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Finite element simulation of the residual stresses in high strength carbon steel butt weld incorporating solid-state phase transformation

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ABSTRACT

This paper presents a sequentially coupled three-dimensional (3-D) thermal, metallurgical and mechanical finite element (FE) model to simulate welding residual stresses in high strength carbon steel butt weld considering solid-state phase transformation effects. The effects of phase transformation during welding on residual stress evolution are modeled by allowing for volumetric changes and the associated changes in yield stress due to austenitic and martensitic transformations. In the FE model, phase transformation plasticity is also taken into account. Moreover, preheat and inter-pass temperature are included in the modeling process. Based on the FE model, the effects of solid-state phase transformation on welding residual stresses are investigated. The results indicate the importance of incorporating solid-state phase transformation in the simulation of welding residual stresses in high strength carbon steel butt weld.

1. Introduction

As the spans of bridges are getting longer and the stories of buildings are getting higher, there are strong demands for steels with high strength. The application of high strength steels makes it possible to design not only light weight structures, but also simple structures with simple joint details. Like most structural steels, the fabrication of structural member using high strength steels always involves welding process such as flux cored arc (FCA) welding. During welding, a large number of thermal cycles induce alterations in microstructures as well as physical and mechanical properties of the weld metal and the surrounding heat affected zone (HAZ). Moreover, the process of welding inevitably produces unwanted residual stresses in the welded parts.

Welding-induced residual stresses are stresses that remain in a material as a result of liquid-to-solid phase transformation associated with the solidification and subsequent non-uniform cooling of the weld region altered by phase transformations in the solid state [1]. The formation of residual stresses in welded components is determined by several factors. The contributing factors are largely comprised of structural, material and fabrication parameters. The structural parameters include the geometrical size and joint design. The material parameters reflect the metallurgical condition of the base metal and weld metal. Fabrication parameters include the welding process, conditions, pass sequence and the degree of restraint.

While some residual stresses may be beneficial, most are detrimental to the integrity and the service behavior of the welded part. Particularly, tensile residual stresses near the weld area have adverse effects. The detrimental effects of residual stresses on structural performance may include [1–4]: (1) increasing the susceptibility of a weld to stress corrosion cracking; (2) reducing the fatigue life; and (3) promoting brittle fracture. Thus, accurate prediction and efficient evaluation of the residual stresses would help to assure the sound design and safety of the structure. However, accurately predicting welding residual stresses is a very difficult task because of the complexity of welding process which includes localized heating, temperature dependence of material properties and moving heat source, etc. Reliable simulation tools based on finite element (FE) method are therefore very useful to predict welding residual stresses [5–10]. It can be used to simulate welding temperature field, welding residual stress field and welding deformation.

In the context of carbon steel weld, especially in high strength carbon steel weld, it has been known that solid-state phase transformation should be taken into account in the welding simulation, since the phase transformation induces important physical and

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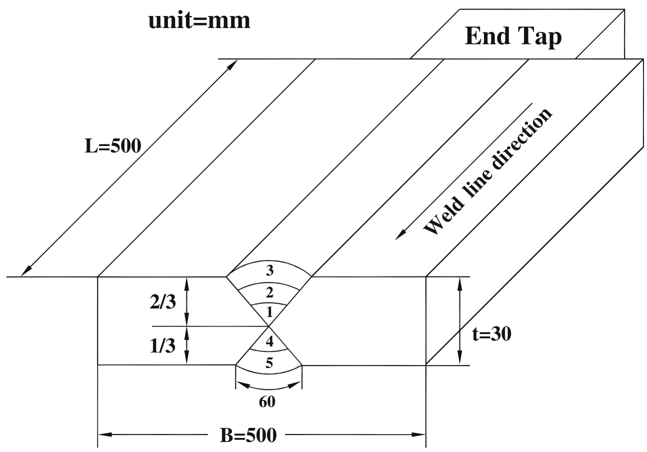

Fig. 1. Specimen geometry and pass sequence.

mechanical effects such as volumetric changes in the material. The volumetric change associated with the metallurgical phase transformation could have a major influence on the residual stress evolution. A number of numerical models have been developed to predict welding residual stresses considering the metallurgical transformation [11–23].

The present research is undertaken to determine residual stresses in a multi-pass butt-welded POSTEN80 steel plate, newly developed high strength steel for the use in bridges, automobiles, pressure vessels and pipelines and offshore construction, etc. A sequentially coupled three-dimensional (3-D) thermal, metallurgical and mechanical FE model considering solid-state phase transformations is developed based on the previous researches [20–23]. In the FE model, the volumetric change and the variation in yield stress of the base metal and the weld metal due to austenitic and martensitic transformations are incorporated. Phase transformation plasticity is also accounted for in the modeling process. Moreover, the mechanical behavior of the material welded such as work hardening and annealing of historical plastic strain [24] as well as temperature-dependent thermal physical and mechanical properties including preheat and inter-pass temperature is taken into account. The effects of solid-state phase transformation on welding residual stresses are investigated through the FE model.

2. Experimental procedure

In this study, microstructural analysis and residual stress measurement of high strength carbon steel butt weld were carried out to investigate the microstructural changes in the weld region and HAZ, and to determine the full volumetric change strain associated with martensitic transformation, which is required input to the FE modeling of the phase transformation effects. The procedure for obtaining the volumetric change strain will be described in detail in Section 3.3. The base material used in this study is high strength carbon steel (POSTEN80) plate with 30 mm thickness. Double 'V' butt joint configuration, as shown in Fig. 1, was prepared for joining the plates. The joint was welded with five passes by FCA welding procedure using MGS-80 electrode of 1.2 mm in diameter as a filler material. Chemical compositions for the base and weld materials are specified in Table 1. The welding specifications used in the fabrication of the joint are provided in Table 2.

After completion of welding, microstructures were analyzed using a OLYMPUS PME3 optical microscope. Samples used for microstructural analysis were cut from the weld metal and the HAZ. Results are shown in Fig. 2. Fig. 2a and b, representing the weld metal and the HAZ respectively, indicate the martensitic structures. Therefore, it is clear that the weld region and HAZ heated over the austenitic temperature during welding experience martensitic transformation.

Residual stress measurement was carried out using the two axis strain gauge with the layering technique. Measuring stresses by strain gauges using the layering technique can obtain the residual stresses on the surface of the structure to be evaluated. The detailed procedure for measuring the residual stresses on the surface of the specimen is as follows: first, strain gauges are attached on the bottom surface of the specimen. The periphery of the attached strain gauges is cut into small hexahedron with about 10 mm sides, and about 3 mm thickness. Residual stresses in the small pieces are released by cutting the specimen, and longitudinal released strain ε_x and transverse released strain ε_y are measured. Longitudinal residual stress σ_x and transverse residual stress σ_y can be obtained from the following equations using measured strains:

$$\sigma_x = -\frac{E}{1-\nu^2}(\varepsilon_x + \nu\varepsilon_y) \quad (1)$$

$$\sigma_y = -\frac{E}{1-\nu^2}(\varepsilon_y + \nu\varepsilon_x) \quad (2)$$

where E is Young's modulus and ν is Poisson's ratio.

3. FE simulation of the welding process

Welding is a very complicated phenomenon in which coupled interactions between heat transfer, metallurgical transformation and mechanical field exist. Complex numerical approaches are

Table 1
Chemical compositions of the base metal and the weld metal used (mass, %).

Material	C	Si	Mn	P	S	Cr	Ni	Cu	V	Mo	B
POSTEN80	0.07	0.3	0.91	0.015	0.004	0.45	0.97	0.02	0.038	0.45	0.0016
MGS-80	0.05	0.44	1.35	0.006	0.001	0.6	2.3			0.25	

Table 2
Welding process specifications.

PASS	Current (A)	Voltage (V)	Velocity (mm/s)	Remarks
1	250	30	2.7	Preheat temperature (°C) 110
2	260	32	2.0	
3	260	35	1.9	
Turn over				
4	250	30	4.1	Inter-pass temperature (°C) 200–250
5	250	30	3.3	