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Effect of tailored martensitic transformation in a thick weld: Residual stresses mitigation, heterogeneous microstructure, and mechanical properties

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ABSTRACT

The residual stresses, microstructural heterogeneities, and mechanical properties were extensively examined in a 25 mm thick weld consisting of two regions which respectively undergo phase transformation at relatively low (100 °C) temperature (LTT) and high (670 °C) temperature (HTT) during cooling. Due to the LTT martensitic transformation, which features a transformation strain of ~4000 με, large compressive residual stress (−510 MPa) was generated as confirmed by neutron diffraction and contour method. Meanwhile, significant heterogeneities were observed in terms of the chemical composition, yield strength, and microhardness across the interface between the LTT and HTT regions. The dependency of martensitic transformation starting temperature (M_s) on chemical composition is empirically formulated, and it reveals that the dependency of M_s on the Ni and Cr compositions becomes stronger when the temperature is lower than 200 °C. The maximum change of residual stresses (σ_x^{max}) exponentially decreases as M_s decreases in the manner of $\sigma_x^{max} = 97.5 \exp(M_s/227)$-649. The fracture behavior was found highly dependent upon the volume fraction of retained austenite influenced by M_s. While a ductile fracture mode was found in the cellular LTT region containing relatively higher amount of retained austenite (~10%), the interface shows transgranular brittle fracture features and sub-cracking due to the relatively small amount of retained austenite and the predominant martensite constituent.

1. Introduction

Although residual stresses are self-balanced inside the component, tensile residual stresses can be detrimental to the structural integrity by accelerating susceptibility to brittle fracture, fatigue, creep, and stress corrosion cracking [1, 2]. To be specific, during heating and cooling, welding residual stresses are inherently generated due to thermal-mechanical misfit among different parts within the joining bodies [3]. One innovative approach to mitigate the residual stresses is the utilization of phase transformation from austenite (γ) to martensite (α') at relatively low temperature, which induces volumetric expansion and readily compensates for the thermal shrinkage followed by tensile stress evolution during cooling of steel welds [4, 5].

Up to the present, some studies have been performed on the topic of low transformation temperature (LTT) welding [6–34]. These studies can be classified into three categories: (i) alloy design, which can achieve low martensite transformation starting temperature (M_s) and finishing temperature (M_f), and which allows the confirmation of the residual stress reduction using X-ray synchrotron, neutron diffraction, and contour method [6–12]; (ii) monitoring of phase changes and strain evolution, and development of numerical methodologies to simulate and validate the residual stress reductions [13–23]; and (iii) mechanical properties of the welded joints and the implications of the stress reduction regarding distortion, cracking, and fatigue performance improvement [24–32]. These extensive efforts were summarized in the recent review papers [33, 34].

First, Ohta et al. early on suggested a 10Cr-10Ni alloy consumable having an M_s of 180 °C and showing enhanced fatigue strength up to 60% with the development of compressive residual stresses, which intensify the crack closure [6]. Based on the LTT phenomenon, compressive residual stresses were clearly reported in plate type welds using neutron diffraction [7, 8], X-ray/synchrotron [9, 10], contour, and hole

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drilling methods [11, 12]. Various in situ and ex situ experiments were performed to directly investigate the martensitic transformation [13, 14], retained austenite amounts as a function of Ni composition [15], and strain/phase changes under loading [16]. Second, several numerical analyses were conducted to simulate the delayed martensitic phase transformation and to predict the resultant residual stresses in various conditions of welds, for example, a boxing fillet welded joint [17], 4-mm thin and 20-mm thick welded plates [18, 19], different interpass temperatures [20], and a Cr-W type consumable case [21]. Finally, Wang et al. showed a fatigue life increase of 47 times at 162 MPa using their developed Cr-Ni welding electrodes [24]. Eckerlid et al. reported improvements of the impact toughness of LTT welds at −40 °C and the fatigue strength up to 90% at 2×10^6 cycles compared with the welds using traditional consumables [25]. In addition, the LTT weld is beneficial for the prevention of the cold cracking [26] and for the controlling of welding-induced angular distortion and fatigue strength properties [27–32].

In summary, most of the investigations have been devoted to the martensite transformed alloy design, assurance of the compressive residual stresses, and the resultant superior fatigue behavior of the joints [33, 34]. However, considering that the LTT weld inherently involves martensitic phase transformation and a dissimilar nature of austenitic welding consumable and ferritic base metal, it is essential to carefully examine the spatial variations in chemical composition, microstructure, austenite/martensite volume fractions and their influence on mechanical and fracture behaviors of the components.

In this paper, we present: (1) a joining specimen combined with consumables respectively experiencing phase transformation at relatively low (100 °C) temperature (LTT) and high (670 °C) temperature (HTT); (2) localized heterogeneities across the interface between the LTT and HTT regions of welds in terms of chemical composition, retained austenite amount, yield strength, and microhardness; and (3) two-dimensional map of the residual stresses measured by neutron diffraction and contour method. Most importantly, we discuss (i) the relationship among the chemical composition, martensitic transformation temperature and residual stress, and (ii) the effect of retained austenite volume fraction on mechanical and fracture behaviors.

2. Material, Processing, and Microstructure

2.1. Materials and Welding Parameters

As-received commercial high-strength low-carbon steel (0.05C, 0.1 Si, 1.2 Mn, 0.01 P and balance Fe, in wt%) was prepared as the base metal (BM) with dimensions of 600 mm long by 150 mm wide and 25 mm thick, as can be seen in Fig. 1(a). The x, y, and z directions are defined as the longitudinal, transverse, and normal directions of the plate specimen, respectively. Two plates of BM were joined with a 30° groove of half-V shape and a 4 mm gap at the bottom. Two different welding metals (WM) were used: (1) the conventional ferritic welding consumable alloy was utilized for the first three welding passes, and (2) the 10.2Ni-9.6Cr based austenitic alloy was used for passes four to twelve, Fig. 1(b).

Table 1
Chemical compositions of the base metal and weld consumables phase transformed at low temperature (LTT) and high (HTT) temperature.

Element (wt%)	C	Si	Mn	Ni	Cr	S	P	Fe
Base metal	0.05	0.1	1.2	–	–	–	0.01	Bal.
Weld metal								
HTT	0.04	0.37	1.32	1.53	–	0.006	0.016	Bal.
LTT	0.05	0.4	1.55	10.2	9.6	–	–	Bal.

The welding alloys are named as the HTT and LTT weld metals, respectively, in Table 1. An automatic submerged arc welding (SAW) method was applied to fabricate the specimen. This process is intended to produce high amounts of tensile residual stresses by using high heat input (1.8 kJ/mm) and fast welding speed (650 mm/min) as summarized in Table 2. The current SAW has been generally processed with two times higher heat input and five times faster welding speed than are used in previous manual welding methods [9, 15, 16]. During the welding processes, the weld plates were clamped on both sides along the welding direction.

2.2. Microstructural Heterogeneities and Chemical Composition Variations

Metallographic microstructure was examined by optical microscopy (OM) in the cross section of the weld. The locations for the optical microscopy analyses were 5 mm (*face*), 12.5 mm (*center*), and 20 mm (*root*) from the top surface, as shown in Fig. 1(c), and as marked by the numbered squares in Fig. 2. Overall, the results are consistent with the previous literature [9, 12, 21, 22]. The microstructure of the LTT weld metal exhibits a cellular structure consisting of martensite (dark) and retained austenite (bright) due to the Cr-Ni chemical segregation in area 1 (*face*); martensite phase is visible in area 2 (*center*) due to the lower quantity of retained austenite phase. In the HTT weld metal, areas 3 (*root*) and 4 (*interface*) clearly show acicular ferrite and bainite/tempered martensite structures, respectively, because of the ferritic consumable of the HTT region. Along the *center* (areas 5 to 8), the weld shows distinct microstructural characteristics depending on thermal effects during welding, e.g., a coarse grain heat-affected zone (CGHAZ) near the fusion line (FL), fine grain HAZ (FGHAZ, 1 mm from the FL), intercritical HAZ (ICHAZ, 5 mm from the FL), and BM (20 mm from the FL). Owing to the sufficiently high peak temperature, which caused

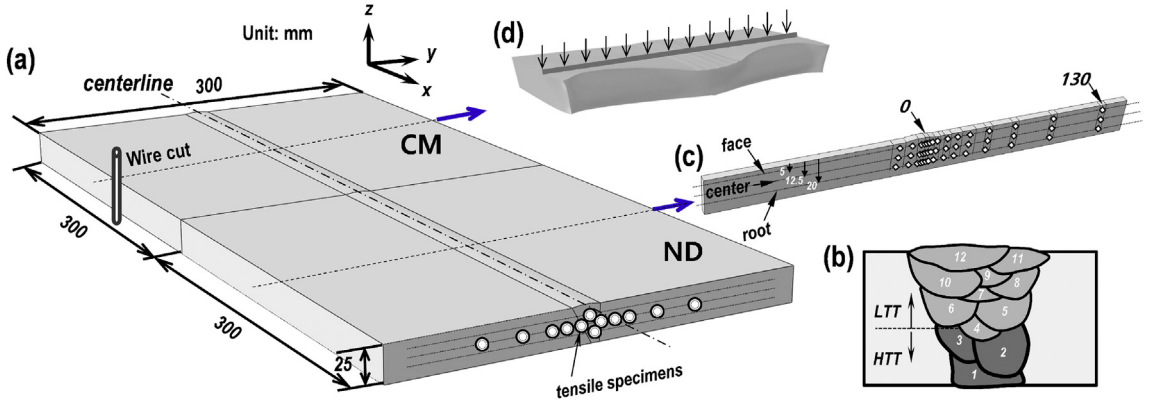

Fig. 1. Schematics of (a) the sample dimensions and measurement locations for the neutron diffraction (ND) and contour method (CM), (b) welding passes by low (LTT) and high (LTT) transformation temperature consumables, (c) the reference specimen for "stress-free" lattice spacing (d_o) measurements, and (d) the contour plane and constraints (arrows) on cutting for CM.