FRACTURE OF BI-MATERIAL JOINTS : EFFECT OF STRENGTH MIS-MATCH ON CRACK RESISTANCE CURVES

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This paper deals with the influence of strength mis-match on CTOD (δ_5) and J-integral R-curves obtained from homogeneous and electron beam welded bimaterial SENB specimens of two aluminium alloys. The R-curves of cracked weld specimens (bimaterial) are compared to the R-curves of the homogeneous weld metal. Various proposals to estimate the J-integral for homogeneous and mis-matched SENB specimens have been considered. The homogeneous specimens of two different aluminium alloys, namely 2024-FC and 2024-T351 with yields strengths of 80 and 360 MPa respectively, as well as bi-material SENB specimens simulating highly under- and overmatched welds obtained with electron beam welding of these two materials have been tested at room temperature. The 5 mm thick specimens contained short (a/W=0.15) and long cracks (a/W=0.5).

It is concluded that the local CTOD (δ_5) measurements on such complex specimen configurations produced mis-match and geometry independent R-curves, whereas, standard J estimation scheme and some modified J formulations (J_{CMOD} or J_{VLL}) for mis-matched and shallow cracked configurations still showed the effects of strength mis-match and crack size on the R-curves.

INTRODUCTION

Fracture mechanics defect assessment procedures generally assume that any discontinuities found during fabrication or after a component has entered its service life are located in material of uniform mechanical and microstructural properties. In practice, however, the different regions of conventional weld or bi-material joints exhibit significantly different mechanical properties. All fusion welding processes produce a heat affected zone (HAZ), which results in material properties different from those of base and weld deposit. Additionally, there are many structural components containing dissimilar (bimaterial) weld joints with a high degree of strength mis-match and such joints are most susceptible regions for defects and/or cracks. The failure behaviour of a welded structure associated with a defect in the weld zone will certainly be influenced by the differences of the strength levels (strength mis-match can be defined by the strength mis-match factor, $M=\sigma_{YW}/\sigma_{YB}$) of the weld metal ($\sigma_{YW}$), heat affected zone (HAZ) and base metal (σ_{YB}).

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For example, for cracked girth welded pipes, there are no currently available reliable estimation techniques to evaluate the structural performance of such pipes. Predictions are usually made using base metal stress-strain data and cracked weld metal resistance curves. Obviously, such a procedure can lead to conservative or non-conservative predictions depending on the strength mis-match ratio, M and relative weld joint size with respect to the uncracked ligament of the specimen on which R-curves are determined. Therefore, the effect of weld strength mis-match on elastic-plastic fracture parameters (CTOD & J-integral), resistance curves and hence on the standard fracture toughness test procedures should be determined since these procedures are frequently used to determine the fracture toughness properties of welded and bi-material joints.

Commonly used standard procedures to evaluate fracture toughness (J or CTOD) of homogeneous specimens [1-4] cannot be extended in a straightforward manner to strength mis-matched weld configurations. In fact, the experimental way to calculate the J-integral from the area under the load-load line displacement curve ($F-V_{LL}$) cannot be generally applied to inhomogeneous specimens [5-8]. Also, in the case of a specimen with a crack located in the middle of the highly overmatched weld, remote plasticity may develop in the base metal (i.e relaxes the crack tip stress state) and hence the standard J-integral estimated can be significantly overestimated [6-7]. The standard CTOD inferred from remotely measured crack mouth opening displacement (CMOD) can also provide toughness properties influenced by the strength mis-match of the weld metal. It is generally believed that for deeply weld metal cracked ($a/W=0.5$) mis-matched bend specimens, standard CTOD and J-integral procedures can be used if the weld width ($2H$) is greater than the uncracked ligament ($W-a$) of the bend specimen. However, the limit of the applicability of present toughness testing procedures with respect to the degree of mis-match levels and weld widths need to be established.

The GKSS developed δ_5 clip-on gauges at the original fatigue crack tip over a gauge length of 5 mm [10] directly measures the CTOD without being related with any remote quantity measured on specimens. This way, the δ_5 clip permits an easy measurement of the CTOD of a mis-matched specimen which can be considered as a crack driving force [8]. With the help of finite element calculations, new procedures have been developed to evaluate the J-integral for SENB specimens with a crack located in the middle of a mis-matched weld [9, 11-13]. Furthermore, mis-matched specimens with shallow cracks ($a/W < 0.2$) create an additional difficulty to determine the fracture toughness of welds on such specimens since a decrease in a/W ratio changes the ratio of $H/(W-a)$ which is an important parameter for crack tip as well as ligament plasticity mechanism.

This paper presents the results of an experimental study on the influence of mis-match on CTOD and J R-curves obtained from deep and shallow cracked bend specimens. Further, the influence of the different methods to evaluate the J-integral will be discussed.

EXPERIMENTAL PROCEDURE

Two different aluminium alloys, namely Al 2024-FC (Material **A**) and Al 2024-T351 (Material **B**) with yields strengths of 80 MPa and 360 MPa respectively, were used to fabricate 5mm thick electron beam (EB) welded bi-material SENB specimens as shown in Figure 1. The mechanical properties and the stress strain curves of those aluminium alloys are given in Table 1 and Figure 2 respectively. The undermatching weld joint (UM) was simulated by EB welding the lower strength material **A** strip of 8 mm width (2H) on the higher strength material **B**. For overmatched specimens (OM), a strip of higher strength material **B** with identical width was welded to simulate the weld metal as material A served as a base metal. By using these combinations, 5 mm thick SENB specimens with a high degree of mis-matching; M=0.22 and M=4.5 were obtained for undermatching and overmatching cases respectively. Such an experimental matrix enabled us to conduct fracture toughnesss tests on homogeneous all weld metal specimens (**A** and **B**) to compare with UM and OM specimens as shown in Figure 1.

The tests were carried out at room temperature with the SENB specimens (B=5mm, W=50mm) having shallow (a/W=0.15) and deep fatigue cracks (a/W=0.5) located in the middle of the transverse strip which simulates the mis-matched weld. Homogeneous SENB specimens of the same dimensions made from both materials have also been tested. The experimental approach used was to measure the crack tip opening displacement, CTOD (δ_5) with the GKSS made δ_5 clip-on gauges at the original fatigue crack tip over a gauge length of 5 mm [10], the crack mouth opening displacement (CMOD), the crack propagation using the DC-potential drop method [14] and the load line displacement (V_{LL}) as a function of applied load. The CTOD (δ_5) parameter has been experimentally compared with the standardised CTOD for numerous homogenoeus and weld materials using deep notched SENB and CT specimens and therefore the validity of this parameter has already been established [17, 18, 10].

EVALUATION OF J-INTEGRAL

The problem of measuring a meaningful J-integral value on a mis-matched weld specimen is very hard to solve, since it is not easy to distinguish between the contributions from the weld metal at the vicinity of the crack tip and from the base material to the remotely measured load line displacement (V_{LL}) normally used in J estimate. For many mis-matched weld configurations, CMOD measurements can also be considered as a remote quantity due to the asymmetric crack tip opening or/and remote plasticity at the lower strength part of the test pieces. This effect can be particularly extreme on shallow cracked specimens. Therefore, it would be ideal, if the critical crack tip characterising parameter can be **locally quantified or measured** on mis-matched or bi-material joints and not be inferred from remotely measured quantities, like J-Integral and standardised CTOD.

The application of a crack tip parameter such as J to a crack in the mis-matched weld metal of finite size or at a bi-material interface relies on an existing stress field at the crack tip comparable to the known stress and displacement field of homogeneous materials. However, a mis-matched weld metal or a bi-material interface induced by some degree of triaxiality influences the crack tip stress field and crack tip plasticity development and hence global plastic deformation behaviour of the specimen substantially. Attempts have been made by Joch et al. [12, 15] to accomodate this effect in η-factor with some modifications for strength mis-match to calculate J from the area under load-load line displacement curve in case of deep notches. Futhermore, Kirk et al. [9, 11, 13] have proposed a new J-estimation scheme for homogeneous and mis-matched specimens for a large range of crack size (a/W from 0.1 to 0.5).

In this study, four different J-estimation schemes for SENB specimens have been used for homogeneous and for weld joint simulated highly mis-matched specimens.

J-VLL

The J values were estimated for homogeneous specimens using the area under load-load line displacement curves [4] and these values will here be refered to as J-VLL. It takes the following well known formula :

$$J = \frac{\eta U}{B(W - a_0)} \qquad (1)$$

where : U is the total area under load-load line displacement curve,
$\eta = 2$ for deep notched (a/W=0.5) SENB specimens.

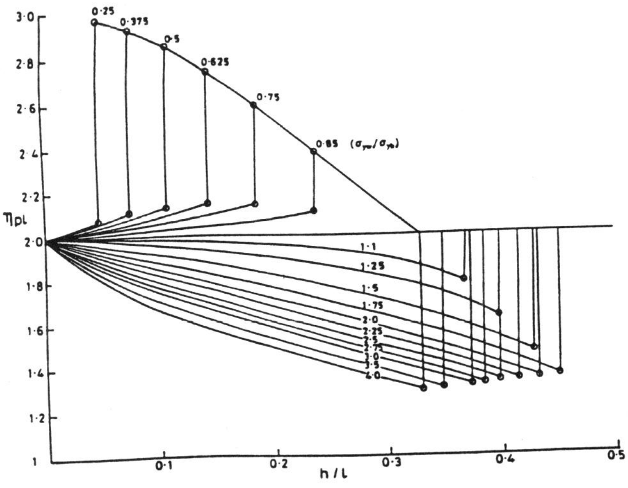
However, Sumpter has proposed [16] a modification of the η-factor for shallow cracked SENB specimens (a/W<0.282) and η-factor can be obtained by the following relationship:

$$\eta = 0.32 + 12(a_0 / W) - 49.5(a_0 / W)^2 + 99.8(a_0 / W)^3 \qquad (2)$$

This equation was used to obtain the η-factor for shallow cracked homogeneous (all-weld metal) specimens.

J-VLL-MM

The J-values for deep notched mis-matched specimens were also calculated from the load-load line displacement curves by using equation 1. But the η-factor replaced by a factor η_{-MM} appropriate to fully plastic behaviour in mis-match welds developed by using simple part-circular slip lines by by Joch and Ainsworth et al. [12, 15]. In this scheme, the η_{-MM} factor depends on the mis-match ratio, M, and H/(W-a_0), shown Figure below. According to this plot, significant undermatching effect occurs on the η_{-MM} factor at smaller H/(W-a) for higher undermatching (η_{pl} >2.0).



Variation of η-MM (η pl) with h/l and mis-match factor, M= σ_{YW}/σ_{YB} [15].
Note: h=H and l=W-a

J-CMOD

The J-values estimated from the area under the load-CMOD curves as proposed by Kirk et al. [9, 11 and 13] for **homogeneous** specimens containing both shallow and deep cracks. The J-CMOD was estimated by the following equation 3;

$$J = \frac{K^2}{E'} + \frac{\eta_C A}{B(W - a_0)} \tag{3}$$

where A is the plastic part of the area under load-CMOD curve and η-factor takes the form of :

$$\eta_C = 3.5 - 1.4167(a_0/W) \tag{4}$$

J-CMOD-MM

J is estimated from the area under load-CMOD curve by eqn. (3). But, the η_C-factor is modified for strength mis-matched weld specimens containing again both shallow and deep cracks [13] and given by the following relationship:

$$\eta_{C-MM} = \left[3.5 - 1.4167(a_0 / W)\right]\left[\frac{\sigma_{YB}}{\sigma_{YW}} + \left(\frac{1-\sigma_{YB}/\sigma_{YW}}{2}\right)\right] \qquad (5)$$

These definitions of J determination procedures have been used to calculate the respective J-values for homogeneous and mis-matched specimens containing both shallow and deep notches. The J R-curves obtained for homogeneous and mis-matched specimens were compared to identify the effects of crack size and strength mis-matching on the J R-curves.

RESULTS AND DISCUSSION

CTOD(δ_5) R-curves

Figure 3 presents the CTOD(δ_5) R-curves of all shallow and deep cracked specimens (a/W=0.15 and a/W=0.5) of homogeneous and mis-matched configurations, Fig. 1. The mis-matched specimens are compared with respective homogeneous specimens made by the material where the crack was located (all-weld metal specimens). Therefore, the R-curves obtained from undermatching specimens (UM) are compared with the R-curves of material-**A** (Fig. 3a) and similarly, the ones obtained for overmatching (OM) case with the results of material-**B** (Fig. 3b).

A slight dependence of the R-curves of the homogeneous specimens on the crack size can be seen in these plots, with the short crack leading to a higher crack growth resistance curve due to the loss of crack tip constraint at shallow cracked specimens. The comparison between the mis-matched and the homogeneous specimen results clearly shows that even an extremely high over- and undermatching (see. Fig. 2) have limited influence on the CTOD(δ_5) R-curves due to local nature of the δ_5-clip measurements which does not include any remote deformation to the crack tip plasticity. The presence of bimaterial boundaries at the vicinity of the crack tip plastic zone will inevitably interact with the plastic zone development and cause a discontinuity. For such cases, any measure of global or remote deformation (such as CMOD and VLL) of the specimen should not be used to define the crack tip plasticity since there will be no unique correlation between local crack tip and global deformations. Obviously, using the crack tip opening displacement (CTOD) measured locally by the δ_5-clip, the resistance curve of a cracked inhomogeneous structure only depends on the material where the crack is located.

It is generally believed that the mis-match effect on fracture toughness can be small if the width of the weld metal (2H) is greater than the uncracked ligament (W-a) of the bend type specimen. However, decreasing weld metal width for a given uncracked ligament size increases the interaction of the weld metal plasticity with the surrounding base plate and hence an effect of mis-match on standard

CTOD or J R-curves can be expected, since one measures the applied displacement remotely. On the contrary, the CTOD(δ_5) R-curve of the very small weld metal regions (2H/(W-a)<<1) shows, as presented in Figure 3, identical R-curves to the homogeneous (all weld metal, A and B) specimens without any effect of surrounding base plate, although one may expect that by decreasing the a/W and 2H/(W-a) ratios, the effect of mis-matching on CTOD should increase. However, this is true if one obtains the CTOD or J from remote displacement measurements such as V_{LL} and CMOD.

Therefore, it will be a difficult task to obtain unique R-curve of a given material using a fracture parameter (standard CTOD and J) inferred from a measure of a global deformation of the specimen.

The J R - Curves

Figure 4 presents the J R-curves obtained for both homogeneous shallow and deep cracked specimens using expressions (1) and (3) with the use of appropriate η-factor. For deep notched specimens, the ESIS-procedure [4] was used for the calculation of J from the area under the load-load line displacement curves (J-VLL). The modification proposed in [16] for the η-factor for small cracks brings the two R-curves of two different crack lengths together, Fig. 4. The calculation of J from the area under load-CMOD curve as proposed in [9, 11, 13] also provides a unique resistance curve independent of the crack size (a/W=0.15 and a/W=0.5). Therefore, it can be concluded that both modifications of the η-factor for crack size combined with the use of respective load-displacement curves provides crack size independent J R-curves for the homogeneous specimens tested which exhibit a slight tendency for increased crack growth resistance for the shorter crack.

In Figure 5, the J-integral has been calculated from the total area under load-load line displacement curve for deep notched homogeneous and mis-matched specimens. For homogeneous specimens η is taken as usual equal to 2. For mis-matched configurations, η values were obtained from the plots given by Ainsworth et al. [12, 15]. According to their work based on the slip line solution, the η_{-MM} values depend not only on the mis-match ratio (M) but also on the half heigth of the weld (H) over ligament ratio (W-a), H/W-a. The η_{-MM} values of 2.7 and 1.55 were used for undermatched and overmatched cases respectively. Consequently, if the homogeneous η value of 2 is used to estimate J for mis-matched welds, the fracture toughness of an overmatched weld will be overestimated since the η_{-MM} value is lower than that for a homogeneous specimen. The converse applies for an undermatched specimen [12]. However, it is apparent that the undermatched specimens shown in Fig. 5a, still produce higher R-curves than all weld metal specimen. For an overmatched case, the situation is reverse since this J estimation procedure provides in this case lower R-curves than homogeneous all-weld metal (material-**B**) specimen. Another difference between Figures 3a and 5a is that CTOD(δ_5) is slightly lower for UM than homogeneous while J-VLL is higher for UM than homogeneous. The magnitude of the discrepancy is larger for J-VLL R-curves. For OM specimens the CTOD(δ_5), Fig. 3b, is again much more consistent than J-VLL, Fig. 5b with significantly different R-curve shape possibly due to the use of lower value of η=1.55.

Figure 6 presents the J R-curves for mis-matched and homogeneous specimens containing shallow and deep notches, where J is calculated from the area under load-CMOD curves with η_C factor given by eqn. (4) for homogeneous specimens and eqn. (5) for mis-matched configurations. It is obvious that this procedure provided two rather different groups of R-curves which represent the homogeneous and mis-matched specimens. This J estimation procedure apparently provides almost crack size independent R-curves for all-weld metal and mis-matched specimens seperately. A very large difference between the R-curves obtained for undermatched and all-weld metal material-**A** specimens can be seen in Fig. 6a, although for both specimens the material where the crack tip located is identical. For the overmatched case, however, the reverse situation was obtained by getting the lower R-curves for overmatched specimens compared to the material-**B** specimen R-curves, Fig. 6b.

Clearly, the use of J estimation procedure using the area under load-CMOD curve and an adjusted η_C factor for homogeneous and mis-matched specimens did not produce unique R-curves of the material-**A** and material-**B**. One of the reasons for this discrepancy might be the very high mis-match ratio (M=4.5 and 0.22 for OM and UM cases respectively) of the specimens. The second reason might be the, relatively small weld width to uncracked ligament ratio, 2H/(W-a), of 0.32 and 0.19 for deep and shallow crack respectively where a significant effect of mis-match on J or standard CTOD toughness should be expected.

Comparison of the Figs. 5 and 6 with Fig. 3 has significant implications for fracture toughness testing procedures of mis-matched welds. The CTOD(δ_5) technique has a unique capacity to provide material resistance curve independent of both crack size and strength mis-match of any degree due to its local nature.

CONCLUSIONS

The CTOD(δ_5) technique and different J estimation procedures were used to determine the J R-curves of two aluminum alloys by using homogeneous (all-weld metal) and highly mis-matched SENB specimens with shallow and deep notches (a/W=0.15 and 0.5). The following conclusions can be drawn from this experimental study:

- For testing of weldments using standard, bend-type specimen, simple and direct CTOD(δ_5) technique provides crack growth resistance curves with limited influence of the;

  a) crack size (a/W=0.15-0.5) and

b) strength mis-match (UM or OM)
compared to the J R-curves obtained using various procedures.

- Commonly known limits of 2H > (W-a) and degree of mis-match (about 50%) for application of standard or recently proposed J-estimation procedures (as discussed in this study) for mis-matched welds do not apply to the CTOD(δ_5) technique due to its local nature of displacement measurement at the original fatigue crack tip.
- Shallow cracked homogeneous specimens (a/W=0.15) give J R-curves similar to the ones obtained from deeply notched specimens, provided the modified η (eqn. 2) is used to calculate J as proposed in [16].
- The formulations (3-5) proposed in [13] to calculate J from the area under load-CMOD curves for homogeneous and mis-matched SENB specimens does not provide unique J R-curves for both materials-**A** and -**B** using mis-matched specimens. J was highly overestimated with the use of undermatched specimens and the converse is true in the case of overmatched welds. However, this procedure produces R-curves little influenced by the crack size for homogeneous and mis-matched configurations separately.

NOMENCLATURE

a	Current crack length
a_0	Crack length before initiation of crack growth
A	Area under load-CMOD curve
B	Thickness of the specimen
H	Half heigth of the middle strip which simulates the weld
J	J-integral
J-CMOD	J calculated from the area under load-CMOD curve for homogeneous specimens
J-CMOD-MM	J calculated from the area under load-CMOD curve for mis-matched specimens
J-VLL	J calculated from the area under load-load line displacement curve for homogeneous specimens
J-VLL-MM	J calculated from the area under load-load line displacement curve for mis-match specimens
U	Area under the load-load line displacement curve
VLL	Load line displacement
W	Width of the specimen
δ_5	CTOD measured with GKSS made δ_5 clip-on gages at the original fatigue crack tip over a gage length of 5 mm
η	Factor to estimate J from the area under load-load line displacement curve
η-MM	Factor to estimate J from the area under load-load line displacement curve for mismatch configurations
η_C	Factor to estimate J from the area under load-CMOD curve

$\eta_{C\text{-}MM}$	Factor to estimate J from the area under load-CMOD curve for mis-match configurations
σ_{YB}	Yield strength of the base metal
σ_{YW}	Yield strength of the weld metal

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Table 1 : Tensile properties of the two aluminum alloys.

Material	E-modulus [MPa]	Yield stress [MPa]	Ultimate stress [MPa]	Elongation at fracture [%]
A (Al 2024-FC)	70300	80	190	19
B (Al 2024-T351)	70300	360	560	15

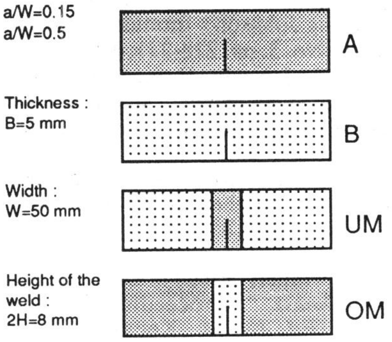


FIG. 1 : Homogeneous and simulated mis-matched weld SENB specimens. For UM and OM specimens, middle strips which represent welds were electron beam welded.

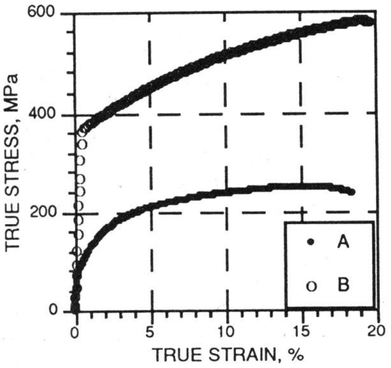
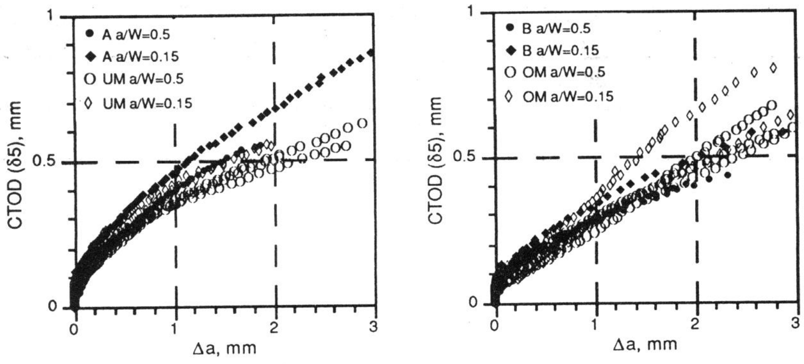
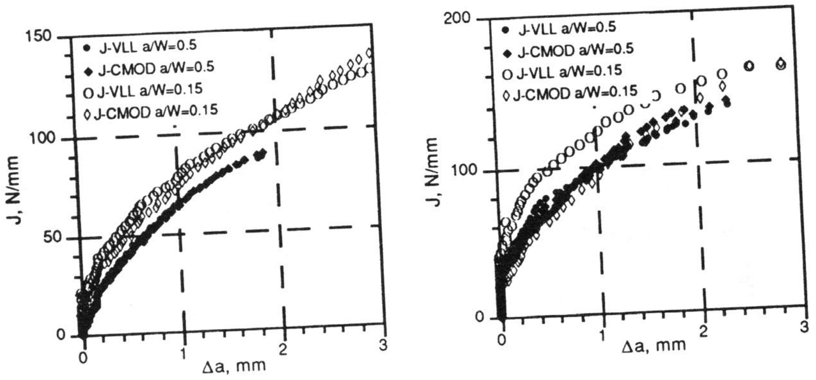


FIG. 2 : The stress-strain curves of the two aluminum alloys; material-**A** (2024-FC) and **B** (2024-T351)



a) b)

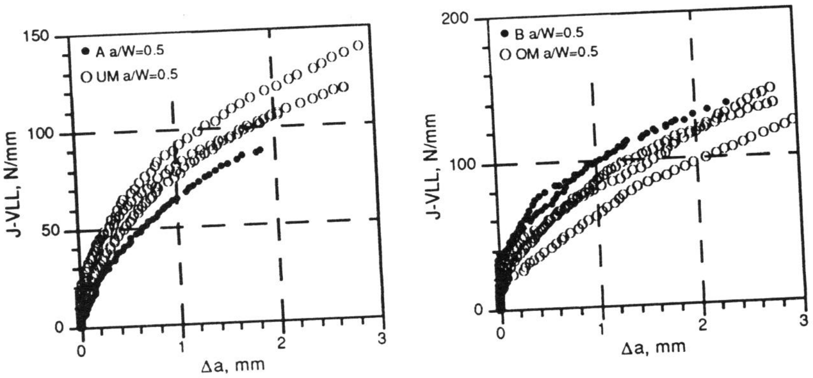
FIG. 3 : The CTOD (δ_5) resistance curves of the SENB specimens contained shallow and deep cracks showing unique R-curves independent of crack size and mis-matching; a) crack is located in material-**A**, b) crack is located in material-**B**.



a)

b)

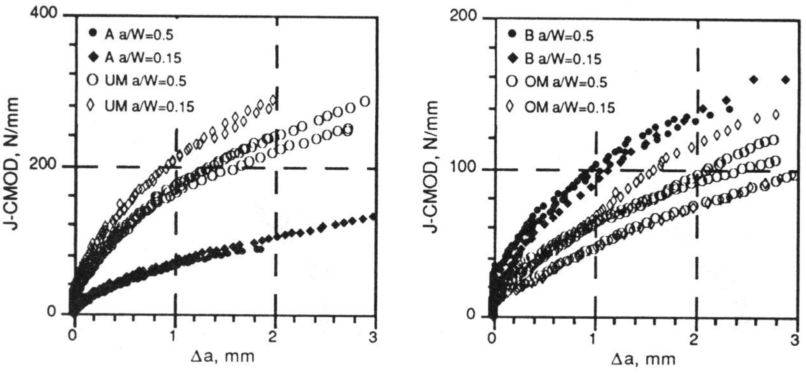
FIG. 4 : The J R-curves obtained from shallow and deep cracked homogeneous SENB specimens a) material **A**, b) material **B**. (Note : J-VLL is calculated by eq. (1) and J-CMOD is calculated by eq. (3))



a)

b)

FIG. 5 : The J R-curves obtained from deep notched homogeneous and mis-matched SENB specimens showing some dependence on strength mis-matching; a) crack in material-**A**, b) crack in material-**B**. (Note: For homogeneous specimens, J is calculated by eq. (1), for mis-matched specimens, J is calculated by eq. (1) with modified η-factor ($\eta_{\text{-MM}}$) as referred in ref. 12, 15).



a)

b)

FIG. 6 : The J R-curves of the SENB specimens contained shallow and deep cracks showing different R-curves for homogeneous and mis-matched specimens;
a) crack is located in material-**A** ; b) crack is located in material-**B**.
(Note: J-CMOD is calculated by eq. (3) with η_C given by eq (4) for homogeneous specimens and η_C given by eq. (5) for mis-matched specimens)