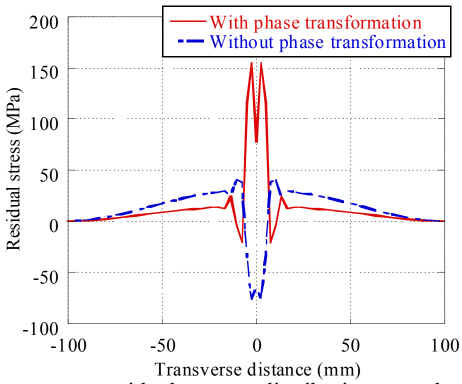


Fig.12 Transverse residual stress distribution on the bottom surface

5. Conclusions and future works

In the present work, we developed a new computational approach to predict welding residual stress with considering solid-state phase transformation. In the developed model, the JMAK equation is used to describe diffusive phase change (bainte change), and K-M relationship is employed to trace displacive phase transformation (martensite transformation).

Using a simple plate model, the influence of solid-state phase transformation on welding residual stress was studied. The simulation results suggest that solid-state phase transformation significantly reduced the longitudinal tensile stress especially near the weld zone. On the contrary, it increased the transverse residual stress.

Compared with single pass welded joint, multi-pass joint is more popularly used in practice. Therefore, our next task is to investigate how solid-state phase transformation affects the formation of residual stress in multi-pass joints.

Acknowledgements

The authors would like to thank Mr. Nawafune for performing the numerical simulations and Mr. Kawahara for helping to develop the new computational approach.

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