ASSESSMENT OF FATIGUE PRECRACKING METHODS FOR FRACTURE TOUGHNESS TESTING OF Q+T WELDMENTS

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The purpose of this work was to compare two fatigue precracking techniques for fracture toughness specimens made of over-matching weld joints containing residual stress. The influence of "Local Compression-LC" and "Step-wise High R-ratio-SHR" fatigue precracking techniques were assessed. LC technique is unsuitable to obtain uniform fatigue crack front profile in over-matched weld joints which contain regions of lower strength materials. SHR technique is more appropriate by using suitably maximum fatigue load and R-ratio.

INTRODUCTION

Existent fracture toughness test standards and procedures such as BS 5762-79, ASTM E 1290-93, ASTM E 1152-87, ASTM E 813-89, ASTM E 399-90, EGF P2-92 (1) and "The GKSS test procedure for determining the fracture behavior of materials" (2) require fatigue precracked specimens with almost the same restrictions on the fatigue crack front shape, length and the loading conditions (particularly with regard to the level of maximum load and stress loading R-ratio). Straight precrack fatigue front enables equal conditions of testing (and replay testing). It enables also continuos transition of stress state near outer surfaces plane-stress to plane-strain condition at the midthickness. The specimens which have uniformed shaped precrack fatigue front yield valid fracture toughness values with less scatter than the specimens with non-uniform precrack fatigue front, Koçak et al (3). All above mentioned standards and documents are concerning with the testing of homogeneous metallic materials, base materials. Unfortunately, at present there is no available specific standards or appendixes to present standards for fracture toughness testing of weldments.

It is almost impossible without modification to meet requirements about fatigue crack front in CTOD testing of over-matched weld joints (containing residual stress in as-welded condition) on through thickness specimens, especially in the case of over-matched weld joints combined with under-matched layers in the midthickness of the specimen.

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MATERIALS, WELDING, PRECRACKING PROCEDURE

High strength low alloyed HSLA steel was used in quenched and tempered condition (Q+T) corresponding to grade HT80. The plates of thickness 40 mm were welded by FCAW procedure using specially developed electrodes. The roots of X-grooved multi pass weld joints have been welded by low strength electrode (B-two passes, C-four passes) with the aim to omit preheating. Mechanical properties of all weld metal were determined by round tensile specimen (∅5 mm, DIN 50125) extracted from root and cap region of weld joints in the direction of the weld axis, Tab. 1.

TABLE 1- Mechanical properties of base material and all weld metal, (T=20°C).

Material	$R_{p0.2}$ MPa	R_m MPa	$R_{m\text{-}true}$ MPa	E MPa	$e_{\text{-elongation}}$ %	M
Base material	711	846	911	208986	19.6	-
Homogeneous WM root	807	867	905	209592	16.9	1.14
Nonhomog. 2x root passes	773	857	901	205808	14.4	1.09
Nonhomog. 4x root passes	759	791	810	205758	15.8	1.07
Overmatching WM cap	852	964	1017	198414	15.6	1.20

In order to prevent the development of to large plastic zone during the fatigue precracking which may affect toughness measurements the maximum load to be used for three point bend specimens (SENB) was calculated in accordance with all mentioned standards and documents, (see Tab. 2).

TABLE 2- Calculated maximum precrack fatigue load, F_{max}, for a/W=0.48.

Criteria	$F \leq 0.6F_y$	$\blacklozenge = K_{max}/E < 1.5^{-4}\ m^{0.5}$		$F \leq P_M, P_f$	$F \leq 0.4P_L$	$\lozenge = K_{max}/E < 3.2^{-4}\ m^{0.5}$		$F \leq P_f(K_f)$
Material	$F_{max}(F_y)$ kN	K_{max} N/mm$^{1.5}$	$F_{max}(\blacklozenge)$ kN	F_{max} kN	F_{max} kN	K_{max} N/mm$^{1.5}$	$F_{max}(\lozenge)$ kN	F_{max} kN
Base material	102.7	991	31.0	64.2	68.4	2115	66.1	82.1
Homogeneous WM root	116.5	976	30.5	72.8	77.7	2082	65.1	93.2
Nonhomog. 2x root passes	118.3	976	29.8	71.4	57.1	2083	63.6	89.2
Nonhomog. 4x root passes	106.4	976	29.8	68.7	54.9	2082	63.6	87.6
Overmatching WM cap	123.9	941	29.4	76.9	82.0	2008	62.8	98.4

The maximum precrack loads were calculated by using limit load as:

$$F_{max}=(B_{root}/B)\cdot F_{max\text{-}root}+(B_{cap}/B)\cdot F_{max\text{-}cap} \qquad (1)$$

which was defined on mechanical properties and ratio of root-cap (see Tab. 3).

According to the standards and documents R-ratio (F_{min}/F_{max}) used for fatigue precracking should not exceed 0.1. Higher R-ratio for a given maximum precracking load, F_{max}, reduces the applied stress intensity range and increases the mean load, $F_m=(F_{max}+F_{min})/2$ and consequently prolongates the precracking time.

TABLE 3- Maximum precracking loads of mis-matched weld joints with soft root layers.

Type of weld joint	x	Measured portion B_x mm	Ratio B_x / B B=36	$R_{p0.2\text{-}avr}$ MPa	M_{avr}	F_{max}					
						$F \leq 0.6F_y$ kN	$F \leq (\blacklozenge)$ kN	$F \leq P_M, P_f$ kN	$F \leq 0.4P_L$ kN	$F \leq (\lozenge)$ kN	$F \leq P_f$ kN
A	root	6.26	0.174	844	1.19	118.3	29.0	80.4	64.3	61.9	97.4
	cap	29.7	0.826								
B	root	9.97	0.277	830	1.17	116.4	29.0	78.1	62.5	61.9	95.8
	cap	26.03	0.723								
C	root	15.73	0.437	811	1.14	113.7	29.2	75.7	60.5	62.3	93.6
	cap	20.27	0.563								

SENB specimens (36x72x360mm) have been cut from the weld plates, as shown Fig. 1. Machined notch has been located in the through thickness in the middle of weld. It is known that the trough thickness pattern of the welding residual stresses (transverse to the weld length) changes from tensile stress (+) near surface to a compression (-) as balancing stress at about midthickness with maximal values on the middle of the welded plate. The components of residual stresses in tension and in compression will act as an additional stresses to the applied stresses during the loading. Therefore, during the fatigue precracking compressive stresses (at the midthickness region) normal to the crack plane can counteract to the applied cycle stresses. Already weak decrease of effective stress intensity range magnitude at the region where crack growth is inhibiting affect non-uniform crack propagation, Fig. 2. Supposing that the tensile stresses near surface are balanced with the compression ones at midthickness neutral axes of stress. It is shown in Fig. 3 for weld joint type B. The distribution of residual stresses in welds is possible to determine by common known method e.g. neutron diffraction technique, Schröder et al (4).

TABLE 4- Fatigue precracking and deviations of fatigue precrack shape.

Type of weld joint	R	F_{max} N	Specimen	Δa mm	a_0 mm	a_0/W	deviation (mm)	
							ASTM*	GKSS**
Base material	0.1	30	BM-1	4.501	37.500	0.52	2.230	1.486
			BM-2	4.440	37.400	0.52	2.316	1.527
A	0.1+0.7	30.5	A-1	3.854	35.854	0.50	5.678	3.780
			A-2	3.234	35.234	0.49	5.166	3.333
B	0.1+0.7	60	B-1	3.050	36.050	0.50	1.365	0.862
			B-2	2.822	35.822	0.49	2.475	1.832
C	0.1	28.5	C-1	2.303	35.300	0.49	5.895	3.766
		29	C-2☆	6.105	39.105	0.53	14.148	9.43

* $\mathrm{MAX}(a_i)-\mathrm{MIN}(a_j) \leq 0.1 \cdot a_0$, $i,j=1,..,9 \wedge i \neq j$

** $\mathrm{MAX}\left|a_i - a_o\right| \leq 0.1 \cdot a_0$, $I=1,..,9$

☆ specimen was local compressed

The experiments and calculation by FEM shows that specimens loaded by F_{max}=60kN were in linear range. Shape and distribution of residual stresses are changed through the thickness. In spite of this, it is possible in most cases by weld joints on majority weldments to determine suitable fatigue mean load $F_{m,RS}$ and

R_{RS}-ratio which gives an assurance for acceptable shape of precrack fatigue front ($R_{RS}=(2\cdot F_{m,RS} - F_{max})/F_{max}$ and $0.1 \leq R_{RS} \leq 0.7$).

The "Local Compression" stress relief technique had been introduced by Dawes (5) to achieve uniform fatigue crack front profiles in welds. To obtain a straight fatigue crack front, a total plastic strain applied across the thickness of the specimen should be 1%. SENB specimen with 4 soft root passes has been treated with thus techniques before fatigue precracking with the R-ratio of 0.1. Obtained precrack fatigue front has shown in Fig. 4. As it is seen from Fig. 5 that the cone of compression stress is quite changed in shape. It is, also obvious, that thinner part of high strength material (right) caused less plastic deformation of low strength material in midthickness.

CONCLUSION

The "Local Compression" techniques is unproductive for obtaining uniform fatigue precracking front profiles of welds which have deposed lower strength materials in the root.

The "Step-wise High R-ratio" method is appropriate by using suitably maximum fatigue load F_{max} and step R-ratio ($R_1=0.1$, $R_{2,RS}=(2\cdot F_{m,RS} - F_{max})/F_{max}$ and $0.1 \leq R_{2,RS} \leq 0.7$). Calculated F_{max} should be low enough to ensure applied stress plus maximum residual stresses in the linear elastic range during fatigue precracking of lower strength region in weld joint.

Always, residual stresses are not obstructing rise of uniform shape fatigue crack front. But, appropriate mean load $F_{m,RS}$ could cause more straigther fatigue front than in the case of specimen without residual stresses (base materials). That means that these specimens enables to obtain lowest toughness comparable CTOD values with less scatter.

When the crack front is located through thickness direction of weld, the criterion $K/E \leq 1.5\cdot 10^{-4} m^{1/2}$ ($E \approx 210 GPa \Rightarrow K \leq 1000\ Nmm^{-3/2}$) is unsuitable.

Standards and documents in recommendations concerning the CTOD fracture toughness testing of weldments where fatigue precrack conditions are determined of (F_{max}, R-ratio) should take care about distribution and size of residual stresses.

SYMBOL USED

M = Mis-matching factor, ratio between yield stresses $R_{p0.2,WM}/R_{p0.2,BM}$
B_{root} = part of law strength material in the weld joint.
B_{cap}= part of high s strength material in the weld joint.
Δa= increment of precrack fatigue length (mm)
a_0=mean precrack fatigue length (mm)
$F_{m,RS}$=optimum fatigue mean load determined by considering residual stresses (N).
R_{RS}=optimum ratio determined by considering residual stresses.

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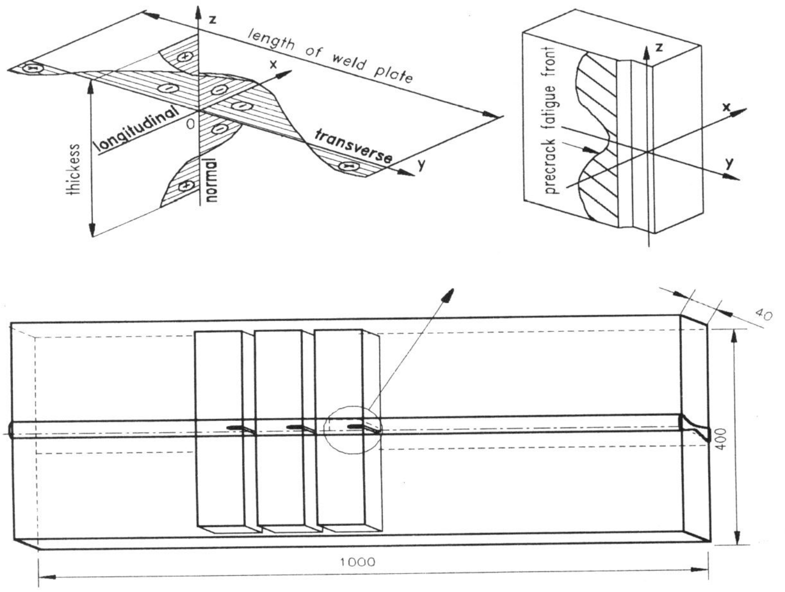

Figure 1 Weld plate, the location of SENB specimens and shematic showing the effect of through thickness ressidual stress on fatigue precrack front shape.

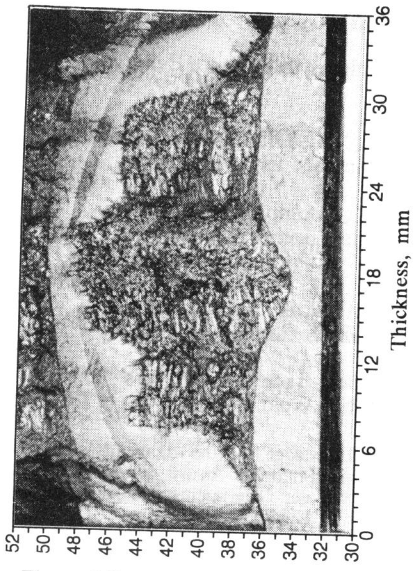

Figure 2 Precrack fatigue front by using SHR techniques.

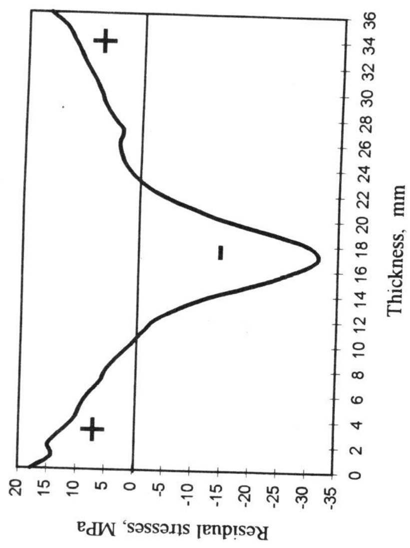

Figure 3 Distribution and size of the residual stresses through thickness of specimen.

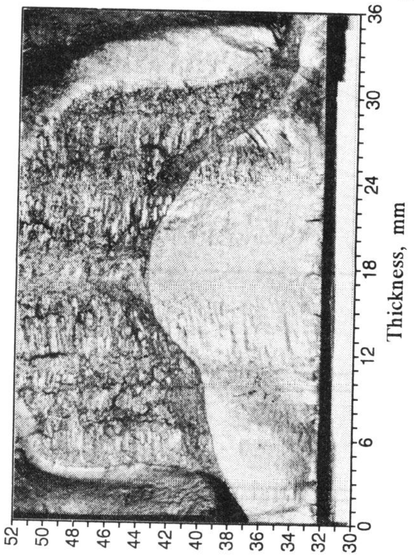

Figure 4 Obtained precrack fatigue front by using LC techniques.

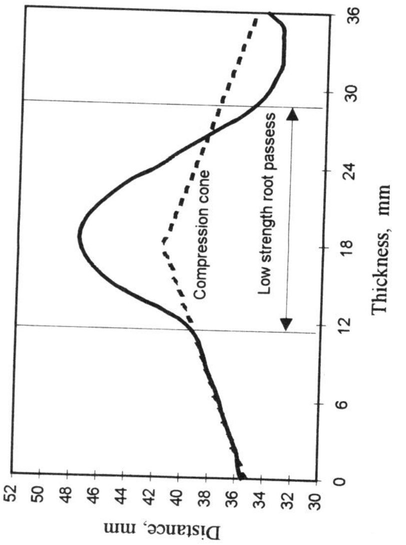

Figure 5 Distribution of compression stresses in mis-match weld joint.