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Fatigue crack propagation in threshold regime under residual stresses

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ABSTRACT

The effect of residual stress on the fatigue crack propagation was analysed for a loading regime close to threshold stress intensity factor range. Fatigue crack propagation experiments were performed on single-edge-notched bending specimens machined from a welded plate. The residual stresses induced a variation in the crack propagation rate along the crack front. By varying the stress ratio and the stress intensity factor range, different shapes of crack front can be realized. From the shape of the crack front and the variation of the crack front, the resulting residual stresses and local stress intensity can be determined by means of finite element modelling. By using some simplifications, it is possible to estimate the limit values of the stress intensity factor induced by the residual stresses at selected regions.

1. Introduction

Weld joints can contain various types of flaws such as slag inclusions, gas pores or stick spots. From such flaws during the service, a crack can initiate, grow slowly and finally lead to catastrophic failure. Fatigue behaviour of a welded structure is complicated by many factors intrinsic to the nature of welded joints [1]. The residual stresses as consequence of thermal multi-pass welding cycles can be a dominant effect on fatigue crack propagation. There have been many studies on the effect of residual stresses on fatigue crack propagation behaviour [2–8]. The majority of the studies have analysed the effect of transversal or longitudinal distribution of residual stresses in welded plate, and their effect on fatigue crack propagation. Just a few studies are dealing with through thickness residual stress distributions along the fatigue crack front [9,10]. The numerous measurements show that residual stresses through thickness vary from tension to compression [10–12].

The information about residual stress distribution through the thickness is very important, because the local stress intensity factor along the crack front can cause fast fatigue crack propagation and a final catastrophic failure. Failure can occur when the applied superimposed value (external applied stress intensity factor K_{app} and stress intensity factor induced by residual stresses K_{RS}) in one region of the crack front achieves the fracture toughness of the material, especially in brittle materials. This can be exhibited also as a local "pop-in" effect in ductile materials with local brittle zones [13]. It is well known that the mean stress has a significant effect on fatigue crack propagation. Therefore, residual stresses, which change the local stress ratio, have a large effect on the fatigue life time of components. In order to estimate the variation of stress intensity factor along the fatigue crack front, it is necessary to consider actual fatigue crack fronts during fatigue crack propagation. Determination of residual stress on fatigue crack growth is difficult, because the applied stress intensity factor K_{app} can be significantly different from local effective crack driving force value which is affected by residual stresses K_{RS}. Problems arise if the fatigue crack front is uneven, because in this case, the local stress intensity factor range can additionally vary through the thickness. In order to visualize the effect of residual stress on fatigue crack growth in the threshold region, the specimens cut out of the welded plate are subjected to low maximum stress intensity factor (which is kept constant) and two significantly different fatigue loading range $R_{app} = 0.05$ and $R_{app} = 0.90$ where $R_{app} = K_{min}/K_{max}$ is the loading ratio. It will be shown that such experiments are useful to determine stress intensity induced by residual stresses.

In order to take into account irregular shape of the fatigue crack front, a finite element method was applied for stress intensity factor determination.

2. Experimental procedure

2.1. Material and specimen

In this study, a high-strength, low-alloy HSLA steel (ASTM grade HT 50), in a quenched and tempered condition, was used as the

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Nomenclature

a	crack length
B	thickness of specimen
BM	base metal
da/dN	fatigue crack growth rate
F_{max}	maximum fatigue load
F_{min}	minimum fatigue load
H	width of weld gap
K_{RS}	value of stress intensity factor caused by residual stresses
M	mismatch factor (ratio of the yield stress of the weld metal to the yield stress of the base metal)
K_{app}	applied stress intensity factor
K_{max}	maximum stress intensity factor
K_{min}	minimum stress intensity factor
R_{app}	applied stress loading ratio
W	width of specimen
$R_{p0,2}$	yield stress of material
R_m	ultimate maximum stress of material
ΔK_{app}	range of applied stress intensity factor
K_{cl}	crack closure stress intensity factor

base metal (BM). Fig. 1 shows the arrangement for the welding of the plates. A Flux Cord Arc Welding (FCAW) procedure was applied for the welding in order to produce welded joints in over-matched configuration. The chemical compositions and mechanical properties of the base metal and the weld metal are given in Tables 1 and 2. The strength mismatch factor M, i.e., the ratio of the yield stress of the weld metal to the yield stress of the base metal, is 1.19. In Table 2, $R_{p0.2}$ is the engineering yield strength (offset at 0.2% of plastic strain), and R_m is the engineering ultimate tensile strength-UTS.

Welding with filler wire for over-match configuration was made with preheating at temperature of 55 °C. Welding was performed using MAG procedure (82% Ar and 18% CO_2). The heat input was in the range of 16–20 kJ/cm, and the suit cooling time between 800 and 500 °C was $\Delta t_{8/5} = 9-12$ s. The interpass temperature was 150 °C.

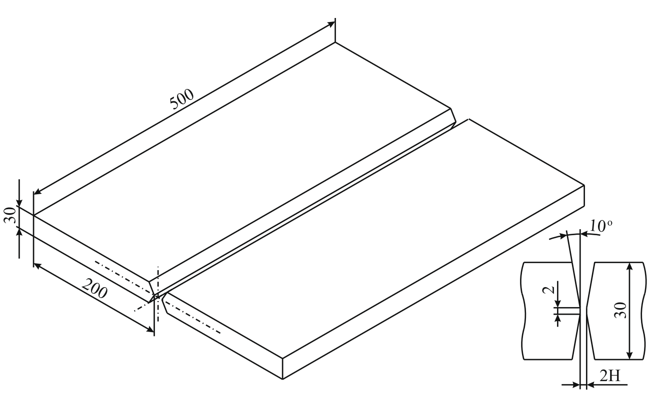

Fig. 1. Welding arrangement (2H = 6, all units in mm).

Table 1
Chemical composition of base metal and weld metal in weight percentages.

Material	C	Si	Mn	P	S	Cr	Mo	Ni
Over-match	0.040	0.16	0.95	0.011	0.021	0.49	0.42	2.06
Base metal	0.123	0.33	0.56	0.003	0.002	0.57	0.34	0.13

Table 2
Mechanical properties of base metal and as-welded weld metal.

Material	E (GPa)	$R_{p0.2}$ (MPa)	R_m (MPa)	M $R_{p0.2,WM}$/ $R_{p0.2,BM}$	Charpy Cv (J/80mm^2)
Over-match	184	648	744	1.19	>40 J at −60 °C
Base metal	203	545	648	–	>60 J at −60 °C

In order to estimate effect of residual stresses on fatigue crack growth, the specimens are cut out from the welded plate. Standard specimens with a through thickness notch were cut out of the welded plate as shown in Fig. 2. The notch was machined in the center line of welded joint. The thickness B and width W are the same, $B = W = 25$ mm. The machined notch was 4 mm in depth.

2.2. Preparation of specimen

In order to eliminate the effect of the notchs radius on the initial fatigue crack growth, a very sharp notch radius between 0.01 and 0.015 mm was prepared by a razor blade polishing technique. In pre-preparation stage, the specimen was subjected to four-bend compression loading, as is shown in Fig. 3. It is supposed that in the early shape under cycling compression loading of the notch, the residual stresses have less effect on initial fatigue crack growth [14]. The generated pre-crack was very small (below 0.1 mm), and it is similar in length along through thickness.

2.3. Fatigue crack propagation experiment

The single-edge-notched specimen was subjected to three point bending. The sequence of fatigue loading is listed in Table 3. Note that the mean crack lengths (see Table 3) are calculated at the end of the fatigue test, during post-examination fractographic analysis of the fracture surface, see Fig. 4. Fatigue was performed under constant load (i.e., constant load ratio R_{app}, as well) from the beginning until the end of each sequence of loading. Both crack stress intensity factors K_{max} and ΔK_{app} increase. The increase of the maximum applied stress intensity factor was up to 6%, what can be as-

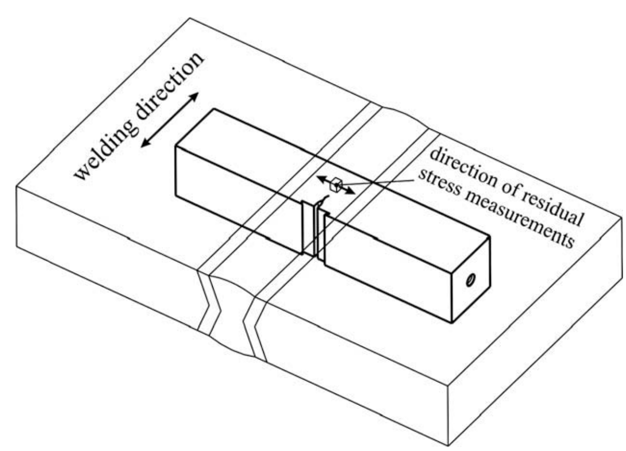

Fig. 2. Position of specimen, notch orientation and consider residual stresses acting in the welding plate are sketched.