On the Crack Driving Force and Fracture Resistance of Mismatched Weldments

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Abstract

Theoretical analysis and 2D-3D finite element calculations of the crack problem in a mismatched welded joint have been carried out, from which a procedure based on the ETM (Engineering Treatment Model) for estimating the crack driving force for mismatching crack problem has been suggested. The out of plane effect of undermatching on the constraint state around the crack tip has also been discussed.

The assessment of the safety tolerance of cracks in mismatched welded joints is an attractive topic for both theoretical research and application. Compared to the fracture analysis of homogeneous materials, the key feature of the mismatching crack problem as shown in Fig.1 is that additional parameters are involved: these are the geometric parameter ***H***, the half height of the weldment; and the mismatching material parameters defined as:

$$M = \sigma_{YW} / \sigma_{YB}; \qquad M_n = n_W / n_B \tag{1}$$

where the subscripts W, B refer to the weld and base metal, respectively; σ_{YW}, σ_{YB}, n_W and n_B represent the yield stresses and hardening exponents for base and weld metal, the case M<1 refers to undermatching, M>1 refers to overmatching.

The engineering approaches of fracture mechanics in common use are based on the analytical results of homogenous materials. For example, for a material obeying the Ramberg-Osgood law and deformation plasticity, the crack driving force can be calculated by the "EPRI Fracture Analysis Handbook" as follows:

$$J = v_1 \left(\frac{F}{F_Y} \right)^2 + h_1 \left(\frac{F}{F_Y} \right)^{1+1/n} \tag{2}$$

where J, F, F_Y are J-integral, load, and limit load, respectively; n is the hardening exponent; v_1, h_1 are functions of n and geometry.

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However, for the crack in a mismatched weld joint, the following two questions are of interest:

–For a bi-material system such as a mismatched welded joint, are the relations of the deformation theory still applicable?

–How are limit load and hardening exponent to be determined in this case?

Figs.2a, b show two groups of 2D FE results for CCT specimens with different values of M and H, where δ_5 is the CTOD measured at two points with 5mm distance over the crack tip. From Fig.2a one may find that neither the limit load from the homogeneous base metal nor from the weld metal could be used as a reference load to control the crack driving force behaviour in the cases of mismatching. This means: there is a distinct effect of M on the limit load; the same is true for parameter H (refer to Fig.2b).

In the BS method PD-6493 (1991) the relation between Φ, the dimensionless COD, and the applied strain ε is expressed as a "COD-Design Curve":

$$\Phi = \frac{\delta}{2\pi a \varepsilon_Y}; \quad \Phi = \left(\frac{\varepsilon}{\varepsilon_Y}\right)^2 \quad \text{for } \frac{\varepsilon}{\varepsilon_Y} \le 0.5; \quad \Phi = \left(\frac{\varepsilon}{\varepsilon_Y}\right) - 0.25 \quad \text{for } \frac{\varepsilon}{\varepsilon_Y} > 0.5 \qquad (3)$$

where a, δ, ε, ε_Y are crack length, CTOD, applied strain and yield strain of the material, respectively. For a mismatched weldment, the following questions are also of interest:

–How to establish the relationship between the applied strain ε in a "design curve" and the applied load in an engineering structure with mismatched welded joints?

–Which yield strain or stress should be applied in eq.3? From weld metal or base material?

Fig.3 shows the comparison between CTOD and the strain defined at points with different distance to the centre of the crack (see Fig.1a) obtained by 3D FE analysis of a thin undermatched CCT. The CTOD-ε relation depends strongly on the definition of the applied strain, which has to be taken into account for structural assessments.

Furthermore, mismatch has an effect on the stress-strain distribution, so that the constraint state around the crack tip could also be changed. The problem is: How to estimate the effect of mismatch on the constraint state at the crack tip ?

Focused on these questions a series of 2D and 3D finite element (FE) analyses have been performed for the structures as shown in Fig.1 with varying geometric parameters and M values. Fig. 4 shows a typical crack driving force curve for undermatching condition. From this diagram one finds that the relation between load and crack driving force (CTOD or J) can be approximately divided into four stages according to the load levels: **I**) linear elasticity and initial small scale yielding; **II**) local yielding; **III**) net section yielding or ligament yielding, and **IV**) global-yielding. Expressions for the load-driving force relations in each stage and the transition points between the stages will be described hereafter.

In engineering application, for many structural materials the stress-strain relation can be expressed as a piece-wise power law:

$$\frac{\varepsilon}{\varepsilon_Y} = \frac{\sigma}{\sigma_Y}, \qquad \sigma \leq \sigma_Y; \qquad \frac{\varepsilon}{\varepsilon_Y} = \left(\frac{\sigma}{\sigma_Y}\right)^{1/n}, \qquad \sigma > \sigma_Y \tag{4}$$

For this kind of material behaviour the "Engineering Treatment Model (ETM)" has been developed for the homogeneous material as well as for the mismatched CCT configuration with a small a/W ratio [1]. Based on the theoretical and FE analysis results and taking the curve shown in Fig.4 as the fundamental relation between load and crack driving force in mismatching conditions, a modified ETM procedure for mismatching is proposed as follows:

I. $F<F_{YML}$ (initial small-scale yielding)

$$\delta_5 = K^2(a_{eff,M})/(E\sigma_{YW}); \qquad \text{with} \quad a_{eff,M} = a + Y_m r_Y \tag{5}$$

where F, K, Y_m and r_Y are load, stress intensity factor, mismatching shape factor and plastic zone modification, respectively.

II. $F_{YML}<F<F_{YMN}$ (local yielding)

$$\delta_5 / \delta_{L0} = \left(F / F_{YML}\right)^{\frac{4}{n_W+1}} \tag{6}$$

where $F_{YML}=k_M F_{YS}$, k_M is a constant slightly depending on geometry and is usually taken as 0.9; F_{YS} is the smaller of the two limit loads from the structures made of homogeneous base or weld metal, δ_{L0} is determined by eq.5 when $F=F_{YML}$.

III..$F>F_{YMN}$ (net-section yielding)

$$\delta_5 / \delta_{N0} = \left(F / F_{YMN}\right)^{\frac{1}{n_{m1}}} \tag{7}$$

where F_{YMN} is determined by the slip-line solution in mismatching condition [2]; δ_{N0} is determined by the joint condition $F=F_{YMN}$; n_{m1} depends on the shape of the slip-line field; if the slip-lines are confined to the weld metal it is close to n_W, otherwise it depends on M and can be expressed as a composite of n_B and n_W. The details are described in [2]. Fig. 5 shows the comparison between the predictions of ETM-Mismatch procedure and experimental results for CCT specimens with centre mismatched welded joint[3]. The predictions is on the safety side with the difference less than 50%. Fig.6 is the comparison between the ETM procedure [2, 5, 6] and FE for a cylinder vessel with a nozzle joined by undermatched welded metal with a crack. Again, a very good prediction is noted

The in-plane effect of undermatching on the constraint state around a crack tip has been discussed in [2]. For the out-plane effect a 3D FE analysis has been done for the CCT shown in Fig.1a with different thicknesses. In extreme undermatching condition an example of the distributions of the maximum principal stress around crack tip at different sections is plotted in Fig.7, in which it is noteworthy that the amplitude of the stress at the middle section is about two times greater than at the section near the traction-free surface, and so is the constraint intensity. Fig.8 shows the constraint parameter Q defined by O'Dowd & Shih[4], the difference of it between the middle and the near free surface being greater than 1. With respect to constraint the conclusion is that strong undermatching in narrow weldments may lead to a severe working condition for weld metal since brittle fracture is promoted.

It is clearly that the mismatching leads to different crack driving force behaviour and constraint state at crack tip. Using the ETM-Procedure recommended in this paper it is possible to calculate the crack driving force in mismatching condition within definite accuracy. In the near future detailed guidelines for assessing cracks in mismatched welds using the ETM will be presented.

Reference

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[2] Hao, S., Cornec, A., and Schwalbe, K.-H., GKSS Tech. Note: WAW/93/15.
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[4] O'Dowd, N. P. & Shih, C. F., 1991, J.M.P.S., V.39, pp.337-347.
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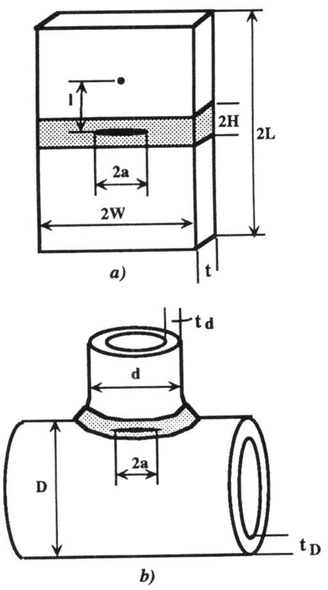

Fig.1 The models analysed

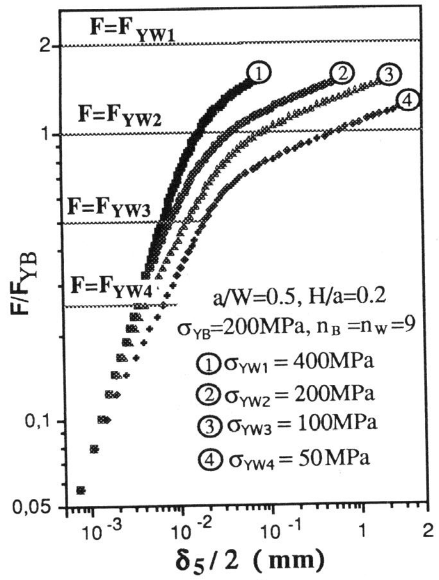

Fig.2a Crack driving force curves with varying M

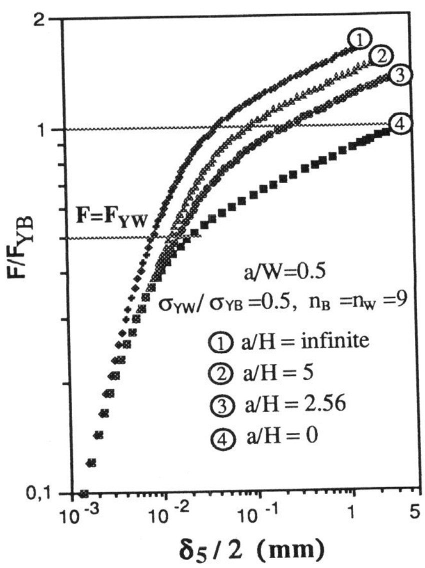

Fig. 2b Crack driving force curves with varying H

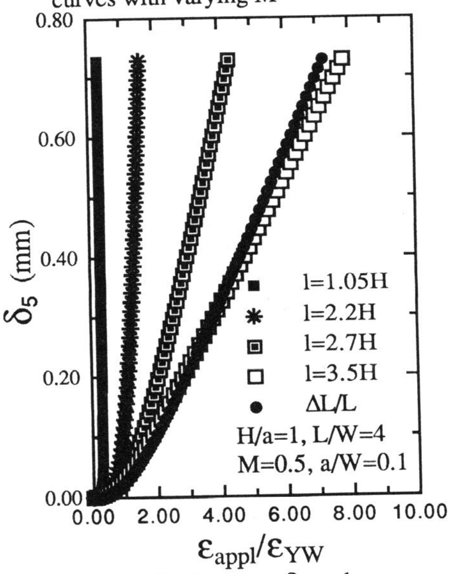

Fig.3 The relation between δ_5 and the applied strains measured at different points

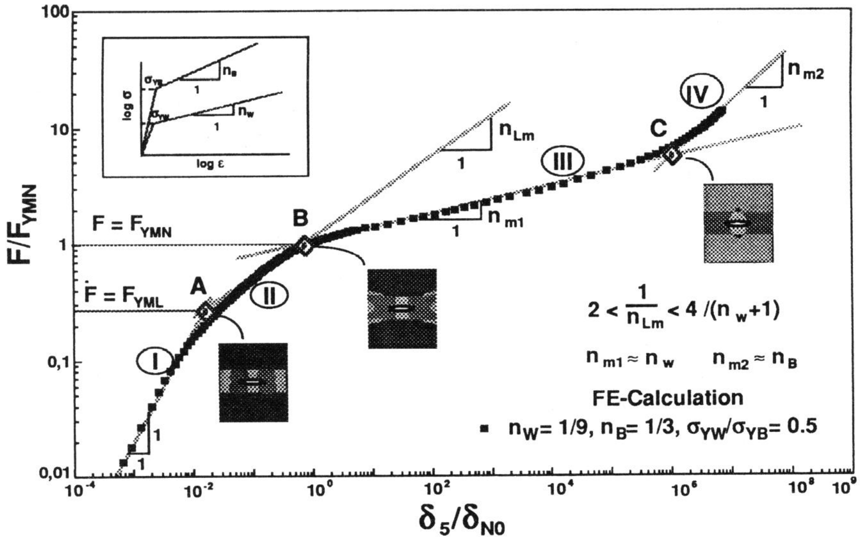

Fig.4 The Basic Structure of Load-Crack Driving Force Curve
I: initial small-scale-yielding; II: local yielding;
III: net-section (ligament) yielding; IV: global yielding

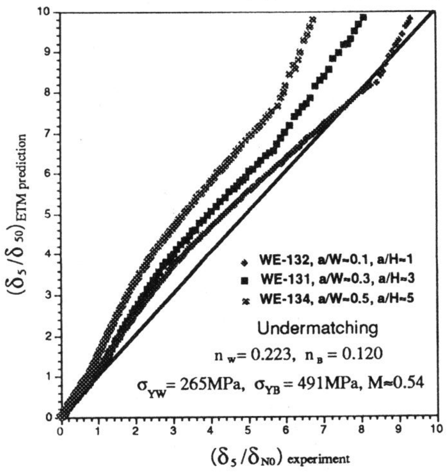

Fig.5a Comparison of δ_5 between measurement and ETM

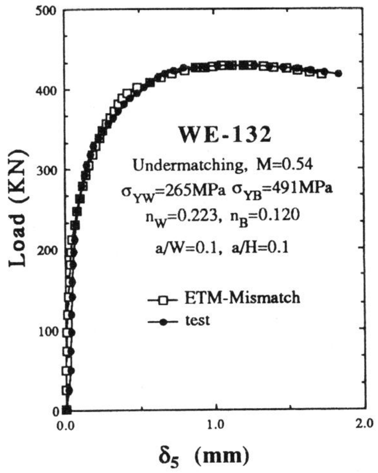

Fig.5b Comparison of the crack driving force curves between measurement and ETM

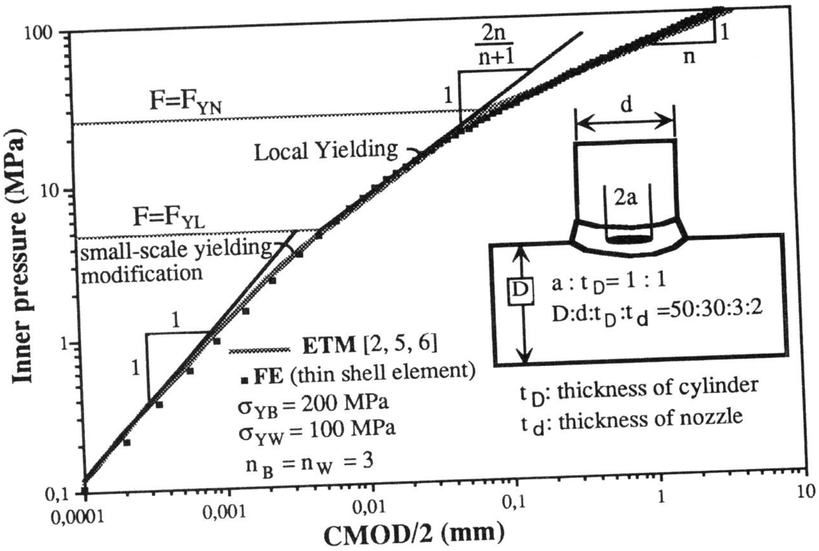

Fig.6 Comparison of the crack driving force curves between the FE and ETM

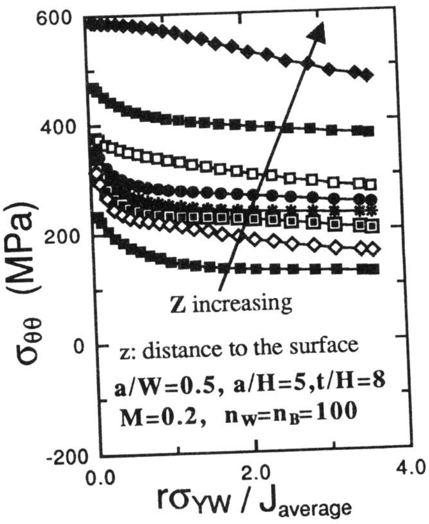

Fig.7 Distribution of the principal stress in the thickness direction for an undermatched CCT

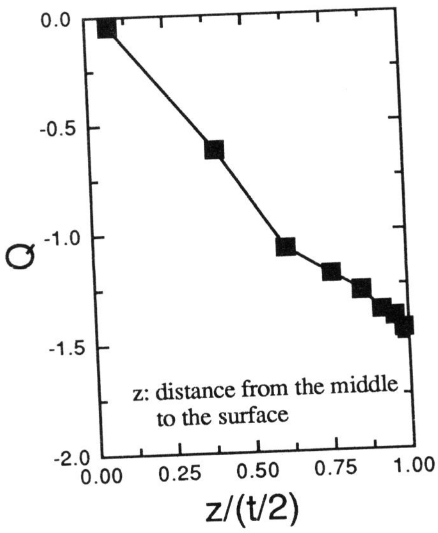

Fig.8 Distribution of the constraint parameter Q in the thickness direction for an undermatched CCT