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Research on fatigue behavior and residual stress of large-scale cruciform welding joint with groove

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ABSTRACT

Fatigue fracture behavior of the 30 mm thick Q460C-Z steel cruciform welded joint with groove was investigated. The fatigue test results indicated that fatigue strength of 30 mm thick Q460C-Z steel cruciform welded joint with groove can reach fatigue level of 80 MPa (FAT80). Fatigue crack source of the failure specimen initiated from weld toe. Meanwhile, the microcrack was also found in the fusion zones of the fatigue failure specimen, which was caused by weld quality and weld metal integrity resulting from the multi-pass welds. Two-dimensional map of the longitudinal residual stress of 30 mm thick Q460C-Z steel cruciform welded joint with groove was obtained by using the contour method. The stress nephogram of Two-dimensional map indicated that longitudinal residual stress in the welding center is the largest.

1. Introduction

Welding is a main technical method in the area of shipbuilding, nuclear power, petrochemical industry, aerospace industries. With the rapid development of large engineering structure, the large-scale welded construction is expected to be widely used in the engineering structure. Thus, the requirements for the fatigue strength and other mechanical performances of welding structure become increasingly higher more higher as the size of welded joint increases. It is well-known that welding joints are often the weakest portions of welding structures and their quality directly affects the integrity of welding structures. In general, most of welded joints work under the condition of cyclic loading, so fatigue failure is the main failure mode of welding joint. With the wide applications of the large-scale welded structures in the engineering structure, more attention is focused on fatigue strength assessment. For instance, Zhou et al. studied the fatigue properties of friction stir welds in Al 5083 alloy which is widely used in the automobile industry for producing large body sheet material with high fuel efficiency [1]. Pao et al. also studied the fatigue crack growth in friction stir welded for another Al alloy 7050 [2]. Zheng et al. presented the experimental and numerical investigation on the fracture of large-scale welded thin-walled AA 6061 panels under out-of-plane global loading condition for comparison with fatigue load [3]. Hong et al. analyzed the fatigue crack propagation behavior of friction stir welded Al–Mg–Si alloy [4]. Usually, the ability of the large-scale welded joint under static load is very strong, but worse under cyclic loading. Therefore, it is necessary to pay high attention to fracture and fatigue-related failure assessments. The works of Huo and Masubuchi are universally adopted to assess the fracture and fatigue-related failure [5,6]. Residual stress and stress concentration as the main factors influencing the fatigue performance of welded structure have always been the concerned. Scientists have carried out a lot of research work about the influence of residual stress and stress concentration on the fatigue performance of welded structure. Venkateswara Rao et al. discussed the influence of parent metal heat treatment condition on the residual stress distribution in dissimilar metal welds of maraging steel to quenched and tempered medium alloy medium carbon steel and further on its fatigue properties [7]. James et al. presented single-line residual stress profiles for 8 mm 5083-H321 aluminum plates joined by gas metal arc (MIG) welding and reported the effect on residual stress and strain values of a sequence of applied fatigue loads [8]. Also, Teng and Chang investigated the effect of residual stresses on fatigue crack initiation life for butt-welded joints [9]. Besides experimental studies, numerical simulations were also used for thoroughly analyzing the residual stress

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distribution in weld. Bhatti et al. proposed a framework for efficient prediction of residual stresses in large welded structure [10]. In particular, for large-scale and high-strength steel welded structures, the distribution of longitudinal residual stress in the welded joint is rather complicated. The current testing methods of residual stress such as X-rays, synchrotron X-rays and neutron diffraction are still unable to achieve accurate or convenient measurement in the welded joint [11,12]. A new method is necessary to select for testing internal residual stress of the large-scale and high-strength steel welded structures. Woo et al. tested the through-thickness distributions of residual stresses in two extreme heat-input thick welds using neutron diffraction, contour method and deep hole drilling. They found that the contour method is the most accurate and convenient way of residual stress testing for such large structures [13]. Braga et al. used two different residual stress measurement techniques: contour method and neutron diffraction to obtain the welding residual stress profile of butt joints of S355 structural steel modified by post-welding rolling technique. A good agreement between the results of both measurement techniques was found, illustrating the capability of the contour method to provide data otherwise available only using costly neutron and synchrotron radiation [14]. Similar conclusion was drawn by Zhang et al. when they carried out the cross-sectional mapping of residual stresses in a VPPA weld [15]. The contour method as a reliable and promising technique was adopted in the present work.

2. Experimental procedures

2.1. Experimental material and method

In this study, as-welded joint is bearing cruciform welded joint with carbon-dioxide arc welding. The materials were chosen to span a wide range of hardness and modulus, including base material of Q460C-Z and welding material of GHS-60. The chemical composition (wt.%) and mechanical properties of Q460C-Z steel plates were shown in Tables 1 and 2, respectively. The chemical composition (wt.%) and mechanical properties of GHS-60 were shown in Tables 3 and 4, respectively. The cross-sectional macrostructure of the 30 mm thick Q460C-Z steel welded specimens was shown in Fig. 1.

It can be seen that the metallographic structure of base material consists of white pearlite and black ferrite. Acicular martensite and bainite were observed in fusion zone. Serious grain coarsening also appears in the fusion zone. Therefore, the serious grain coarsening makes the fusion zone into the weak area of welded joint. Besides, quenching martensite also appears in this region, which leads to the reduction of plasticity and toughness. Thus, crack is prone to produce in this region. Weld centerline consists of coarse columnar dendritic grains, which are perpendicular to the weld pool boundary.

2.2. Fatigue testing

Fatigue tests of the 30 mm thick Q460C-Z steel cruciform welded joint with groove were completed. The size of fatigue specimen was shown in Fig. 2. All tension–tension fatigue tests were carried out under constant amplitude loading with stress ratio $R = 0.1$ at room temperature in air environment. Tests were conducted on 200 kN high frequency fatigue testing machine with static load error for full measuring range between ±0.2% and dynamic load error between ±2%. The frequency is resonance frequency determined by fatigued sample and high frequency fatigue testing machine.

The stress level and fatigue life jointly determines the fatigue performance of sample. The relationship between applied stress and fatigue life is represented in S–N curve. According to S–N curve, the fatigue strength corresponds to a cyclic number can be obtained. Fatigue testing data should be analyzed according to the principle of statistical method established by IIW [16].

The fatigue resistance data are based on the number of cycles N to failure. The data are represented in S–N curves.

$$N = \frac{C}{\Delta\sigma^m} \tag{1}$$

where m and C are material constants; N is the number of cycles N to failure; S is stress range ($\Delta\sigma$).

2.3. Contour method

The basic principle of contour method to determine the residual stress over a cross-section is based on the fact that the displacements of the cut surface are created due to the release of residual stresses. The cross section after stress release is compared to the contour of an assumed flat surface. If the external stress that is applied to the cutting surface after deformation can change the state of cutting surface into original state, then, this external stress is equivalent to the original residual stress before cutting. Thus, the cutting deformation contour of welded joint can be used to get the original internal residual stress of welded joint. Hence, through the recovery of the surface contour after stress released to the original contour of an assumed flat surface, the distribution of welding residual stress can be calculated using an elastic finite element method. The main experimental procedures should be carried out as follows [17]:

(a) *Cutting:* Samples need to be cut into two parts along the plane of testing stress under the fully-constrained condition (see Fig. 3). The cutting surface will be out of shape for the stress release. Therefore, the deformation of cutting surface is caused by the elastic stress release. Meanwhile, we also should make sure that no cutting-induced stresses occur in this process.

(b) *The measurement and fitting of surface profile:* The high-precision measuring device is applied to measure the contour of cutting surface. Average the contour data of two cutting surfaces, and fit the cutting surface to smooth surface.

(c) *Stress analysis:* See the measured contour as the boundary conditions, and the elastic finite element method is adopted to analyze the original stress.

3. Results and discussion

3.1. Fatigue properties analysis

Fatigue date of the bearing cruciform joint with groove and three fatigue design S–N curves recommended based on the analysis of literature[5] and IIW (International Institute of Welding)

Table 1
Chemical composition (wt.%) of base material.

Composition	C	Si	Mn	P	Nb	Cu	V	Ti	Cr
Content	0.16	0.41	1.55	0.018	0.019	0.02	0.026	0.014	0.03