Brite-Euram Project No :BE95-1426

Contract No:	BRPR-CT95-0024
Task No:	1
Sub-Task No:	1.2
Date :	June 15, 1998
Document No:	SINTAP/GKSS/14

STRUCTURAL INTEGRITY ASSESSMENT PROCEDURES FOR EUROPEAN INDUSTRY

SINTAP

REPORT : SUB-TASK 1.2

RESULTS FROM BIMATERIAL TESTING PROGRAMME

(DRAFT FOR COMMENTS)

Preparted by GKSS Research Center
Max-Planck Str.
21502 Geesthacht
Germany

Author : Yun-Jae Kim

CIRCULATION

INTERNAL (GKSS)

Prof. K.-H. Schwalbe
Dr. Mustafa Koçak

EXTERNAL (TASK 1 MEMBERS)

Dr. R.A. Ainsworth	**(NEL)**
Dr. Graham Wardle	**(AEA)**
Dr. C. Wisener	**(TWI)**
Mr. A.C. Bannister	**(BS)**

SUMMARY

This report summarises the results from activities in SINTAP Sub-Task 1.2, bi-material testing programme, of which is to investigate the mis-match effect on fracture behaviour of bi-materials with the model welds. Within three institutes (AEA, UK; NE, UK; GKSS, DE), extensive experimental data have been generated for the past two years, which can be categorised as follows:

- mismatch effect at room temperature
    1. mismatch effect on fracture toughness for weld metal cracks
    2. mismatch effect on fracture toughness for HAZ cracks
- mismatch effect within ductile to brittle transition temperature
    3. mismatch effect on fracture toughness for weld metal cracks
    4. mismatch effect on fracture toughness for HAZ cracks

It has been found that at room temperature the strength mismatch affect fracture toughness (J, CTOD and d5) for both weld metal cracks and for HAZ cracks. Such effect is expected and can be explained from the mismatch effect on local triaxial stress at the crack tip. On the other hand, within ductile to brittle transition temperature, little effect of the strength mismatch on fracture toughness has been observed. Several possible reasons for this “unexpected” results are given in the text; the effect of J and CTOD estimation equations from bimaterial testing; the mismatch-related variables employed in testing (mismatch ratio and geometry parameter (W-a)/H); scatter within transition temperature. It is likely that, once analysis of the mismatch corrected J estimation within Sub-Task 1.4 activities is completed, the test results can be re-assessed to make conclusions concrete.

Finally several outstanding issues for future development, particularly related to toughness testing of weldments are given.

TABLE OF CONTENTS

1. INTRODUCTION

The objective of the Task 1 in SINTAP is

- to quantify the mechanical and fracture behaviour of mismatched (welded) joints with mechanical heterogeneity (strength mis-match)
- more importantly to provide recommendations for the most appropriate defect assessment and testing methods of quantifying the behaviour of mismatched joints.

In order to achieve this goal, the Task 1 is covering the following Sub-Tasks (STs);

ST 1.1 Review
ST 1.2 Bi-material testing
ST 1.3 Multi-pass weld evaluation
ST 1.4 Modelling
ST 1.5 Procedure development and validation

This report summarises final results obtained in Sub-Task 1.2: Bi-material testing programme. Three institutes were involved in bimaterial testing activities: AEA Technology (UK), Nuclear Electric Ltd (UK) and GKSS Research Centre (Germany).

Understanding fracture behaviour of mismatched welded joints is quite complex due to many sources. Firstly, tensile and fracture properties of the weld metal are different from those of the base plate. Even those properties within the weld metal can be different. Moreover, the HAZ properties can differ from those of the base plate and weld metal. The weld configuration (such as V-, K-, or X-grooves) adds additional complexities. Thus to obtain “meaningful” insight of the mismatch effect on fracture behaviour of weldments, the “model” weld would be often quite useful, which has a “well-defined (homogeneous)” weld metal and a simple weld configuration (such as a rectangular shape). Such model welds can be produced, for instance, by EB welding or by diffusion-bonding. The underlying idea of the Sub-Task 1.2 is to investigate the mis-match effect on fracture behaviour of bi-materials with the model welds. It gives a contrast to that of Sub-Task 1.3 which is to investigate the mis-match effect on fracture behaviour of bi-materials with the “real” multipass welds.

In this report, results obtained in the experimental programme are presented in two main categories: (i) in the upper shelf (at room temperature) and (ii) within the ductile to brittle transition temperature. Firstly, the experimental programme in the upper shelf is summarised in Sec. 2 and the main results are discussed in Sec. 4. Then the experimental programme within the ductile to brittle transition temperature is summarised in Sec. 5 and the main results are discussed in Sec. 6. Section 7 concludes and provides future recommendations.

2. SUMMARY OF EXPERIMENTAL PROGRAMME AT ROOM TEMPERATURE

3.1 Programme at AEA

AEA investigated the mismatch effect on fracture behaviour of mismatched SENB specimens. The materials used in experiments are A533B-1 steels heat treated in order to produce different yield and ultimate strength values, which are summarised in Table 3.1. The test matrix is shown in Table 3.2 for weld metal cracks and in Table 3.3 for HAZ cracks. The mismatched specimens were produced by electron beam (EB) welding of two A533B steels. It should be noted that the EB weld welding produces thin (~3 to 4 mm) EB welds and heat affected zones (HAZs) , both of which have higher strengths than the higher strength A533B steel. The resulting mismatched specimens with weld metal cracks are schematically shown in Fig. 3.1, together with hardness profiles. For HAZ testing, the notch was placed in the HAZ at 1mm from the fusion boundary, Fig. 3.1.

Table 3.1

Material (A533B-1 steel)	YS (MPa)	UTS (MPa)	Elongation (%)	R.A (%)
Material 1	739	849	16.4	63.5
Material 2	497	647	23.7	69.0

Table 3.2 : Test matrix for weld metal cracks

Material	Mismatch?	M	a/W	(W-a)/H	Results
1	Homogeneous	1.0	0.65	N/A.	J, δ_{BS}, δ_5-Δa
2	Homogeneous	1.0	0.65	N/A.	
1/1/1	Evenmatched	1.0	0.45	6.3	
			0.65	3.0	
1/2/1	Undermatched	0.53	0.45	6.3	
			0.65	3.0	
2/2/2	Evenmatched	1.0	0.45	6.3	
			0.65	3.0	
2/1/2	Overmatched	1.90	0.45	6.3	
			0.65	3.0	

NB :
1. All specimens were side-grooved by 20%.
3. EB welding was used to weld the material 1 and 3.
3. In all cases, the notch was placed in the centre of the weld metal.

Table 3.3 : Test matrix for HAZ testing

Material	Mismatch?	M	a/W	(W-a)/H	Results
1/1	Evenmatched	1.0	0.45	N/A.	J, δ_{BS}, δ_5-Δa
		1.0	0.65	N/A.	
2/2/2	Evenmatched	1.0	0.45	6.3	
			0.65	3.0	
1/2/1	Undermatched	0.53	0.45	6.3	
			0.65	3.0	

NB : 1. All specimens were side-grooved by 20%.
3. EB welding was used to weld the material 1 and 3.
3. In all cases, the notch was placed in the HAZ at 1 mm from the fusion boundary (Fig. 3.1)

3.2 Programme at NE

Within NE, J-resistance behaviour of highly mismatched CCT specimens was investigated, made of two different ferritic steels. The materials as well as the testing matrix are summarised in Tables 3.4 and 3.5. In all cases, the crack was placed in the centre of the weld metal.

Table 3.4

Material	YS (MPa)	UTS (MPa)	Elongation (%)	R.A (%)
Material A : BS 4360 Grade 43A	265	431	44	71
Material B : FE 510	504	605	28	76

Table 3.5 : Test matrix

Material	Mismatch?	M	a/W	(W-a)/H	Results
A	Homogeneous	1.0	0.4	N/A.	J-Δa
B/A/B	Undermatched	0.53	0.4	3.5	
B	Homogeneous	1.0	0.4	N/A.	
A/B/A	Overmatched	1.90	0.4	1.75	

NB : 1. All specimens were side-grooved by 10%.
3. EB welding was used to weld the material A and B.
3. In all cases, the notch is located in the centre of the weld metal.

3.3 Programme at GKSS

Within GKSS, two sets of experimental data on R-curve behaviour of mismatched SENB specimens were reported. The first set was produced from mismatched SENB specimens produced by EB welding of two austenitic steels (Table 3.6), of which the test matrix is summarised in Table 3.7. Another set of test was produced by diffusion bonding of two Ti alloys, commercially pure (CP) Ti and Ti-6Al-4V. The diffusion bonding process provides several advantages: firstly it is easy to control the bonding quality, and secondly it can produce a relatively distinct interface region. The material properties as well as test matrix is summarised in Tables 3.8-3.10.

Table 3.6

Material	YS (MPa)	UTS (MPa)	Elongation (%)	R.A (%)
Material L : AISI 316L	300	610	55.84	
Material X: X6CrNi1811	240	620	60.13	

Table 3.7 : Test matrix

Material	Mismatch?	M	a/W	(W-a)/H	Results
X	Homogeneous		0.5	N/A.	J, δ_{BS}, δ_5-Δa
			0.15	N/A.	
L/X/L	Undermatched	0.8	0.5	1.54	
			0.15	3.62	
L	Homogeneous		0.15	N/A.	
			0.15	N/A.	
X/L/X	Overmatched	1.25	0.15	1.54	
			0.15	3.62	

NB :
1. All specimens were non side-grooved
2. EB welding was used to weld the material A and B.
3. In all cases, the notch is located in the centre of the weld metal.

Table 3.8

Material	YS (MPa)	UTS (MPa)	Elongation (%)	R.A (%)
Material Ti : commercially pure Ti	300	500		
Material Ti64: Ti-6Al-4V	900	950		

Table 3.9 : Test matrix for weld metal cracks

Material	Mismatch?	M	a/W	(W-a)/H	Results
Ti	Homogeneous		0.5		δ_5-Δa

Ti64	Homogeneous		0.5		
Ti64/Ti/Ti64	Undermatched	0.33	0.5	2	
				1	
				0.5	
				0.25	
Ti/Ti64/Ti	Overmatched	3.0	0.5	2	
				1	
				0.5	
				0.25	

NB : 1. All specimens were non side-grooved
2. Diffusion bonding was used to weld the material A and B.
3. In all cases, the notch is located in the centre of the weld metal.

Table 3.10 : Test matrix for interface /sub-interface crack in dissimilar joints

Material	M	a/W	crack location	Results
Ti/Ti64	3.0	0.5	interface	δ_5-Δa
Ti/Ti64	3.0	0.5	sub-interface at less than 1mm from the interface	δ_5-Δa

DOCUMENTS PRODUCED WITHIN SINTAP SUB-TASK 1.2

AEA & NE

- G. Wardle, R.P. Birkett and B.K. Neale, “The Fracture Toughness of Mis-Matched Ferritic Steel”, *Mis-Matching of Interfaces and Welds*, Edited by K.-H. Schwalbe and M. Koçak, 1997, GKSS research Centre Publication, Geesthacht, Germany, pp. 371-383.
- G. Wardle and S Jacques, “Experimental J-integral (J), Crack Tip Opening Displacement (CTOD) and Local CTOD (d5) Measurements Made on Strength Mis-Matched Welded Specimens”, AEAT-0894, AEA Technology, September 1997.
- G. Wardle and S Jacques, “Fracture Toughness Test results for Weld Strength Mis-Matched HAZ Specimens”, R6 R/NE/218, AEA Technology, October 1997.
- B.K. Neale, “The Fracture Behaviour of Mismatched Centre-Cracked Welded Specimens in Tension”, Nuclear Electric Ltd, EPD/GEN/REP/0191 /97, March 1997.

GKSS

- H.-M. Bauschke and M. Koçak, “Strength Mis-Match Effect on R-Curve Behaviour of Austenitic Steel Welds”, *Mis-Matching of Interfaces and Welds*, Edited by K.-H. Schwalbe and M. Koçak, 1997, GKSS research Centre Publication, Geesthacht, Germany, pp. 385-397.
- G. Cam, L. Bunge, K.-H. Bohm and M. Koçak, “Fracture behaviour of the diffusion bonded Ti-alloys”, *GKSS Report,* Geesthacht, Germany, 1998.

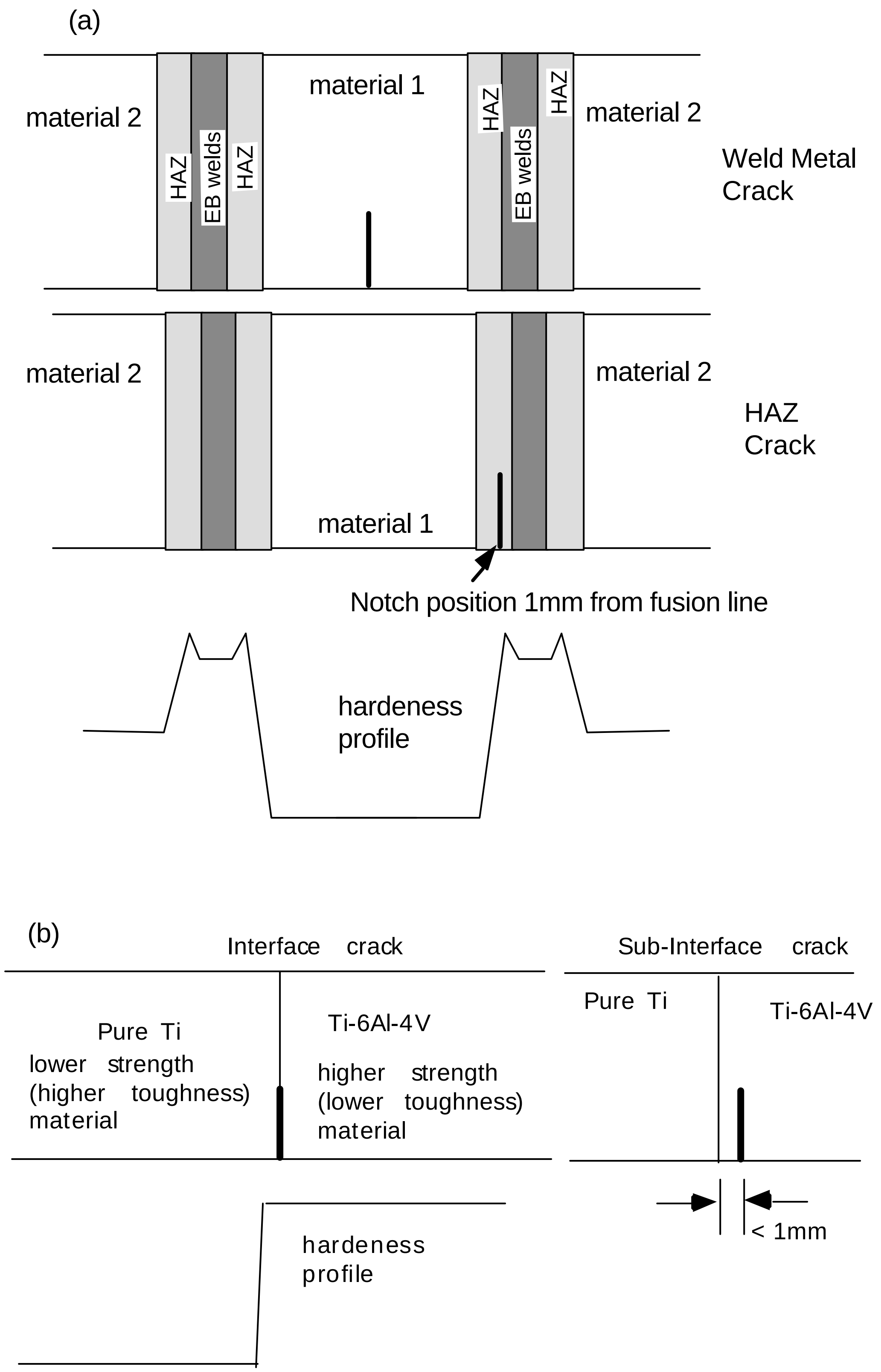


Fig. 3.1. *Schematic illustrations of the specimens and hardness (strength) profiles : (a) bimaterial specimens tested at AEA, (b) bimaterial specimens (made of two Ti alloys) tested at GKSS.*

3. RESULTS AND DISCUSSIONS :
TESTS AT ROOM TEMPERATURE

Before we discuss the results obtained within Sub-Task 1.2, one difficulty should be pointed out, related to J and CTOD testing of bimaterial specimens. Evaluation of fracture mechanics parameters, J and CTOD, from raw experimental data require certain calibration functions (J and CTOD estimation equations). However, it has been shown that such calibration functions are affected by the strength mismatch. Meaningful conclusions of the mismatch effect on fracture behaviour of bimaterial joints could be obtained only when J or CTOD has been determined correctly from bimaterial testing. Although several proposals have been made on mismatch corrected J estimation procedures [see 6-8], they differ appreciably depending on the mismatch level and (W-a)/H, and no consensus has been reported yet. Due to the lack of mismatch specific toughness testing procedure, it is still a common practice to evaluate J or CTOD for mismatched specimens based on the homogeneous testing procedure (“without mismatch corrections”). Although some of the results were interpreted “with mismatch corrections”, it is not clear whether the results are indeed correct since all proposals regarding mismatch correction differ. Unfortunately up to present, none of the above issues has been resolved, and thus conclusions from experimental works are not likely to be concrete.

As pointed out, the use of the J-integral or standardised CTOD in bimaterial testing involves one difficulty ; it requires a “correct” J estimation procedure. Pending accurate mismatch corrected J and CTOD estimation procedures, the use of the δ_5 technique [], could offer a certain advantage since it does not require any calibration function.

Finally, it is worth noting at this point that there are two important mismatch-related variables: the strength mismatch M and the geometrical variable (W-a)/H, **Fig. 3.1**. A comprehensive understanding on fracture behaviour of bimaterial joints thus requires detailed understanding of the effect of M as well as of (W-a)/H on fracture behaviour.

3.1 WELD METAL CRACKS

We first summarise and discuss the results for weld metal cracks, i.e., the crack is located in the centre line of the weld metal. The case when the crack is located in the interface of the base plate and weld metal (heat affected zone, HAZ) will be discussed in the next section.

Effect of Strength Mismatch

The effect of strength mismatch on the J-R or CTOD-R curves (without the mismatch correction) is schematically shown in **Fig. 3.2.** Typically, the higher overmatching provides the stiffer R-curve, compared to that of the material where the crack is located. On the other hand, for undermatching, it is reversed; the higher undermatching provides the flatter R-curve. Experimental results from both AEA and NE confirms such tendency, **Fig. 3.3.** The similar tendency has been also found in d5-R curves obtained from the GKSS experiment on Ti alloys, **Fig. 3.4.**

Such effect of the strength mismatch on resistance curves can be explained from the mismatch effect on local triaxial stress states at the crack tip, Fig. 3.5. For a given (W-a)/H ratio, higher overmatching is associated with the lower triaxial stress at the crack tip, which in turn is responsible for stiffer R-curve. On the other hand, higher undermatching is associated with the higher triaxial stress at the crack tip, which in turn is responsible for flatter R-curve.

Effect of (W-a)/H

Within AEA experiments, the effect of (W-a)/H on the resistance curve was addressed, by changing the crack length a/W from a/W=0.45 to 0.65 while fixing the value of H. Note that the standard toughness testing procedures for homogeneous specimens permit a/W ranging between 0.45 and 0.65. However, for mismatched specimens, the change in a/W implies the change in (W-a)/H, which may in turn affect the fracture toughness. It was found that the resulting R-curves were indeed different. The general tendency they found is that the larger (W-a)/H (thus shorter a/W) is associated with the lower R-curve. It gives a clear contrast to the homogeneous specimen where the R-curve is not expected to be influenced by a change of a/W from 0.45 to 0.65.

Within GKSS, the effect of (W-a)/H on d5-resistance curve has been systematically looked at in Ti bimaterial testing by changing H with the fixed a/W. The resulting resistance curves are shown in Fig. 3.4. For overmatching, decreasing H (increasing (W-a)/H) is associated with the stiffer δ_5-R curves. For undermatching, the effect is opposite: decreasing H (increasing (W-a)/H) is associated with the flatter δ_5-R curves.

Such effect of (W-a)/H on fracture toughness can be also explained from the mismatch effect on local triaxial stress states at the crack tip, Fig. 3.5. For a given overmatching, increasing (W-a)/H reduces the triaxial stress states at the crack tip and thus is responsible for increasing the toughness. For undermatching, increasing (W-a)/H increases the triaxial stress states at the crack tip and thus is responsible for decreasing the toughness.

One interesting point is that for undermatching, the triaxial stress states at the crack tip almost do not change up to (W-a)/H 8, and thus the resulting d5-R curves are similar as shown in Fig. 3.4. It means that for undermatched (deeply cracked) bend specimens, the toughness data resulting from the specimen with (W-a)/H<8 can be regarded as that for the weld metal. On the other hand, for overmatching, the triaxial stress states at the crack tip decreases if (W-a)/H>8, which implies that the toughness data resulting from the specimen with (W-a)/H<2 can be regarded as that for the weld metal.

Uniqueness of Resistance curves: Mismatch Corrected J and CTOD Estimation Scheme

One of the issues in J or CTOD testing of mismatched bimaterial specimens is whether a unique J-resistance or CTOD resistance curve can be obtained, independent of the strength mismatch level. To resolve this issue, a “correct” J or CTOD estimation procedure specific to the strength mismatch has to be addressed first.

Typically the J integral can be estimated from experimental load-load line displacement or crack mouth opening displacement (CMOD) by

$$J = J_e + J_p = \frac{K^2\left(1-\upsilon^2\right)}{E} + \frac{\eta U_p}{B_N\left(W-a\right)} \qquad (3.1)$$

where K, n and E are the elastic stress intensity factor, the Poisson’s ratio and the Young’s modulus. In eqn. (3.1), Up is the area of the plastic portion under load-load line displacement or load-CMOD record. The plastic eta factor h is a function of the specimen geometry. Several proposals have been made to modify h to cope with the strength mismatch and (W-a)/H. Among those, the mismatch corrected eta factor hMM proposed by Hornet and Eripret for deeply cracked bend specimens is shown in Fig. 3.6. Although specific values of hMM are different depending on the proposals, a general tendency is that, compared to the value for homogeneous specimens, the higher undermatching is associated with the higher value; the higher overmatching with the lower value. Experimental results within this programme as well as in the previous works provided a promising result that the mismatch corrected J-R curves come closer for various strength mismatch ratios, **Figs. 3.7** and **3.8**.

However, it is felt that there are still some issues to be resolved and thus further investigation would be necessary. One objecting argument is that there is no consensus yet on hMM. Although all proposals bear similar tendencies, exact values of hMM differ appreciably for certain values of (W-a)/H. Moreover, validations of the proposed hMM are limited. In this context, within Sub-Task 1.4, various proposals are compared with the FE results, aiming for recommendation of the most appropriate J estimation equation for mismatched SENB, CCT and CT specimens. Another objecting argument is that the strength mismatch induces different constraint (triaxial stress states) at the crack tip (the mismatch effect on local stresses), see **Fig. 3.5**. It is well known that the different crack tip stress triaxialities are responsible for the non-uniqueness of J-R curves. A preliminary study of FE simulation of crack growth in highly mismatched SENB specimens, using cohesive zone type model, also indicated that the J-R curves strongly depend on the strength mismatch [].

Often it has been found that δ_5-R curve is associated with rather unique R-curves, regardless of the strength mismatch, as illustrated in **Fig. 3.9**. However, it is not always the case, as already shown in Fig. 3.4. As for homogeneous specimens, relationships between J, CTOD and δ_5 for mismatched specimens would be useful in order to rationalise the interdependence of crack tip characterising parameter, as described next.

Relationship Between J, d5 and BS CTOD

The relationship between J, δ_5 and BS CTOD was addressed in bend tests of mismatched specimens at AEA. Although consistent relationships could not be found, their results provided the following observations:

- J versus BS CTOD

  At low J-CTOD (within elastic regime) there is good agreement with the relationship observed for the homogeneous material. At general yielding, however, the slope of the relationship decreases to a value below that of the homogeneous material, see Fig. 3.10a for a schematic diagram.
- J versus δ_5

  At low d5 values, δ_5 scales linearly with J. This relationship breaks down at an absolute level of δ_5 higher than observed using the CTOD parameter, i.e. the slope of the J- δ_5 relationship increases. For larger values of δ_5, however, δ_5 tends to scale linearly with J, see Fig. 3.10b for a schematic diagram.
- δ_5 versus CTOD

  For small values of CTOD, there exist one-to-one relationship. As δ_5 level increases, δ_5 becomes increasingly larger than CTOD, see Fig. 3.10c for a schematic diagram.

3.2 HAZ CRACKS

The previous section discussed the test results for weld metal cracks, i.e., the crack is located in the centre line of the weld metal. This section will discuss the test results for HAZ cracks. Within Sub-Task 1.2, there have been two activities on HAZ toughness testing: (1) AEA on A533B-1 steels, and (2) GKSS on Ti-alloys (see Section 2).

AEA found the followings from their experiments:

1. The strength mismatch has a minimal effect on the initiation toughness, but a significant effect on the resistance curve. However, this finding is based on J and CTOD without any mismatch correction, and thus is subject to further consideration.
2. Initiation toughness is affected by normalised crack length a/W, with shallower crack giving the higher values, Fig. 3.11.
3. The R-curves for the undermatched specimens are higher than those for even-matched specimens, Fig. 3.12. In their experiments, the weld metal is fixed, but different base plates were used to produce under- and even-matching (see Section 2). The resistance curves were obtained without any mismatch correction.
4. Most importantly, the crack initially located at the HAZ deviates into the softer plate material, shortly after the ductile tearing has initiated, which makes the resulting test results are "invalid" according to the current homogeneous testing standards. In most of cases, the crack extended from the HAZ into the softer material, which is schematically shown in Fig. 3.13.

AEA experiments provided one important implication to HAZ toughness testing. Due to the significant crack deviation from its plane, the resulting test results are "invalid" according to the current homogeneous testing standards. However, they also found that the results from the "valid" test are similar to those from "invalid" test, thus raising the question whether such restrictions in the current testing standards should be applied to HAZ testing.

One general problem associated with the AEA experiments is the use of the EB welding, which produces thin (~3 to 4 mm) EB welds and associated HAZs. Both regions have much higher strengths than A533B steels, see Fig. 2.1. Such higher strength of the local EB welds and HAZs can provide two consequences. Firstly, although globally the specimen is undermatched, locally it is overmatched, Fig. 3.13. Secondly since the crack is placed in (locally) highly overmatched region, it can deviate and move into the softer surroundings, due to the shielding effect provided by high overmatching. It should be also noted that the fracture event (toughness) can be very sensitive to the crack location, particularly in HAZ toughness testing. Fracture toughness tests on EB welded similar/dissimilar bimaterial joints (this test was performed within another research programme at GKSS) reveal that the fracture behaviour can be quite sensitive to the crack location: the slight change of the crack location within the EB welds and associated HAZs can provide dramatic changes in fracture behaviour. Therefore, for HAZ toughness testing, careful design of specimens would be important. In this context, on-going works in Sub-Task 1.3 are worth noting: the strength levels of the HAZ are controlled to produce series of global (between the weld metal and base plate) and local (between HAZ and the weld metal) mismatch. Results to be obtained within Sub-Task 1.3 could help to explain clearly the results from AEA tests.

On the other hand, the mismatch effect on fracture behaviour of interface cracks was clearly illustrated from GKSS experiments on Ti alloys. As described in Section 2, two different Ti alloys were diffusion bonded, having very different yield strength and fracture toughness. The higher strength is associated with the lower toughness, and vice versa. A careful control of diffusion bonding process could lead to a clear interface between two Ti alloys. Then the notch was placed either at the interface or at sub-interface (within 1 mm from the interface) in the side of the higher strength Ti alloy (Fig. 2.2). Their findings can be summarised as follows:

- When the crack is placed at the interface, the crack grows along the interface in the lower strength (but tougher) material side, Figs. 3.13 and 3.14. The resulting d5-R curve is slightly lower than that of the higher toughness (lower strength) material, but is much higher than that of the lower toughness (higher strength) material, Fig. 3.15.
- When the crack is placed at the sub-interface (within 1mm) in the side of the lower toughness (higher strength) material, the crack kinks to the interface, which provides apparent toughness increase, Fig. 3.14. When the crack reaches the interface, it be-

haves as the interface crack ; the crack grows along the interface in the lower strength (but tougher) material side. The resulting apparent toughness increase can be even higher than that of the interface crack, due to the crack kinking, Fig. 3.15.

The crack deviation observed from both AEA and GKSS experiments can be mechanically explained. When the crack is placed near the interface between strength mismatched materials, as the strength mismatch increases, plastic deformation is intensified in the lower strength material but is relaxed in the higher strength material, Fig. 3.16. Consequently both crack driving force and triaxial stress increase in the lower strength material but decrease in the higher strength material. As a result, the crack growth is promoted to grow into the lower strength, but is shielded in the higher strength material. Thus even though the crack is placed in the higher strength material with possibly poor toughness, it can deviated into the lower strength (but much tougher) material. The resulting toughness will be close to that for the lower strength material which is much higher than that of the higher strength material where the crack tip is originally located, as illustrated in Fig. 3.15. This issue of HAZ crack behaviour will be addressed in more details in Sub-Task 1.4 (HAZ modelling).

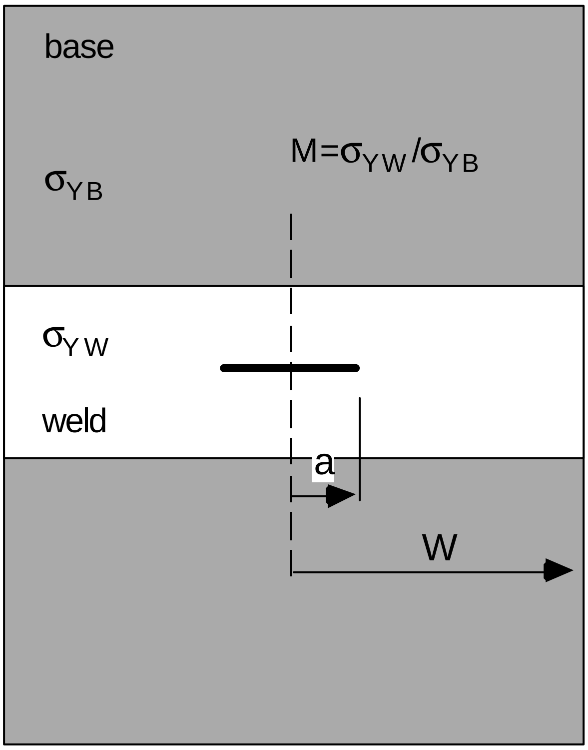


***Fig. 3.1** : Illustration of two important mismatch related variables : M and (W-a)/H.*

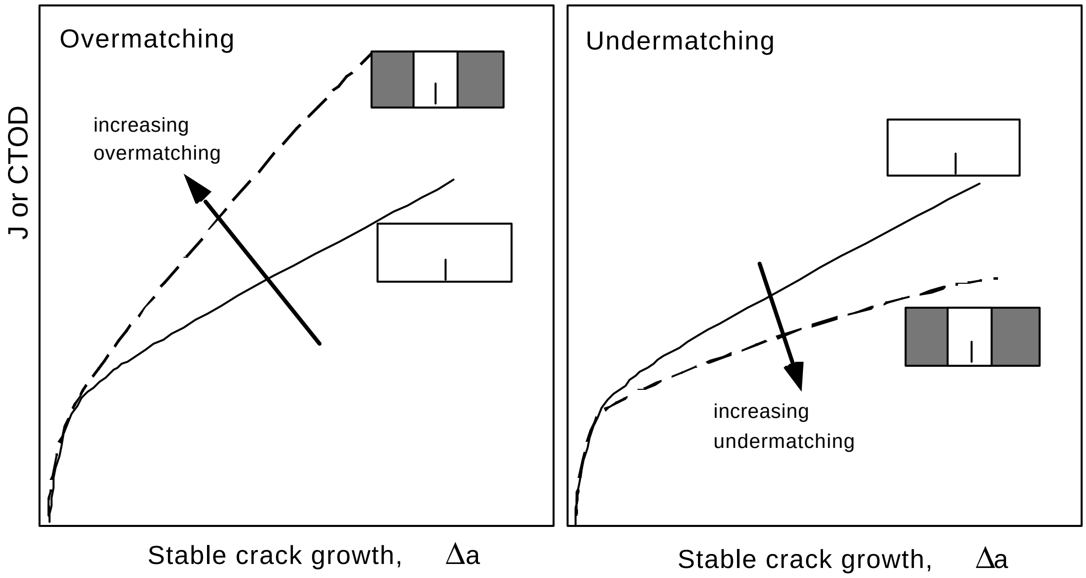


***Fig. 3.2:** Schematic diagrams of the strength mismatch effect of toughness resistance curves of bimaterial joints.*

Fig. 3.3: *J-resistance behaviour of the mismatched CCT specimens tested at NE []. The value of the J integral was evaluated according to the homogeneous testing procedure.*

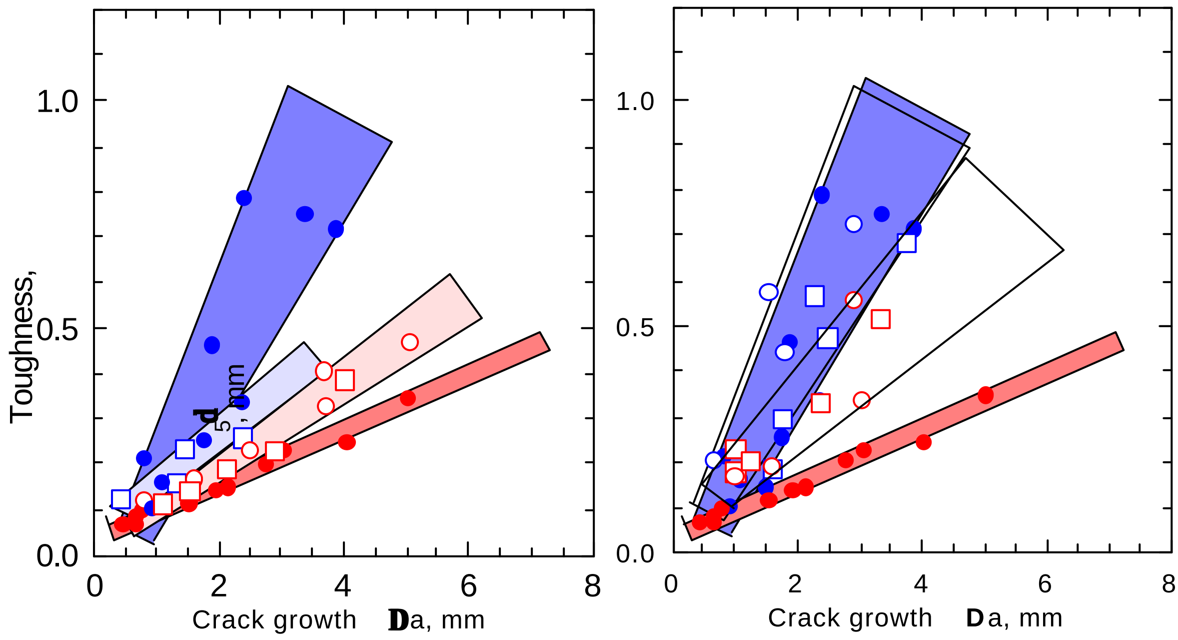


Fig. 3.4 *: Effect of strength mismatch and (W-a)/H on d5-resistance curves for mismatched bend specimens produced by diffusion bonding of two Ti alloys, tested at GKSS.*

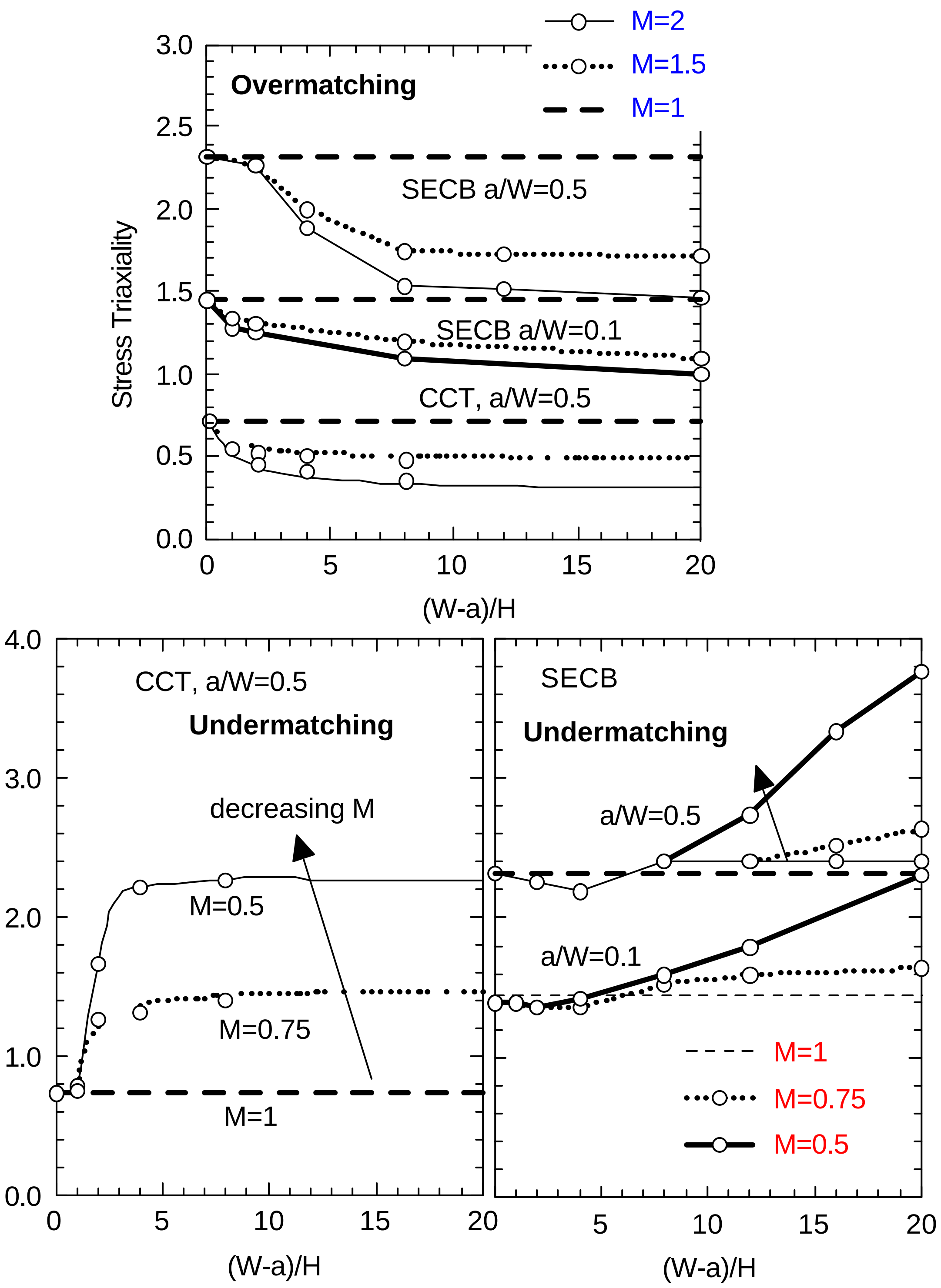


Fig. 3.5 : *Effect of M and (W-a)/H on local crack tip triaxial stress for mismatched specimens with weld metal cracks. The results are obtained from detailed FE analyses based on non-hardening plasticity. The stress triaxiality is defined as the ratio of the hydrostatic stress to the yield stress of the weld metal.*

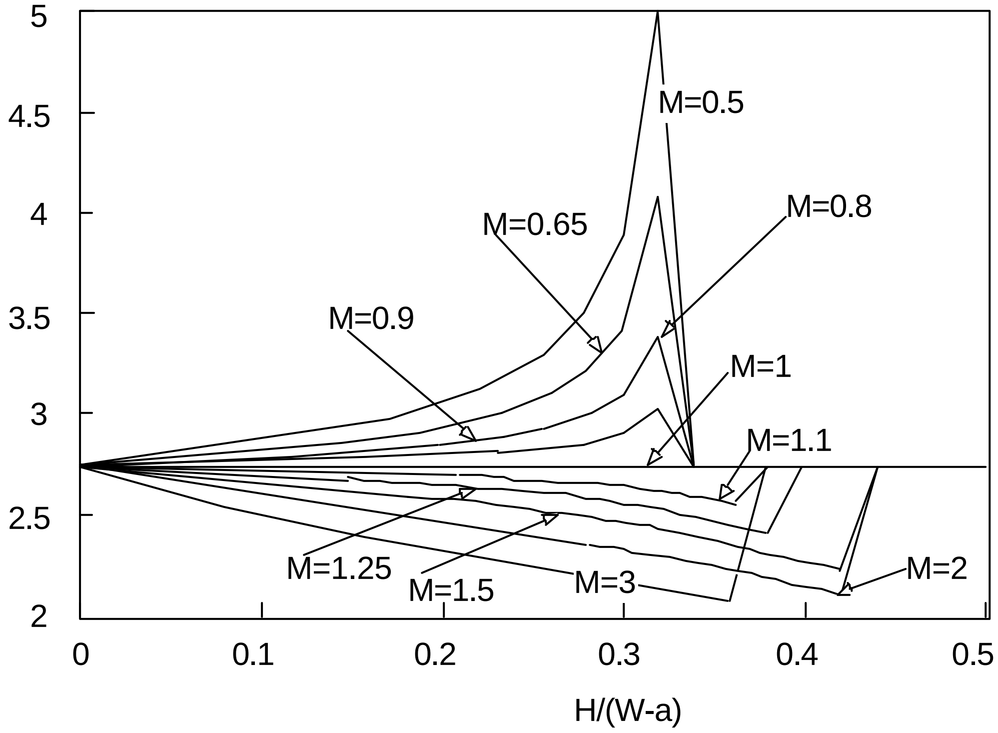
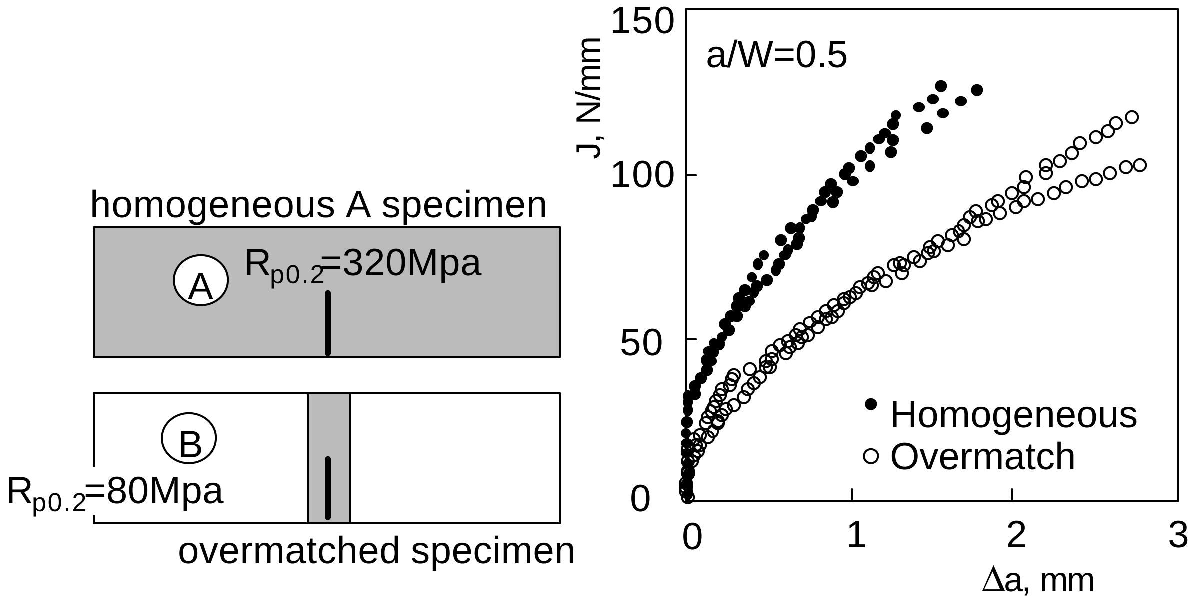
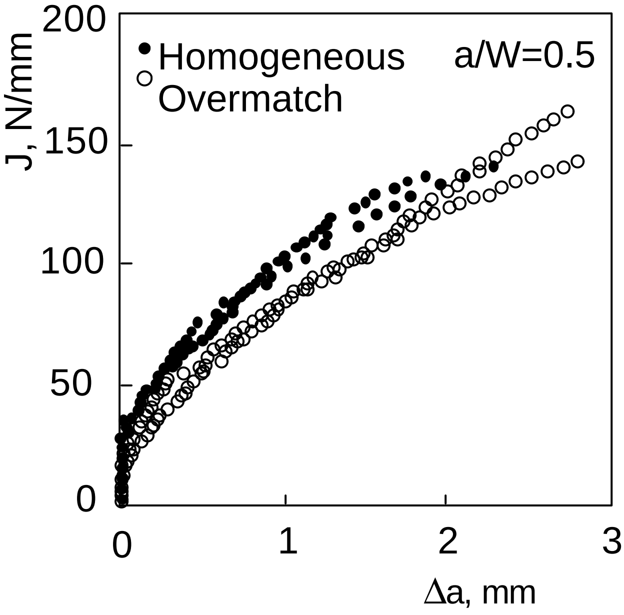


Fig. 3.6: *Mismatch-corrected plastic h-factor for SENB specimens with a/W=0.5, proposed by Hornet and Eripret [].*



without mismatch correction



with mismatch correction

***Fig. 3.7**: Effect of mismatch-corrected J estimation scheme for highly overmatched specimens [].*

Fig. 3.8: *Mismatch corrected J-resistance curves of the mismatched CCT specimens []. See Fig. 3.3 for the corresponding J-resistance curves without mismatch correction.*

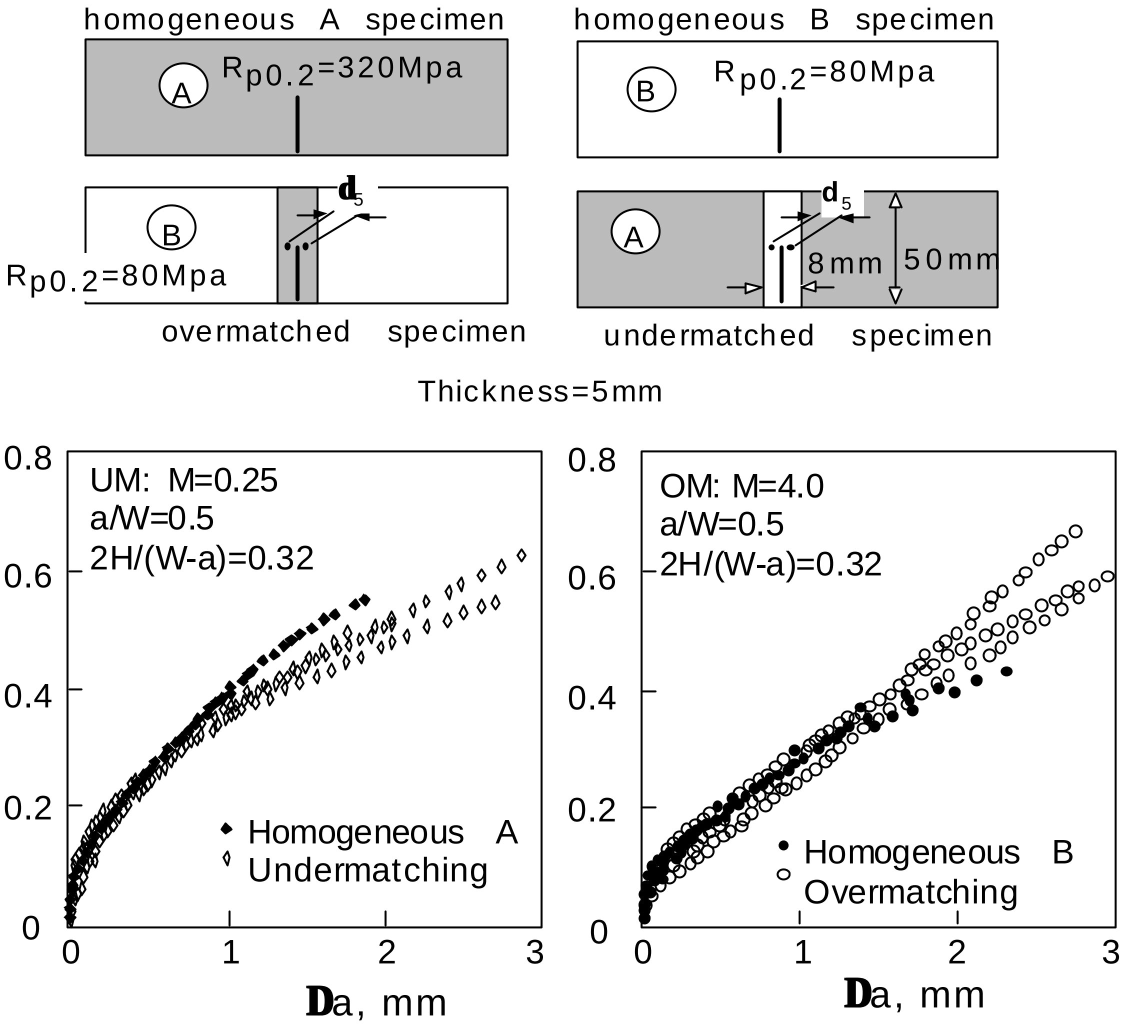


***Fig. 3.9** : Uniqueness of d_5-R curves for highly mismatched bimaterial joints in bending. The corresponding J-resistance curves are shown in Figs. 3.7.*

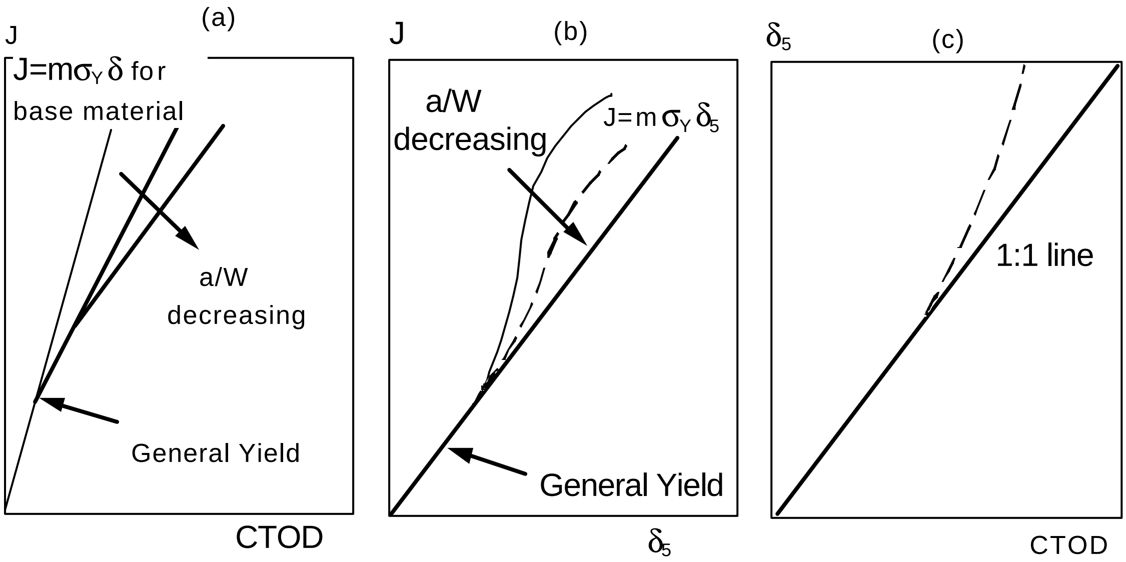


Fig. 3.10 *: Schematic diagrams of relationship between J, d5 and BS CTOD, obtained from deeply cracked bend specimens accompanying stable crack growth.*

Fig. 3.11: *Mismatch effect on initiation toughness (defined at 0.2 mm, $J_{0.2}$, $d_{0.2}$, etc.) in mismatched SENB specimens with HAZ cracks, tested at AEA.*

Fig. 3.12: *Mismatch effect on J resistance curves in mismatched SENB specimens with HAZ cracks, tested at AEA.*

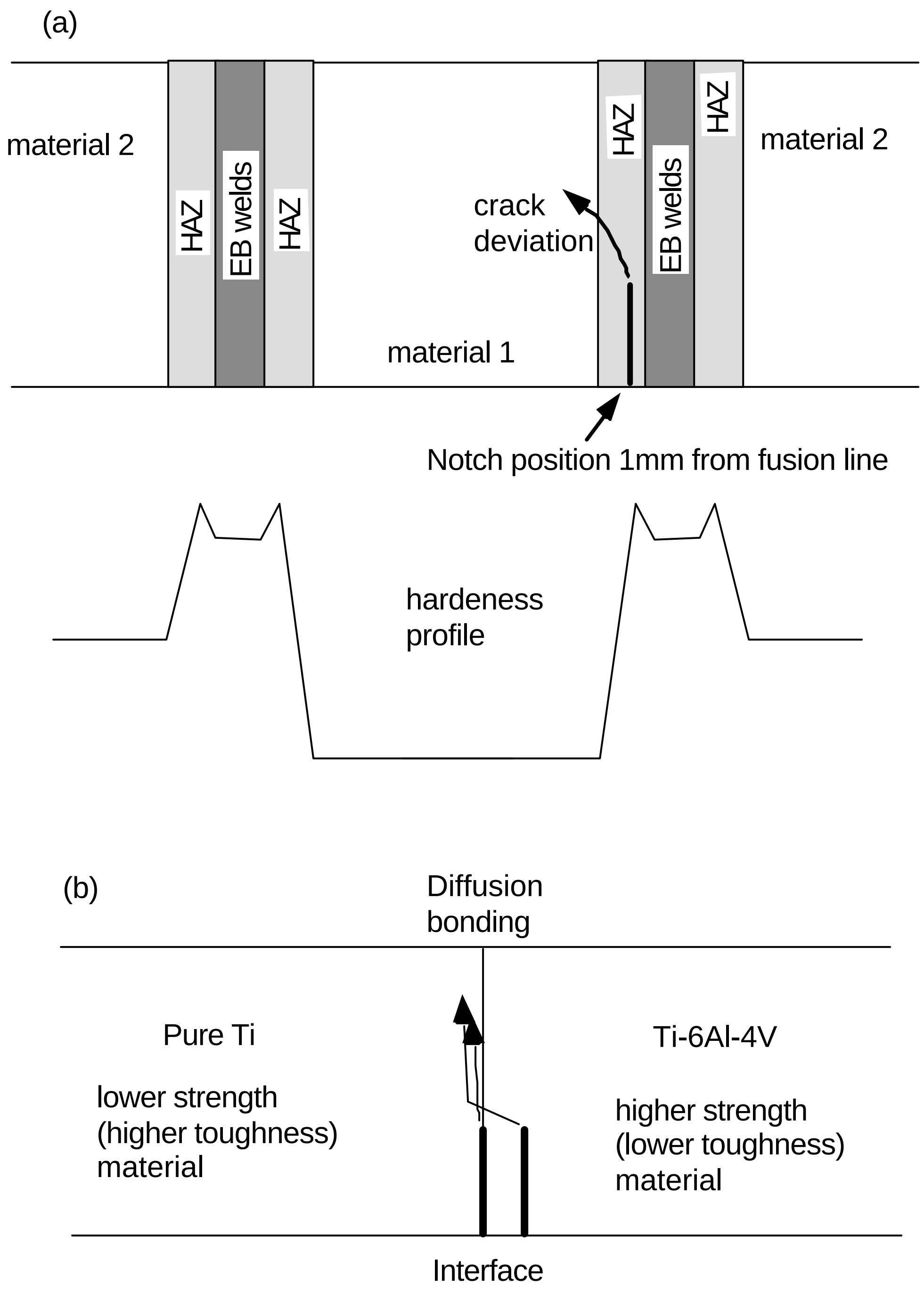


Fig. 3.13: *Schematic diagrams of crack deviation for HAZ crack (tested at AEA) and interface/sub-interface crack (tested at GKSS). The crack deviates into the lower strength material.*

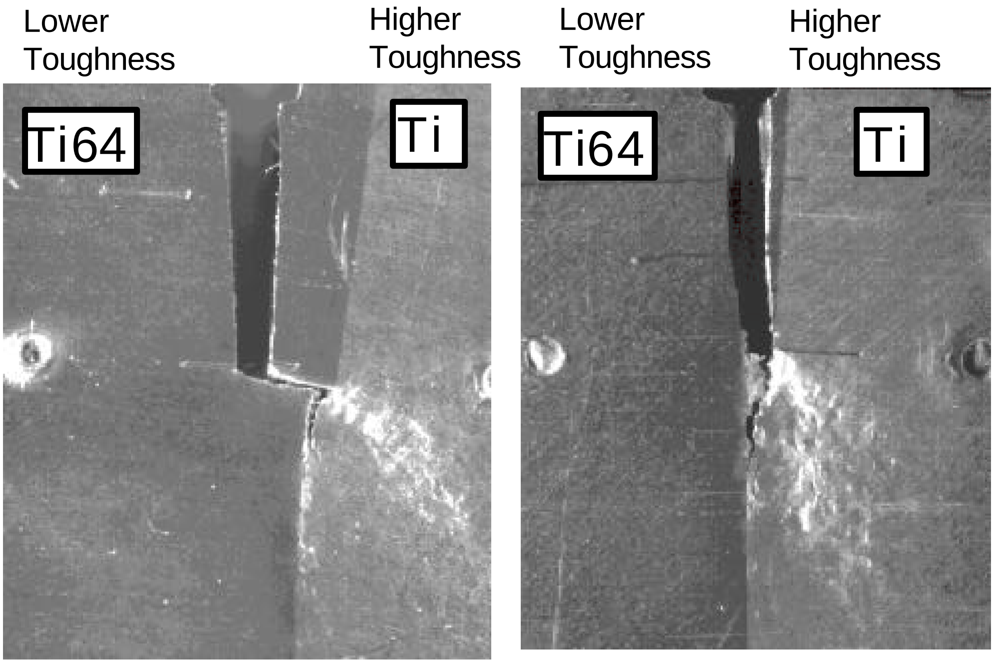


Fig. 3.14 *: Fracture behaviour of sub-interface cracks in dissimilar joints, tested at GKSS.*

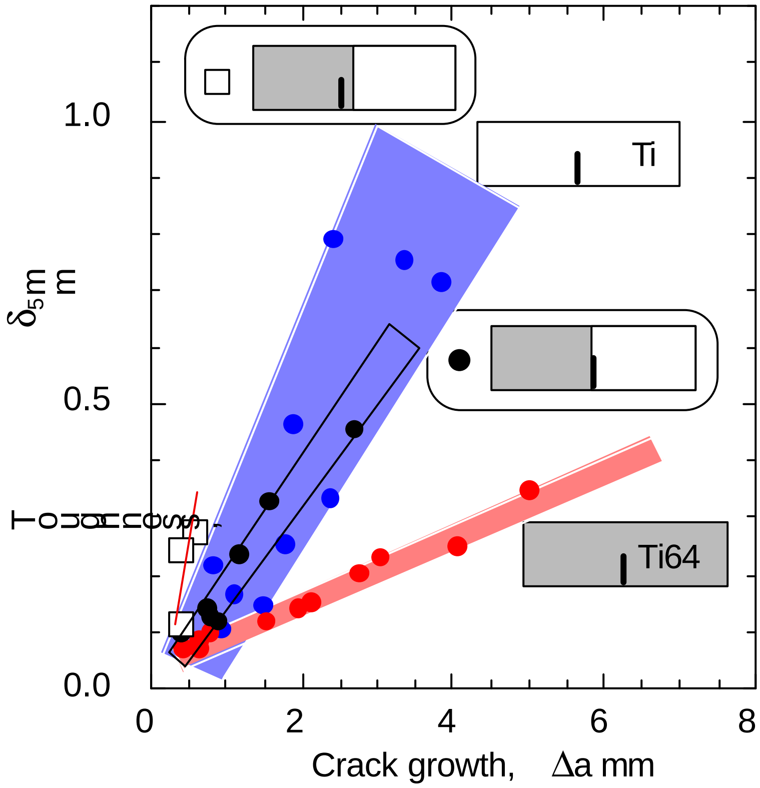


Fig. 3.15 *: d5-resistance curves for interface/sub-interface cracks in DB bonded dissimilar specimens.*

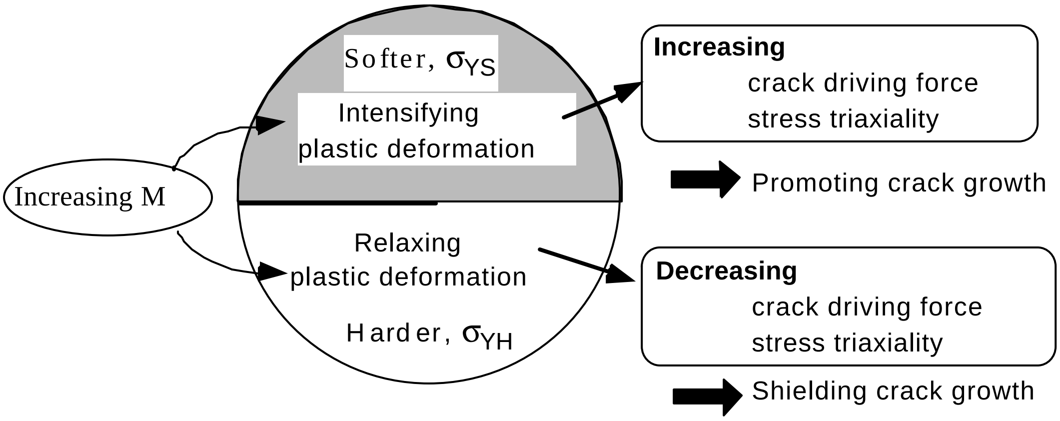


Fig. 3.16 *: Schematic illustration of the strength mismatch effect on fracture behaviour for interface /sub-interface (HAZ) cracks.*

4. SUMMARY OF EXPERIMENTAL PROGRAMME WITHIN DUCTILE TO BRITTLE TRANSITION TEMPERATURE

4.1 Programme at AEA

The mismatch effect on fracture behaviour of mismatched SENB specimens within ductile to brittle transition temperature has been investigated at AEA. The materials are same as those for room temperature (Section 2), A533B-1 steels heat treated in order to produce different yield and ultimate strength values. Tensile test was performed over whole ranges of temperatures investigated. The test matrix is shown in Table 4.1 for Charpy test, in Table 4.2 for weld metal cracks and in Table 4.3 for HAZ cracks.

Table 4.1 : Charpy test matrix

Material	Mismatch?	Test temperature (Celsius)
1	Homogeneous	+20, -10, -25, -40, -70, -100
2	Homogeneous	+20, -10, -25, -40, -70, -100
1/1/1	Evenmatched	+20, -10, -40, -70, -100
1/2/1	Undermatched	+20, -10, -40, -70, -100
2/1/2	Overmatched	+20, -10, -25, -40, -70

NB : EB welding was used to weld the material 1 and 3.

Table 4.2 : Test matrix for weld metal testing

Material	Mismatch?	M	a/W	(W-a)/H	Results
1	homogeneous		0.5		J_c, δ_c, δ_{5c}
2	homogeneous		0.5		
1/1	Evenmatched	1.0	0.5		
1/2/1	Undermatched	approx. 0.7	0.5	approx. 4	
2/1/2	Overmatched	approx. 1.3	0.5	approx. 4	

NB : 1. EB welding was used to weld the material 1 and 3.
2. In all cases, the notch was placed in the centre of the weld metal.
3. test temperature : -160, -140, -120. -100. -80, -60, -40 (deg Celsius)

Table 4.3 : Test matrix for HAZ testing

Material	Mismatch?	M	a/W	(W-a)/H	Results
1/2/1	Undermatched	0.7	0.5	approx. 4	J_c, δ_c, δ_{5c}
2/1/2	Overmatched	1.3	0.5	approx. 4	

NB : 1. EB welding was used to weld the material 1 and 3.

2. In all cases, the notch was placed in HAZ at 1mm from the fusion boundary
3. test temperature at -100 (deg Celsius)

Document produced within SINTAP Sub-Task 1.2

- G. Wardle, R.P. Birkett and S. Jacques, “Fracture toughness measurements made on strength mismatched welded A533B specimens tested within the ductile to brittle transition temperature region”, AEA Report, AEAT-2860, April 1998.

5. SUMMARY AND DISCUSSIONS : TRANSITION TEMPERATURE

The results from Charpy tests are shown in Fig. 5.1. Although the data are not statistically analysed, the following trends can be observed: the mismatch does not affect the Charpy energy and thus the values of impact energy measured on the mismatched testing pieces are indicative of the material in which the V notch was machined. Such behaviour can be understood from the effect of (W-a)/H on fracture behaviour. Typically the Charpy testing pieces are associated with (W-a)/H 1, in the range of which the mismatch effect is minimal, and thus the Charpy energy of the mismatched testing piece is similar to that of the material where the notch is located.

The results from toughness testing are shown in Fig. 5.2. Surprisingly it appears to be little effect of weld strength mismatch on fracture toughness: the material where the crack was placed dictated the fracture toughness level. For instance, for undermatched specimens (notched in the material 1), the toughness values are similar to those of the material 1. For overmatched specimens (notched in the material 2), the toughness values are similar to those of the material 2.

Such lack of the mismatch effect may result from many sources. One possible source is the crucial geometrical parameter (W-a)/H: in AEA testing specimens, (W-a)/H 4. Note that (W-a)/H affects not only local triaxial stress at the crack tip (which affects the critical toughness) but also the J and CTOD estimation equations. Both effects should be considered to draw proper conclusions. The effect of (W-a)/H 4 on local triaxial stress can be seen in Fig. 3.4. For overmatching (M 1.3), the crack tip triaxial stress decreases appreciably from that for homogeneous bending specimens, and thus some amount of toughness increase is expected. Then if one look at the effect of (W-a)/H, such configuration indicates that the plastic eta factor should be reduced. Noting that K_{Jc} (equivalently J_c) in Fig. 5.2 was estimated based on the homogeneous procedures, the values for overmatching should be reduced. On the other hand, for undermatching, (W-a)/H 4 gives almost no effect on the crack tip triaxial stress. Moreover, such configuration gives the J estimation equation close to that for homogeneous specimens. Thus, for the geometry of the undermatched specimens tested at AEA, the strength mismatch has a minimal effect on toughness. The mismatch corrected J estimation equation being developed in Sub-Task 1.4 may help to re-assess the data generated. Finally one may have to consider scatter in the ductile to brittle transition region, which can not be addressed at present.

Within this programme, HAZ testing in the ductile to brittle transition temperature (at -100^{o}C) have been also performed. In this case, the fatigue crack was placed in the HAZ region 1mm from the fusion boundary, see Fig. 2.1 in Section 2. The notch was placed either in the lower strength material (HAZ undermatched) or in the higher strength material (HAZ overmatched). The results again showed that there was no effect of mismatch: the data for the overmatched HAZ specimens fell within the scatter band to data from the undermatched HAZ specimens. As discussed in Section 3, proper interpretation of these results need further information generated within Sub-Task 1.4.

Fig. 5.1 *: Mismatch effect on Charpy impact energy within ductile to brittle transition temperature (AEA test results).*

Fig. 5.2 *: Mismatch effect on critical fracture toughness within ductile to brittle transition temperature (AEA test results).*

6. LINKS TO OTHER SUB-TASKS /ACTIVITY OUTSIDE CONSORTIUM

The Sub-Task 1.2 is linked to other Sub-Tasks within Task 1, **Fig. 6.1**. Sub-Task 1.3 deals with fracture behaviours of “realistic” multi-pass welded plates which have non-uniform weld configurations (V-grooves). On the other hand, Sub-Task 1.2 dealt with “idealised” weldments which has uniform weld configuration and homogeneous material within the weld. Therefore, results in Sub-Task 1.2 can provide meaningful results to interpret fracture behaviour of multi-pass welded plates. In particular, Sub-Task 1.3 also concentrates on the local mismatch (between the HAZ and the weld metal) on HAZ fracture behaviour. Thus the results generated in Sub-Task 1.4 will be linked to those generated in Sub-Task 1.2 (HAZ toughness).

Sub-Task 1.2 is by nature very closely linked with Sub-Task 1.4 (Modelling) in many aspects. First of all, the mismatch corrected J estimation scheme will be discussed in Sub-Task 1.4 in more details (the mismatch corrected plastic h-factor solutions). Moreover, for interfacial cracks in dissimilar joints or for HAZ cracks, the strength mismatch effect on fracture parameters (J or CTOD) as well as local stresses will be fully discussed in Sub-Task 1.4 (HAZ Modelling). Finally systematic results of the strength mismatch effect on local crack tip triaxial stress will be given (strength mismatch effect on local stresses). Therefore this report is complementary to those from Sub-Task 1.4, which will be a milestone report due June 1998.

Sub-Task 1.2 is also related to other activities outside the SINTAP, Fig. 6.1. It should be stressed that at present standard fracture toughness testing procedures for mismatched weldments are not yet available, although several standard bodies (such as ASTM, BritishStandards and ISO) are currently working on testing procedures for weldments. The results from Sub-Task 1.2, together with other Sub-Tasks in Task 1 will be a vital input to those standards.

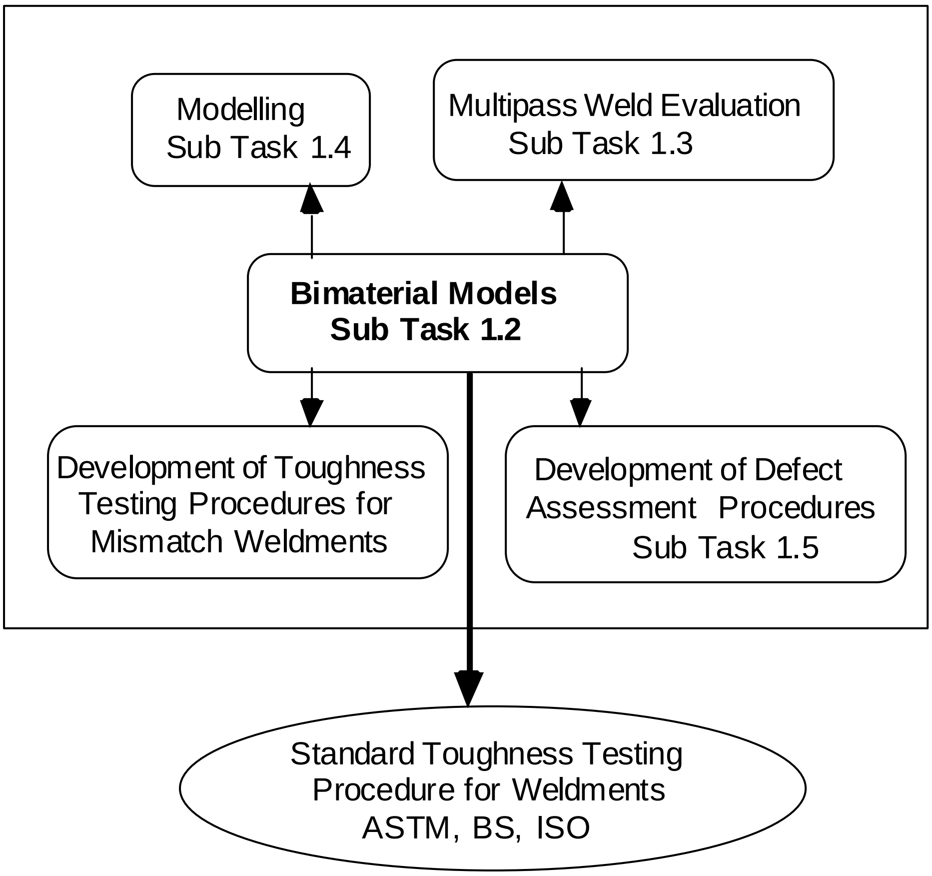


Fig. 5.1: *Links of Sub-Task 1.2 to other Sub-Tasks within Task 1 and to activities outside SINTAP consortium.*

8. CONCLUSIONS AND RECOMMENDATIONS

This report summarises the results from activities in SINTAP Sub-Task 1.2, bi-material testing programme, of which is to investigate the mis-match effect on fracture behaviour of bi-materials with the model welds. Within three institutes (AEA, UK; NE, UK; GKSS, DE), extensive experimental data have been generated for the past two years, which can be categorised as follows:

- mismatch effect at room temperature
    1. mismatch effect on fracture toughness for weld metal cracks
    2. mismatch effect on fracture toughness for HAZ cracks
- mismatch effect within ductile to brittle transition temperature
    3. mismatch effect on fracture toughness for weld metal cracks
    4. mismatch effect on fracture toughness for HAZ cracks

It has been found that at room temperature the strength mismatch affect fracture toughness (J, CTOD and d5) for both weld metal cracks and for HAZ cracks. Such effect is expected and can be explained from the mismatch effect on local triaxial stress at the crack tip. On the other hand, within ductile to brittle transition temperature, little effect of the strength mismatch on fracture toughness has been observed. Several possible reasons for this “unexpected” results are given in the text; the effect of J and CTOD estimation equations from bimaterial testing; the mismatch-related variables employed in testing (mismatch ratio and geometry parameter (W-a)/H); scatter within transition temperature. It is likely that, once analysis of the mismatch corrected J estimation within Sub-Task 1.4 activities is completed, the test results can be re-assessed to make conclusions concrete.

The results from Sub-Task 1.2 provide several outstanding issues, particularly related to toughness testing of weldments:

- Mismatch corrected J and CTOD estimation scheme

    This is an important issue in toughness testing of weldments. Two essential questions should be addressed. Firstly, how the current J and CTOD estimation equations should be modified specific to the strength mismatch? Secondly, if one accepts certain error in J and CTOD, under what conditions the currently codified J and CTOD estimation formulae (established based on homogeneous specimens) can be applied to mismatched specimens? Note that Sub-Task 1.4 will address this issue.

- Uniqueness of R-curve

  Related to the mismatch corrected J and CTOD estimation equation, it would be important to address whether one could obtain a unique resistance regardless of the strength mismatch. If so, the resistance curve behaviour of the homogeneous (base and weld metals) can be easily transferred to that of the bimaterial specimen. If not, then the question remains that under what conditions rather unique resistance curve can be obtained.

- Mismatch Effect on Local Stresses

  The mismatch effect on local triaxial stress states has been reported in Sub-Task 1.4, which will be included in a final report.

- HAZ modelling

  The HAZ crack behaviour is not only affected by global properties (such as global mismatch between the base and weld metal, geometry (W-a)/H etc.) but also sensitive to local properties (such as local mismatch between the HAZ and the weld metal, local microstructures). Thus full understanding of HAZ crack behaviour is certainly quite complex. The mismatch corrected J estimation equation will be addressed in Sub-Task 1.4, together with the mismatch effect on local triaxial stresses of interface cracks. Moreover, experimental works in Sub-Task 1.3 addressing the effect of global and local mismatch on HAZ crack behaviour would be vital to gain better understanding.

References

[1] ESIS Procedure for Determining the Fracture Behaviour of Materials, ESIS P2-92, January 1993.

[2] K.-H. Schwalbe, B.K. Neale and J. Heerens, “The GKSS test procedure for determining the fracture behaviour of materials EFAM GTP 94”, GKSS 94/E/60, GKSS Research Centre, Germany.

[3] Metallic materials - Unified method of test for the determination of quasistatic fracture toughness, ISO/CD 12135 (Rev 3), August 1997.

[3] K.-H. Schwalbe, R.A. Ainsworth, C. Eripret, Ch. Franco, Ph. Gilles, M. Kocak, H. Pisarski and Y.Y. Wang, “Common views on the effect of yield strength mismatch on testing and structural assessment”, Mismatching of Interfaces and Welds, Eds. K.-H. Schwalbe and M. Kocak, 1997, GKSS Research Centre Publications, Geesthacht, Germany, pp. 99-133.

[3] G. Lin, Y.-J. Kim, A. Cornec and K.-H. Schwalbe, “Fracture Simulation of Undermatched Interleaf in Bending Using a Cohesive Zone Model”, Mismatching of Interfaces and Welds, Eds. K.-H. Schwalbe and M. Kocak, 1997, GKSS Research Centre Publications, Geesthacht, Germany, pp. 343-356.

[3] J. Joch, R.A. Ainsworth and T.H. Hyde, “Limit load and J estimates for idealised problems of deeply cracked welded joints in plane strain bending and tension”, Fatigue Fract. Engrg. Mater. Struct. 16, 1061-1079 (1993).

[3] P. Hornet and C. Eripret, “Experimental J evaluation from a load-displacement curve for homogeneous and overmatched SENB and CCT specimens”, Fatigue Fract. Engrg. Mater. Struct. 26, 679-692 (1995).

[3] Y.-Y. Wang, M.T. Kirk, J.R. Gordon, P. Hornet and C. Eripret, “Recommended Practice for Fracture Toughness Testing of Weldments with Strength Mismatch”, Mismatching of Interfaces and Welds, Eds. K.-H. Schwalbe and M. Kocak, 1997, GKSS Research Centre Publications, Geesthacht, Germany, pp. 281-294.

[3] K. Michiba, H. Hiramatsu, H. Hasegawa, H. Matsumara and M. Toyoda, “An experimental study on the behaviour of stable crack growth in heterogeneity, Ed. M. Toyoda, 2nd Workshop on Constraint Effects on Structural Performance of Welded Joints, Osaka University, 1994.

[3] Yun-Jae Kim, unpublished works

Nomenclature

a	crack length
B	thickness of specimen
CCT	centre cracked tensile
CTOD	Crack tip opening displacement based on British Standard
E	Young's modulus
EB	electron beam
F	applied load
H	half height of weld metal strip
HAZ	Heat Affected Zone
J	J-integral without mismatch correction (based on standardised homogeneous procedure)
J_{MM}	J-integral with mismatch correction
M	mis-match factor s_{YW}/s_{YB}
OM	Overmatching
SENB	Single-edge-notched specimens in three point bending
UM	Undermatching
UTS	Ultimate tensile stress
W	(half) width of specimen
d_5	crack tip opening displacement defined for a gauge length of 5 mm
s_Y	yield strength

Subscripts

B	referring to base plate
M	referring to mis-match configuration
W	referring to weld metal