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Effects of low-temperature transformation and transformation-induced plasticity on weld residual stresses: Numerical study and neutron diffraction measurement

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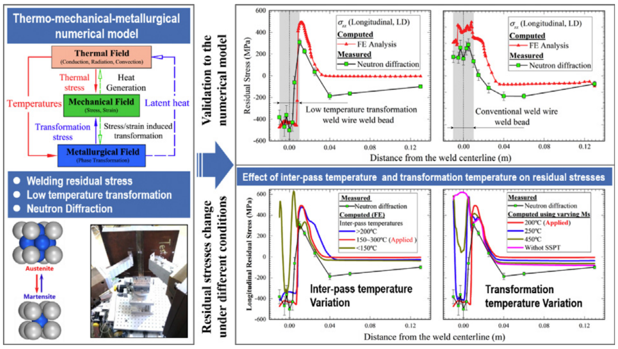
HIGHLIGHTS

- The effectiveness of the LTT weld wire in reducing tensile RS are validated.
- Numerical model in couple with solid-state phase transformation is developed.
- Prediction model is validated by using neutron diffraction technique.
- Thermo-mechanical-metallurgical behavior for LTT alloy is predicted.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the weld residual stresses (RS) in a 25 mm thick ferrite steel plate with newly developed low-temperature transformation (LTT) welding wire were investigated by finite element method and neutron diffraction (ND) measurement. A thermo-elastic–plastic finite element model coupled with solid-state phase transformation (SSPT) was developed to investigate the distribution and formation mechanism of RS, which has been verified by ND measurement. The results demonstrate that the developed LTT alloy can significantly reduce the RS and even generate compressive RS in the weld zone, due to the interrupted cooling shrinkage caused by the LTT. The higher inter-pass temperatures related to the microstructure evolution result in an increased region of compressive stress within the weldment. Moreover, the longitudinal RS in the weld zone gradually changes to tension as the initial temperature of martensitic transformation increases. Notably, the relaxation effect of transformation-induced plasticity on RS and its influence on model accuracy were discussed.

1. Introduction

The increasing application of high-strength steels in hull structures, bridges and pressure vessels has provided significant attention to the production of weld residual stresses (RS) [1,2], because the tensile RS greatly affect fracture, fatigue, stress corrosion cracking and buckling

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strength, etc. [3–6]. Whilst, the compressive RS can provide the feasibility of restoring, refine the martensitic grain, and improve the fatigue properties of cracked joints [5,7,8]. Thus, a valid approach to improve the integrity of weld structures is to introduce compressive RS in the weld zone. Mechanical means (e.g., peening, grinding and vibration aging [9,10]) and post-welding heat treatment are conventional methods in re-modifying the state of RS in welds; however, these techniques are time-consuming and laborious, and sometimes inappropriate for large-scale welded components. Aside from these conventional methods, a new efficient approach to mitigate the tensile RS is utilizing the metallurgical characteristics of the welding consumable [11]. Depending on the heating temperature and cooling rate, the austenite decomposition can be divided into the (1) diffusional (austenite to ferrite or pearlite transformation at high temperature) and (2) displacive (bainitic or martensitic transformation at low temperature) transformations, which trigger off the volume expansion associated with the equimolar volume difference between austenite (face-centered cubic, FCC) and its decomposition phase (body-centered cubic, BCC) [12,13]. The volume expansion caused by the diffusional transformation slightly affects the spatial distribution and histrionic evolution of RS. This phenomenon is attributed to the conversion of the volume expansion into plastic strain, which is largely released for the diffusional transformation temperature that is higher than the plastic temperature of alloy metal, as illustrated in Fig. 1. Instead, elastic strain energy triggered by displactive transformation, which is proportional to temperature, is the basic condition for interrupting thermal contraction during cooling. Thus, displactive transformation shows an advantage in controlling tensile RS. Particularly, the martensitic transformation can proceed at lower temperature compared with bainitic transformation by adjusting the content of austenitic stabilization alloying elements.

In the early of 1960s, soviet scientists proposed to create a state of triaxial compression within and around the region of the weldment through the volumetric misfit caused by austenite-to-martensite transformation [14]. In 1998, Ohta et al. [11,15] focused on this phenomenon and developed a LTT welding wire, which allowed the control of the solid-state phase transformation (SSPT) to offset the cooling contraction strains with the related strain caused by the martensitic transformation. Chen et al. [16] evaluated the mechanical, RS, and microstructure of Q690 steel multi-pass joints using LTT filler metal, and found that the volume expansion triggered by the martensitic transformation reduced the tensile RS significantly and improved the tensile strength. In the newly developed LTT filler materials, welding cold cracking under various constraints and without preheating is nearly completely repressed [17]. The aforementioned LTT alloy is mainly smelted with the alloying elements of chrome, nickel and manganese to lower the initial temperature of martensitic transformation (M_s). Meanwhile, the low carbon content combined with the affixion of nickel can improve the intrinsic toughness and tensile ductility in generated lath martensite. However, the prediction of RS distribution associated with SSPT kinetics is difficult because the effects of microstructure evolution on RS state and mechanical behavior cannot be ignored.

In the recent decades, numerous computational approaches have been developed to describe the coupled thermal-mechanical–metallurgical welding process. The finite element modeling (FEM), which considers the kinetics of metallurgical phase transformation, has been a new branch of welding domain [1]. Nie et al. [10] used the method of thermal compressive deformation to observe the close relationship between the dynamic mechanical behavior of martensite stainless steel and SSPT within a complete thermal cycle. Li et al. [18] investigated the influence of SSPT on RS in P92 steel with varying welding cycles. The comparisons between the measured and predicted results using X-ray diffraction (XRD) showed an excellent agreement, and the findings indicated that the formation of tempered martensite resulted in an increased tensile region in the weld fusion zone. Deng and Murakawa [3] adopted the Inoue model [19] to numerically explain the impact mechanism of transformation-induced plasticity (TRIP) accompanying the volume expansion on RS in LTT steel. The results suggested that the TRIP could significantly relax the variation tendency of longitudinal and transverse RS within martensitic transformation. Dai et al. [20] and Ramjaun et al. [21] constructed a theoretical basis for controlling microstructure evolution by improving the inter-pass temperature to eradicate the tensile RS in the weld zone. Mark et al. [22] and Murakawa et al. [23] determined the RS formation mechanism in stainless steel involving martensitic phase transformation with varying transformation temperatures. Hamelin et al. [24] obtained an improved calculation precision when the thermo-mechanical–metallurgical behavior of alloy was considered. However, they only paid attention on the RS simulation of a single-pass weld, and the reciprocal influence of multi-pass welding thermal cycles was ignored. Thus, a multi-pass welding analysis model should be established to clarify the influence of reheating or tempering process caused by the deposition of subsequent weld bead on the local RS field.

Over the past few decades, the development of measurement characterization methods has constituted a fundamental basis to evaluate the thermo-mechanical–metallurgical behavior of LTT alloy throughout the welding manufacturing process. Neutron diffraction (ND) and contour method (CM) can obtain the interior RS distribution, which cannot be detected by the traditional measurement techniques, such as XRD and indentation methods [25]. CM based on the Bueckner's superposition principle provides a full-field RS distribution that is normal to the cutting

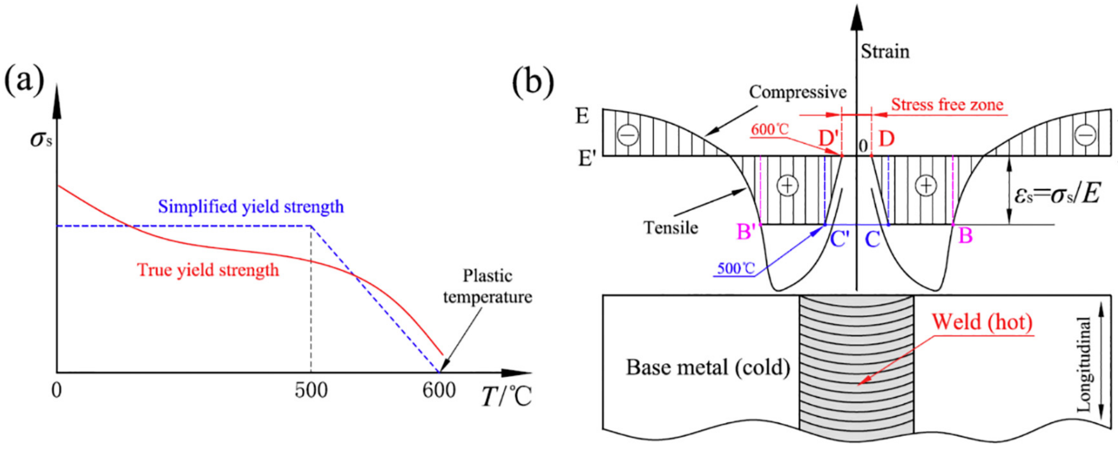

Fig. 1. Schematic illustrations of the (a) yield strength variation and (b) evolution of longitudinal stress and strain for mild steel during cooling.