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The relative effects of residual stresses and weld toe geometry on fatigue life of weldments

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ABSTRACT

The weld toe is one of the most probable fatigue crack initiation sites in welded components. In this paper, the relative influences of residual stresses and weld toe geometry on the fatigue life of cruciform welds was studied. Fatigue strength of cruciform welds produced using Low Transformation Temperature (LTT) filler material has been compared to that of welds produced with a conventional filler material. LTT welds had higher fatigue strength than conventional welds. A moderate decrease in residual stress of about 15% at the 300 MPa stress level had the same effect on fatigue strength as increasing the weld toe radius by approximately 85% from 1.4 mm to 2.6 mm. It was concluded that residual stress had a relatively larger influence than the weld toe geometry on fatigue strength.

1. Introduction

Welded connections are the prime location for fatigue failures. Fatigue cracks usually initiate at the weld toe due to the local stress concentration caused by geometrical changes, residual stresses and also crack-like flaws that can sometimes be found in the weld toe [1–4].

Different improvement methods have been studied and implemented to increase the fatigue life of welded structures. The two main approaches are (a) modification of the weld toe geometry (by, for example, grinding or TIG re-melting) and (b) modification of the residual stress induced by welding (for example by shot peening or post weld heat treatment). The former improves the fatigue strength through reduction of the local stress concentration factor by ensuring a smooth transition between the weld profile and base metal. The latter contributes to fatigue strength increase by reducing tensile residual stresses or even by inducing compressive residual stresses at the weld toe region. There may be limitations for implementation of the mentioned techniques due to the technical complexity and also time and cost issues [5–7].

Among improvement methods, using Low Transformation Temperature (LTT) filler materials is a recent alternative approach to increase the fatigue strength of welded parts in a single step i.e., without applying any costly post-weld treatment. A large number of investigations have confirmed the effectiveness of using LTT filler materials in increasing the fatigue life of welds. This is due to transformation of the weld at low temperatures, typically around 200 °C, which lowers the tensile residual stresses or even produces compressive residual stresses within the weld region and particularly at the weld toe [8–14]. However, LTT consumables are not widely commercially available and there is little experience from practical applications. LTT filler materials are hence not used extensively in industry.

The effect of the weld geometry on fatigue strength of welded parts has been studied extensively. It has been found that the weld toe radius and angle, especially the weld toe radius, is one of the primary geometrical features that control the fatigue life. By increasing the weld toe radius, the angle or both radius and angle the fatigue strength will increase due to a decrease in stress concentration at the weld toe [15–22].

Thus, both residual stresses and geometrical features influence fatigue properties but, there is a lack of information about which has the stronger influence. Therefore, the aim of this paper is to evaluate the relative effects of weld toe geometry and residual stresses on fatigue life. In this regard fatigue strength of cruciform welds produced either using LTT or conventional filler materials has been compared. The effects of geometry and residual stresses at the weld toe have been evaluated and related to fatigue strength.

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2. Material and methods

2.1. Base and filler materials

The base material used in this study was Weldox 700, a high strength steel with a plate thickness of 8 mm. The yield and tensile strengths of the base material were 817 MPa and 852 MPa, respectively. Gas Metal Arc Welding (GMAW) was used for cruciform welding of plates using two different filler materials, a standard high strength (OK Tubrod 14.03) and an LTT metal-cored wire. The compositions of the base material and filler materials are given in Table 1 and mechanical properties of filler materials are summarized in Table 2.

2.2. Welding setup

Four series of welds (L1, L2, C1, C2) were produced, each consisting of 11 samples. Of these, 10 samples were used for fatigue testing and one for geometry and residual stress measurements. L1 and C1 were single-pass welds while L2 and C2 were double-pass welds. L refers to welds produced by the LTT filler material and C refers to the welds produced by the conventional filler material (OK Tubrod 14.03). Ar + 2% CO_2 was used as shielding gas. The welding parameters are summarized in Table 3. Dimensions and the configuration of cruciform test samples together with the welding sequence are shown in Fig. 1. In order to avoid the influence of welding start/stop positions on fatigue properties, they were located on each side of the flanges. One start/stop position is shown in the photograph of the test weld in Fig. 2.

2.3. Fatigue testing

The fatigue testing was performed by applying a constant amplitude sinusoidal tensile load in the longitudinal direction, with a frequency of 29–40 Hz at a stress ratio $R = 0.1$. Testing was stopped before fracture (run-outs) for samples surviving more than 2 million cycles [23].

For evaluation of the test data, the number of cycles (N) was treated as the independent parameter in $\log(N) = \log(C) - m * \log(\Delta\sigma)$. In this equation, C and m are fitting constants. The number of cycles were plotted against the stress ranges ($\Delta\sigma$), and using the least square technique, the mean fatigue strength was estimated [24]. To calculate the characteristic fatigue strength at 2 million cycles, the FAT value, the mean curve is lowered by k standard deviations. Here, a k value of 2.7 was used, based on the number of weld samples [25].

2.4. Weld toe radius and angle measurements

There are several destructive and non-destructive methods for measuring the weld toe radius and angle [15,26–28]. In this paper, the Weld Impression Analysis (WIA) method was used. Detailed information about using this method for measuring the weld toe radius has been published elsewhere [29]. Fig. 3 schematically presents the two geometrical features, i.e. weld toe angle (Θ) and weld toe radius (r), that were measured for the weld samples in this paper. Measurements were done at the centre as shown by the dashed line in Fig. 3a. Three independent measurements were done on the two opposite sides of the web. The evaluation was done at 20× magnification in a stereomicroscope and the result is the average of six measurements.

Table 2
Mechanical properties of all-weld metal.

Welding consumable	R p 0.2 (MPa)	R m (MPa)	A5 (%)	Impact toughness at −40 °C (J)
OK Tubrod 14.03[a]	760	840	23	70
LTT	736	1127	13	49

[a] Typical values.

2.5. Residual stress measurements

Surface residual stresses were measured using the X-ray $\sin^2\varphi$ method. An XSTRESS 3000 X-ray Stress Analyzer, with Cr-Kα radiation and varying φ – angles between −45° and +45° was used to estimate the stresses transverse to the weld toe. The aperture diameter was 2 mm. The stress was measured at the last weld along the centreline of the flanges at 1–40 mm from the weld toe [23]. Measurements were performed on the as received welded plates, with no prior grinding or polishing.

3. Results

3.1. Fatigue testing

In all samples fracture initiated at the weld toes at the short edges of the flanges and propagated through the base metal. The fatigue test results are compiled in *S–N* curves shown in Fig. 4. For comparison, the IIW FAT-71 class [25] for the used specimen geometry is also presented in the figure.

The calculated characteristic fatigue strength (FAT), the mean fatigue strength at 2 million cycles and the slope of the curves are tabulated in Table 4.

It is clear that fatigue strength of LTT welds are significantly higher than for welds produced using the conventional wire (Fig. 4 and Table 4). The fatigue strength of the double-pass LTT welds is the highest, followed by the single-pass LTT welds and finally the single and double-pass welds produced by the conventional wire. From the FAT values in Table 4 it can be seen that a fatigue strength improvement of 22% and 55% is achieved for L1 and L2 welds, respectively, when compared with the IIW FAT value of 71 MPa. Experimental FAT-values for welds produced by the conventional filler material were slightly below the IIW FAT 71. Comparing mean fatigue strength levels at 2 million cycles even more clearly shows the higher fatigue strength of the LTT welds. A direct comparison shows an improvement of 58% for the single-pass welds and 76% for the double-pass welds.

As can be seen in Fig. 4, the fatigue strength is almost similar for all consumables at high stresses, but higher for LTT consumables at lower loads. The slope of the *S–N* lines are 3.74 and 4.41 (Table 4) for welds by LTT fillers. These are higher than the slope of 3 used

Table 1
Chemical composition of base material and filler materials (weight %).

	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Cu	Al	Nb
Weldox 700	0.13	0.3	1.18	0.011	0.003	0.27	0.04	0.13	0.007	0.013	0.01	0.041	0.022
LTT	0.02	0.7	1.3	0.005	0.007	12.8	6.2	0.1	–	–	–	–	–
OK Tubrod 14.03[a]	0.07	0.6	1.7	–	–	–	2.3	0.6	–	–	–	–	–

[a] Nominal composition.