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J_R Curve Testing of Welded Joints of Offshore Steels

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ABSTRACT For the evaluation of cracks in welded structures knowledge about the crack initiation and crack propagation behaviour is important. In general, it can be characterised by a J_R curve. Some failure concepts use J_R curves to determine critical loads for cracked structural elements. J_R curve testing of welded joints may however exhibit a crack propagation behaviour which is basically different compared to homogeneous materials. Due to steep gradients in microstructure and mechanical properties the crack may deviate away from its original location into microstructures with higher crack resistance. The analysis of this phenomenon is the topic of these investigations.

Introduction

During recent years, advanced welding techniques in combination with severe control of welding procedures and weld soundness have led to a steady quality improvement of welded joints of offshore structures. However, in spite of all precautions welding defects as cracks or notches should be taken into account for the assessment of safety of structural elements.

This implies the necessity to perform fracture mechanics investigations on the crack propagation behaviour in welded joints of highly sophisticated offshore structures.

Fracture mechanics investigations on welded joints

In the offshore industry, the most common fracture mechanics test method is the CTOD test which defines critical crack tip opening displacement as failure criterion. An appropriate method to analyse crack propagation behaviour in the upper shelf regime is J_R curve testing, a J integral test method. J_R curve-testing is often applied to characterise the ductile crack propagation behaviour of base materials. The procedure is standardised in ASTM E 1152 (1). At the fusion line of welded joints, crack propagation behaviour may be different as compared to homogeneous materials. Due to steep gradients of microstructural composition and mechanical properties perpendicular to the welds, the crack tends to deviate in certain cases away from the fusion line towards the fine grained zone.

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

	C	*Mn*	*Si*	*P*	*S*	*Al*	*Ni*	*Nb*	*V*	*N*
Base material	0.085	1.46	0.29	0.021	0.002	0.021	0.046	0.025	0.035	0.007

It was the scope of these investigations to analyse propagation behaviour of cracks located close to the fusion line of submerged arc welded joints of steel FeE 355 for offshore applications.

Materials and welding conditions

A 40 mm thick flange plate of a European He-beam was used for the investigations. The steel has been thermomechanically rolled in accordance with SEW 082 (2). Table 1 shows the chemical composition of the steel. It is a vanadium-niobium microalloyed steel with extremely low carbon and sulphur content. Figure 1 shows the typical fine grained ferrite-pearlite microstructure of the steel. The carbon equivalent was calculated according to the IIW formula to be 0.34.

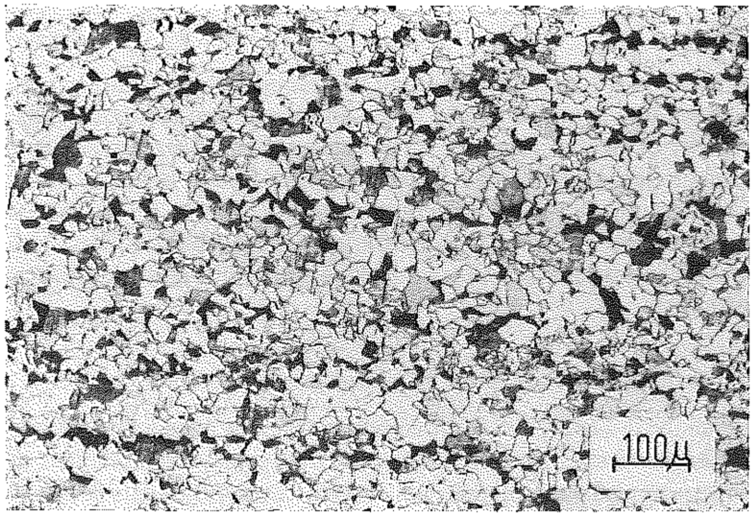
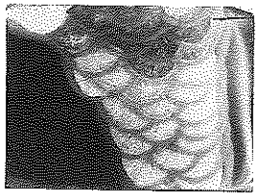


Fig 1 Microstructure of the base material ($M = 100$)

The applied welding procedure was the conventional submerged arc technique. The single bevel was chosen in order to allow sampling in the HAZ microstructure to be investigated. The welding consumables were a conventional wire of S2 Ni 1 type and a basic powder. Table 2 presents the chemical composition of the weld metal. A macrosection and the welding parameters are given in Fig. 2.

Table 2 Chemical composition of the weld metal (wt%)

	C	*Mn*	*Si*	*P*	*S*	*Al*	*Ni*	*Nb*	*V*	*N*
Weld metal	0.073	0.96	0.19	0.008	0.016	0.010	1.01	0.002	0.005	0.010



Voltage	: 29 V
Current	: 600 A
Welding speed	: 35 (50) cm/min
Heat input	: 30 (21) kJ/cm
Cooling time	: 17s

Fig 2 Macrosection of the weld and welding parameters

In order to measure strength distribution perpendicular to the weld, hardness measurements and tensile tests were performed on base material and weld metal. The yield strength of the steel was 430 MPa, the weld metal was overmatched with 525 MPa. The hardness profile is shown in Fig. 3. The maximum hardness in the weld metal was 205 HV 10 and 175 HV 10 in the base material.

Results of Charpy 'V' notch-testing

Toughness properties of the different microstructures in the welded joint have been determined by Charpy 'V' notch specimens with different notch positions. The results are shown in Fig. 4. Base material properties were examined with LT and TL specimens. LT specimens gave excellent toughness properties, e.g., 200 J at $-80°C$ and more than 300 J at room temperature. The corresponding values for TL specimens were approximately 100 J lower at all test temperatures. Weld metal Charpy 'V' notch toughness was lowest with 50 J at $-60°C$ increasing to 160 J at room temperature. For the determination

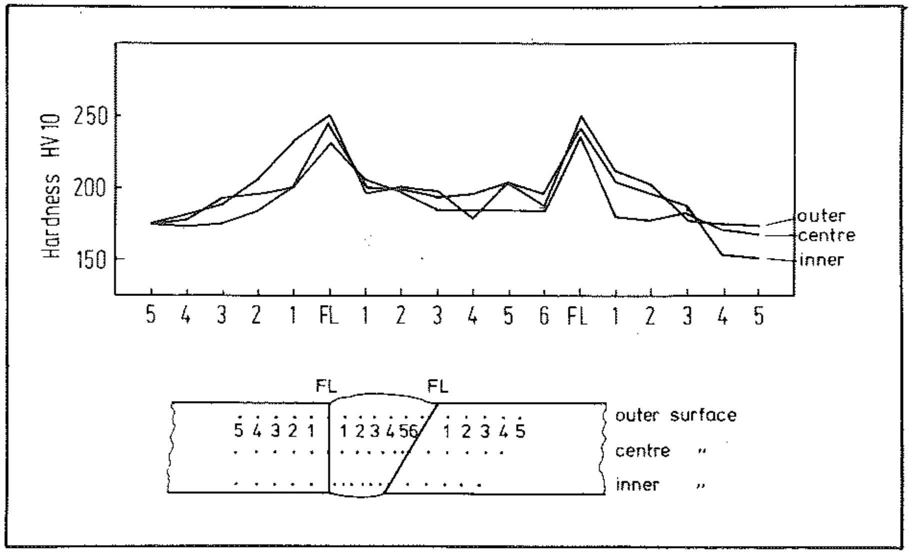


Fig 3 Hardness profile in the welded joint

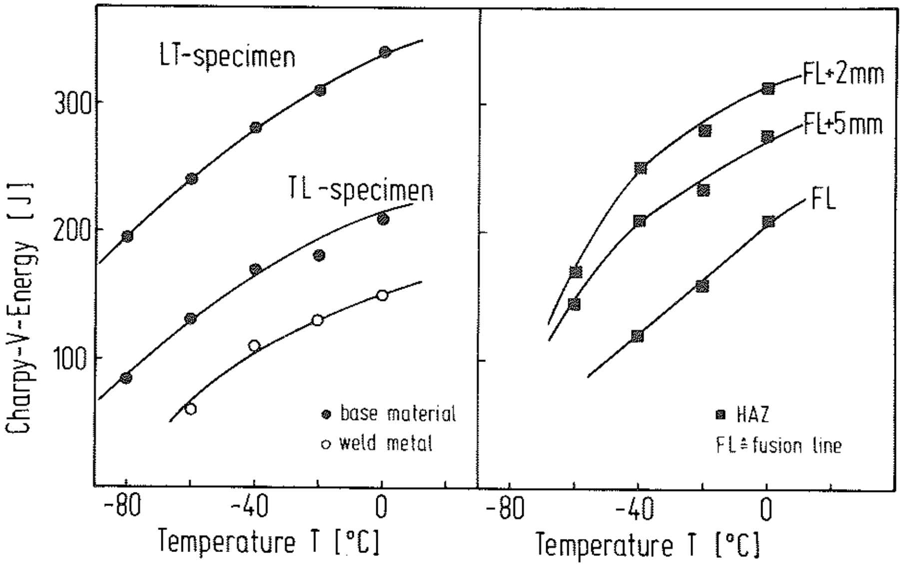


Fig 4 Results of Charpy 'V' notch testing

of HAZ toughness properties different notch positions were chosen: fusion line (FL), fusion line + 2 mm, and fusion line + 5 mm. The microstructure met by these notch positions were the coarse-grained HAZ, the fine grained HAZ, and the subcritical HAZ. As expected, distinct differences in toughness properties were observed. The fusion line microstructure gave the lowest Charpy values, reaching however 200 J at 0°C. The most favourable toughness behaviour was obtained by specimens notched in a 2 mm distance from the fusion line in the fine grained HAZ, where Charpy values were increased by approximately 100 J. With further increased distance from the fusion line the Charpy values decreased slightly; however, over the whole temperature range they were distinctly higher than for the coarse grained HAZ.

J_R curve testing

The main topic of these investigations was to describe crack propagation behaviour of welds pre-cracked at the fusion line. Fracture mechanics three point bend specimens with a thickness of $B = W/2 = 33$ mm and a through-thickness notch were prepared. The a/W ratio was between 0.5 and 0.55. Prior to prefatiguing the welded specimens were locally compressed in the ligament by a one percent reduction of thickness in order to avoid irregular fatigue crack front curvatures.

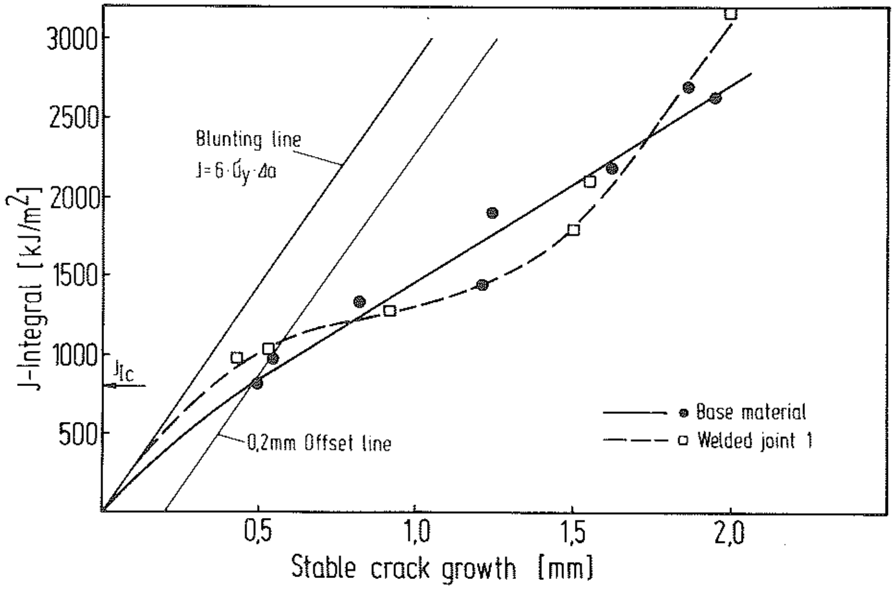


Fig 5 J_R curves for base material and welded joint of steel FeE 355

First the J_R curve of the base material was determined in order to describe the crack initiation and propagation behaviour of steel FeE 355 at room temperature. The J_R curve is shown in Fig. 5. Due to the excellent toughness properties, a blunting line slope with a factor of 6 had to be chosen **(3)**. The resulting J_{Ic} value was about 800 kJ/m^2. The J integral value for physical initiation of stable crack growth was determined with the DC potential drop technique to be about 600 kJ/m^2 which is an extremely high value compared to other structural steels of this type. Crack resistance is excellent; the tearing-modulus, which characterises the crack resistance behaviour, is very high. Crack propagation behaviour in the coarse grained HAZ close to the fusion line is also shown in Fig. 5. It was found that the behaviour was similar to that of the base material up to stable crack growth amounts of 1 mm. However, for larger amounts of stable crack growth, J values strongly increase. Such crack propagation behaviour can hardly be described by a conventional J_R curve of the form

$$J = A \cdot \Delta a^B$$

This behaviour observed in welded specimens can be explained by the deviation of the stable crack away from the fusion line towards the base material. Metallographic investigations of fracture surfaces have confirmed this assumption as shown in Fig. 6. With increasing amounts of crack propagation the crack front leaves the fusion line and deviates to the fine grained zone of the HAZ. In these microstructures fracture resistance is higher and crack propagation requires higher energy levels.

Further investigations on the crack propagation behaviour have been performed. Welded specimens were divided into two series, one having a very straight HAZ fusion line (series 2A), the second showing a bulged fusion line curvature (series 2B). For the latter specimens it was not possible to locate the

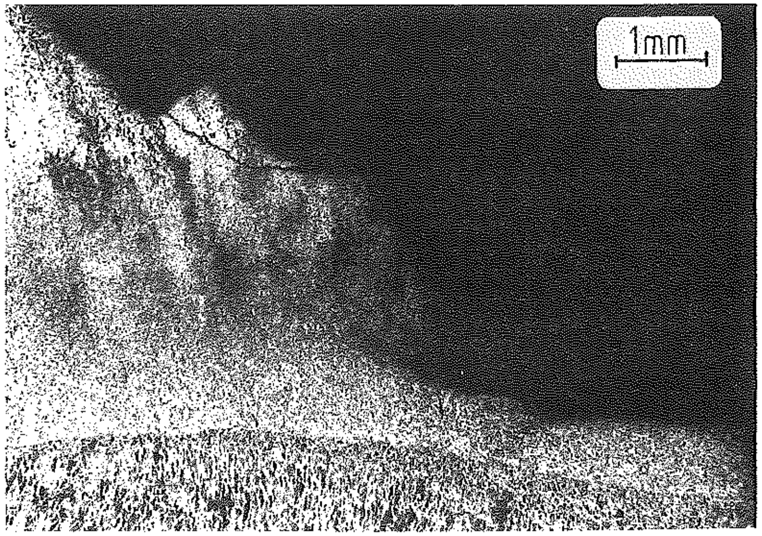


Fig 6 Metallographic investigation of crack propagation behaviour

crack in the coarse grained HAZ only. Crack propagation behaviour of these two test series were quite different. Results are shown in Fig. 7. Specimens with a straight fusion line gave lower J values for small amounts of stable crack growth; however, they increased strongly for Δa values exceeding 2 mm. The J–Δa curve for specimens with bulged fusion lines is in accordance with the

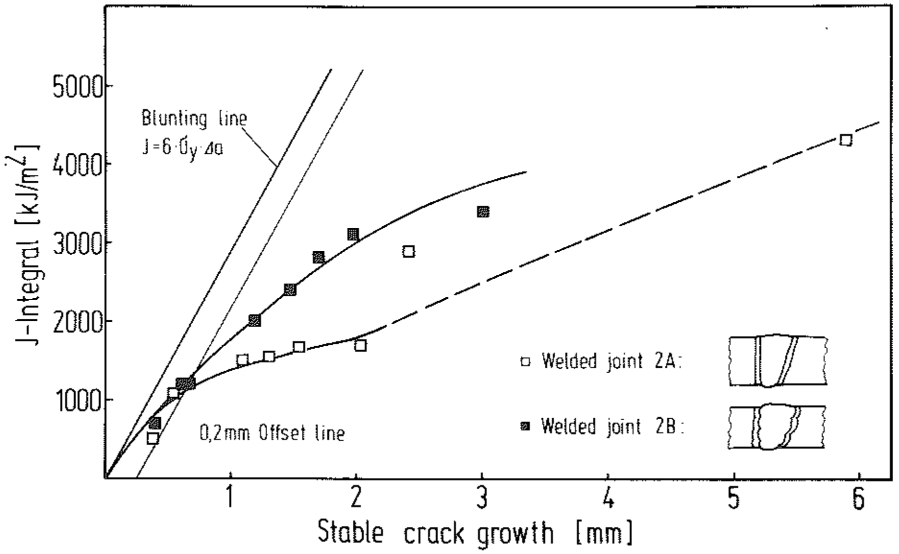


Fig 7 J_R curves for different fusion line curvatures

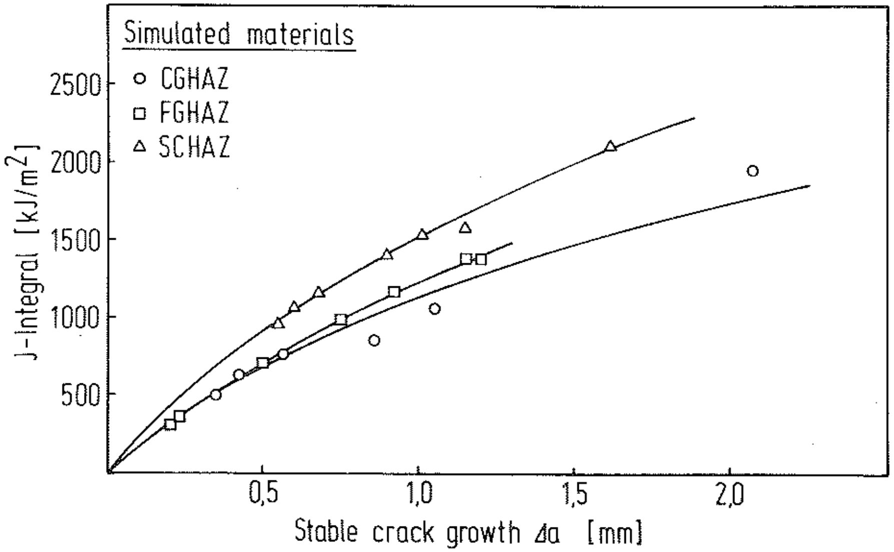


Fig 8 J_R curves for different microstructures

ASTM power law approximation. Up to 3 mm stable crack growth, this J–Δa curve is higher than that obtained for specimens with straight fusion lines.

In order to confirm the assumption, that the increase in J integral values with increasing crack growth is due to crack deviation into other parts of the HAZ, simulation tests were performed. The base metal was heat treated in a welding simulator in order to obtain microstructures representing the coarse grained, the fine grained, and the subcritical HAZ. The peak temperatures in the temperature-time-cycles were correspondingly 1350°C, 950°C and 660°C. The cooling time $t_{8/5}$ was 17 s in all cases like in the welded joint. Simulation specimens had dimensions of $13 \times 26 \times 130$ mm^3.

J_R curves obtained for the different microstructures are presented in Fig. 8. The main result is that the crack resistance increases for lower peak temperatures. This means that the increase of J values strongly depends on crack deviation behaviour within the HAZ of welded joints.

Conclusions

Toughness behaviour of a welded offshore steel grade FeE 355 has been investigated. The base material exhibited excellent toughness properties in the Charpy and in the fracture mechanics tests. Special attention was focused on the propagation behaviour of cracks located in the coarse grained HAZ close to the fusion line. Especially for large amounts of stable crack growth, J_R curve behaviour cannot be described by the ASTM power law approximation. The reasons for the increase in crack resistance could be clarified by metallographic investigations and fracture mechanics tests on weld simulated HAZ microstructures.

The mechanism controlling the crack deviation behaviour has not yet been completely understood up to now. It could be explained by the asymmetric material damage in front of the crack tip due to the asymmetric formation of the plastic zone which is typical for welded joints. Further investigations should focus on this problem.

This favourable crack propagation behaviour may have important consequences regarding safety philosophies for welded joints in offshore structures. Therefore, wide plate tests on welded joints are intended to clarify this phenomenon.

References

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