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Microstructure evolution and mechanical properties changes in the weld zone of a structural steel during low-cycle fatigue studied using instrumented indentation testing

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ABSTRACT

Room-temperature low-cycle fatigue (LCF), instrumented indentation, tensile tests, finite element (FE) analysis, and optical microscopy examinations were carried out to investigate the mechanical properties and microstructures in the weld zone of a structural steel, SS400, in cyclic loading conditions. Five indentation arrases were performed across the weld zone of five specimens, including one virgin specimen and four specimens subjected to LCF loading at different strain levels. The mechanical properties, such as elastic modulus *E*, yield strength σ_y, and strain hardening exponent *n*, were then estimated from indentation testing and FE analysis results. The obtained results and optical microscopy examinations show that the mechanical properties and microstructures in the individual region of the weld zone are not only decided by the metallurgical conditions resulting from the welding but also were highly influenced by the strain level applied during cyclic loading. In the as-welded condition, the values of elastic modulus, yield strength, and strain hardening exponent in the weld metal (WM) are higher than those in the base metal (BM), while materials in heat affected zone (HAZ) reveal a gradual decrease of elastic modulus, yield strength, and strain hardening exponent values from the WM to BM region. It is also shown that with increasing strain amplitudes during cyclic loading, the elastic modulus *E* displays decrease in all regions of the weld zone, both yield strength σ_y and strain hardening exponent *n* exhibit decreasing characteristic in WM and increasing characteristic in BM region, while the yield strength in HAZ region increases, the strain hardening exponent in this region keeps almost unchanged. The dependence of the mechanical properties on the applied strain level is also discussed in terms of microstructural changes in fatigue failure specimens.

1. Introduction

Structural steels are widely used materials in civil and industrial building construction and other structural applications because of the advantageous features such as low cost and excellence in terms of machinability and weldability. In the usage of structural steel, welding has been considered to be an efficient method to form strong joints that allow transferring loads between steel components [1]. During the welding process, the microstructural changes affect mechanical properties in the fusion zone (weld metal-WM) including elastic modulus *E*, yield strength σ_y, strain hardening exponents *n*, hardness *H*, and lead to the difference of these properties between base metal (BM) and heat affected zone (HAZ) of the structural steel weld zone. It has also been indicated that the properties of these zones not only depend on various metallurgical factors during welding but also are intensively influenced by service conditions such as the environment, temperature, state of stress imposed, loading history [2,3]. For steel structures operating under dynamic or alternating loading conditions, the progressive deterioration with the service times of service properties, especially the mechanical properties, has been considered notable [4]. The residual fatigue life studies of existing steel structures in service conditions generally include the assessment of fatigue damage. Such assessment is frequently performed by quantitatively measuring the deterioration of material mechanical properties such as the ultimate strength, elastic modulus, toughness, hardness, and cross section area reduction [5–7]. Therefore, it is essential to investigate the mechanical properties for both the designs of the welded joints against fatigue failure and the integrity assessment of structural steel members that have a welded joint, including elastic modulus, hardness, yield strength, and strain hardening exponent in the structural steel weld zone, as well as their variation during fatigue loading.

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Table 1
Chemical compositions of steel and electrode (in wt%).

Material	C	Si	Mn	P	S	Al	Ca	Cu
SS400	0.05	0.037	0.46	0.013	0.002	0.044	0.0017	–
ER70S-6	0.04	0.92	0.45	0.011	0.015	–	–	0.2

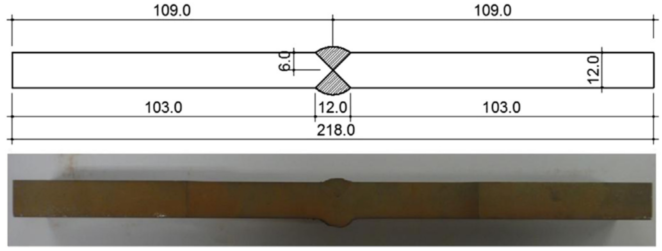
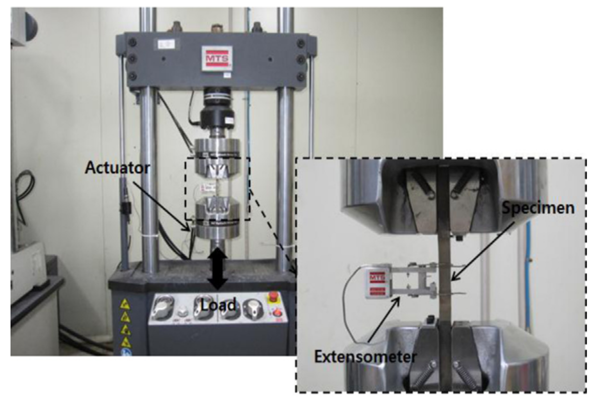


Fig. 1. Double-V groove butt welding plate.

Numerous methods for determining the mechanical properties (E, σ_y, and n) in different zones of steel welded joints have been reported [8–18]. For instance, methods to characterize the properties in welded joint using mini- or micro-tensile specimens testing were used for steel and aluminum [8–10]. However, it has been recognized that preparing mini- or micro-tensile specimens from the welded joints is a rather difficult task due to the small size of joint zones [8]. The method allowed obtaining the material properties relative to different zones of welded joints by hardness measurements using the ultrasonic contact impedance (UCI) was used for S235JR mid steel [11]. In this method, the stress-strain curves relative to different zones of welded joints can be drawn based on ultimate strength σ_u and yield strength σ_y values calculated from the corresponding measured HB hardness using approximate equations and assumptions that elastic modulus E and horizontal plastic plateau were unchanged in the joint zones. These approximated equations and assumptions may affect the accuracy of the obtained stress-strain curves. Among reported methods, instrumented indentation testing (ITT) has been considered as a promising method in practical applications due to its fast, precise and nondestructive merits, and it allows determining various mechanical properties including elastic modulus, hardness, yield strength, strain hardening exponent, facture toughness [12–18]. For example, indentation tests and finite element (FE) analysis were used to investigate the mechanical properties of DP590 steel weld zone [13], spherical indentation was utilized to measure local mechanical properties of welded stainless steel SUS316L at high temperature [15], and micro-indentation and inverse modeling were applied to determine mechanical properties of the weld line of two typical dual phase high strength steels DP600/DP980 [16]. Recently, ITT and FE analysis were conducted to investigate the mechanical properties (E, H, σ_y, and n) in the weld zone of two structural steels SM490 and SS400 [17,18]. Concerning the steel welded joints subjected to low-cycle fatigue loading, the literature on fatigue analysis was well reviewed in [19,20]. In addition, it had been found that combination of full-field techniques (digital image correlation and infrared thermography), hardness measurements using UCI method, and FE analysis can be used to analyze the welded joints under low-cycle fatigue loading [21]. However, ITT was also demonstrated to be an appropriate approach for investigation of steel welded joints under low-cycle loading by successfully applying to study the local mechanical properties and microstructures in individual zone of 304L SS welded joint in both as-welded and cyclic loading conditions [22].

(a) Welded specimens



(b) Test arrangement

(c) Side view of a specimen on the testing machnine

Fig. 2. Specimens and the installation of low-cycle fatigue tests. (a)Welded specimens. (b) Test arrangement. (c) Side view of a specimen on the testing machine.

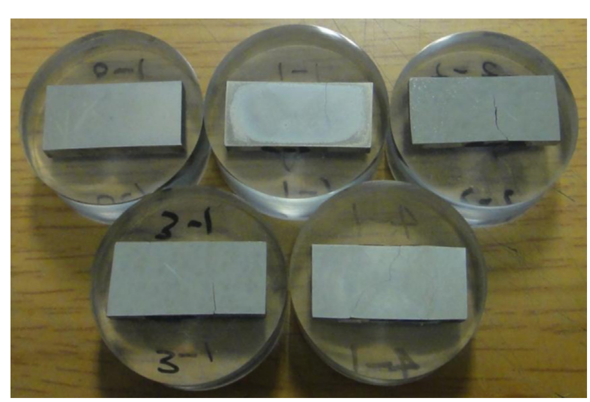


Fig. 3. Five samples for instrumented indentation tests.