

British Energy Generation Ltd

Experimental Validation of the SINTAP Procedure for Strength Mis-Match

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SUMMARY

This report addresses experimental validation of the mismatch procedure resulting from the Brite Euram project, SINTAP (Structural Integrity Assessment Procedure for European Industry). It uses experimental data for mis-matched specimens with idealised weldments from tests performed at AEA Technology. Category 3 (ductile tearing) analyses are performed for both weld metal cracks and HAZ cracks, and predicted maximum loads are compared with the experimentally measured ones. It should be noted that plastic collapse is the dominant failure mechanism for all the tests analysed, and thus the mis-match corrected limit load is a crucial factor in the assessment.

The following conclusions can be drawn from the present validation work, regarding the accuracy of the SINTAP level 3 curve.

- For overmatched specimens with weld metal cracks, the predicted maximum loads are conservative only by ~10%. Such conservatism is likely to result from that involved in the level 3 curve for bend geometries in the presence of Lüders strain. For undermatched specimens with weld metal cracks, on the other hand, specimens failed by complete plastic collapse, and the resulting maximum loads are determined when the tearing locus just touches the L_r^{max} line. The resulting conservatism increases up to ~20%. However, if the failure assessment curve were extended beyond L_r^{max} , a similar level of conservatism to that for overmatching could be expected.
- For HAZ cracks, the conservatism increases to ~30%. Such higher conservatism results from two possible sources. One is a conservative estimate of the limit load, which is rather specific to the present problem. Another source would be a conservative estimate of the J integral for interface cracks, which is general to defect assessment of interface or HAZ cracks.
- In general, the present results strongly support the SINTAP methodology for strength mis-matched structures. It also shows that the assessment of the interface or HAZ cracks gives more conservative results than that of the weld metal cracks. Thus, further investigation on assessment of interface cracks would be required to reduce conservatism.

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NOMENCLATURE

a_o	Initial crack size
a	Crack length
a_j	$=a_o + \Delta a_j$
Δa	Extent of ductile crack growth
Δa_j	Postulated amount of ductile crack growth
B	Specimen thickness
B_N	Specimen net-section thickness
E	Young's modulus
E'	$=E/(1-\nu^2)$ for plane strain; $=E$ for plane stress
h	Half height of weld metal strip
J	J -integral
$J_{0.2}$	Toughness value of J relating to the initiation of ductile tearing
J_e	Elastically calculated value of J , $J_e = K^2/E'$
K_I	Mode I linear elastic stress intensity factor
K_r	Measure of proximity to LEFM failure
$K_{\Omega}(\Delta a)$	Fracture toughness after amount Δa of ductile crack growth
L_r	Measure of proximity to plastic yielding
L_r^{max}	Material property defining the cut-off on the FAD
M	Strength mis-match ratio defined at 0.2% proof stress, $M = \sigma_{yw}/\sigma_{yb}$
$M(\epsilon^p)$	Strength mis-match ratio defined at plastic strain ϵ^p , $M(\epsilon^p) = \sigma_w(\epsilon^p)/\sigma_b(\epsilon^p)$
P	Scalar representing magnitude of primary loading
P_{Lb}	Plastic collapse load for component composed totally of base material b
P_{Lmis}	Plastic collapse load allowing for strength mis-match
w	Specimen width or semi-width
ϵ	Strain
ϵ_e	Strain at stress $L_r \sigma_{ye}$ on equivalent stress strain curve
ϵ^p	Plastic strain
ν	Poisson's ratio
σ	Applied stress
σ_y	Yield strength or 0.2% proof stress
σ_{yb}	0.2% proof stress for base material b
σ_{yw}	0.2% proof stress for weld material w
σ_{ye}	0.2% proof stress for equivalent material
$\bar{\sigma}_e$	Flow stress for equivalent material
σ_u	Ultimate tensile stress
σ_{ub}	Ultimate tensile stress for base material b
σ_{uw}	Ultimate tensile stress for weld material w
$\sigma_b(\epsilon^p)$	Stress at plastic strain ϵ^p for base material b
$\sigma_e(\epsilon^p)$	Stress at plastic strain ϵ^p for equivalent material
$\sigma_w(\epsilon^p)$	Stress at plastic strain ϵ^p for weld material w
ψ_o	Normalised initial remaining ligament, $(w-a_o)/h$
ψ	$=(w-a)/h$
ψ_j	$=(w-a_j)/h$

Abbreviations

CT	Compact tension
EB	Electron beam
EM	Evenmatching
HAZ	Heat affected zone
OM	Overmatching
SENB	Single edge notched specimen in three point bend
UM	Undermatching

1. INTRODUCTION

Within the Brite Euram project, SINTAP (Structural Integrity Assessment Procedure for European Industry), a procedure to assess defects in welded structures with substantial strength mis-match has been produced. The underlying idea is to modify existing procedure for homogeneous structures, such as the R6 procedure [Ref. 1], to incorporate the strength mis-match effect in the vicinity of a crack. Two major modifications include the use of the mis-match corrected collapse load and an equivalent material concept or a mismatch hardening exponent.

As far as validation of the procedure is concerned, finite element validation has been reported [Refs. 2-4]. However, experimental validation of the procedure is currently lacking. For this purpose, experiments were performed at AEA Technology (AEAT), involving testing of mis-matched specimens with idealised weldments [Refs. 5,6].

This report addresses experimental validation of the SINTAP procedure for strength mis-matched structures, using the AEAT test data. It covers two cases of crack locations, weld metal cracks and heat affected zone (HAZ) cracks. Section 2 summarises AEAT testing of strength mis-matched specimens. Section 3 provides comparison and discussion of the predicted maximum loads from SINTAP ductile tearing analyses with the experimentally measured maximum loads. Section 4 contains conclusions of the present report. Finally status notes are given in Section 5.

2. SUMMARY OF AEAT MIS-MATCHED SPECIMEN TESTING

In this programme, an A533B-1 steel material was heat-treated to produce two material types with different yield and ultimate strength values. Mean tensile strength data for those two materials are given in **Table 1**. The yield strength of the higher strength material (designated as M1 material) is about 50% higher than that of the lower strength material (designated as M3 material). It should be noted that the M3 material exhibits Lüders strain of about 0.8%. Although the M1 material does not show any Lüders plateau, the stress strain curve is quite flat at small strains, due to the high yield strength and low hardening capacity.

Strength mis-matched specimens with idealised weldments were produced by electron-beam (EB) welding, and were given a stress relief heat treatment to minimise any residual stress effects due to the EB welding. Resulting hardness profiles across the weldment are shown schematically in **Figs. 1 and 2**. It should be noted that the EB zone and the associated heat-affected-zone (HAZ) have much higher strengths (**Table 1**) and their sizes are not negligible. It will be shown later in Section 3 that consideration of such zones is essential to determine the weld width, h , which is an important parameter for the procedure.

Fracture toughness testing was carried out using compact tension (CT) specimens for homogeneous materials, but using single-edge-notch bend (SENB) specimens for mismatched specimens. In all cases, deep cracks ($a/w=0.45$ and 0.65) were used with total 20% side grooves. The testing matrix is shown in **Table 2**. Detailed information on the testing can be found in two AEAT reports [Refs. 5,6], and further relevant information will be given in the subsequent sections. For the case of the weld metal crack, where the crack is

in the middle of the weld, two different strength mis-matched specimens were tested (**Table 2**): highly over-matched (strength mismatch ratio based on the yield strength, $M = \sigma_{yw}/\sigma_{yb} \approx 1.48$) and highly under-matched ($M \approx 0.67$) specimens. Similarly, for the HAZ crack, two different strength mis-matched specimens were tested (**Table 2**).

3. VALIDATION : DUCTILE TEARING ANALYSIS

The SINTAP procedure for strength mis-match contains a number of steps as set down in Sections 3.1-5 below. For the SINTAP level 2 analysis, appropriate when only yield and tensile strengths of both weld and base materials are known, explicit equations are given in the procedure, which will be given in Section 3.2. For the level 3 analysis, appropriate when full stress-strain data are available, however, an equivalent stress-strain curve should be found, which is given below.

3.1 Define Tensile Properties for an Equivalent Material (only for Level 3 Analysis)

Using uniaxial stress-strain data for the M1 and M3 materials, an equivalent stress-plastic strain curve, $\sigma_e(\epsilon^p)$, is defined as

$$\begin{aligned} \sigma_e(\epsilon^p) &= \frac{(P_{Lmis}/P_{Lb} - 1) \cdot \sigma_w(\epsilon^p) + (M - P_{Lmis}/P_{Lb}) \cdot \sigma_b(\epsilon^p)}{(M - 1)} \\ &= \frac{P_{Lmis}}{P_{Lb}} \cdot \sigma_b(\epsilon^p) \end{aligned} \quad (1)$$

Note that in eqn. (1) the mis-match ratio M is defined at a number of plastic strain values, ϵ^p , as $M(\epsilon^p) = \sigma_w(\epsilon^p)/\sigma_b(\epsilon^p)$, and the limit load P_{Lb} denotes that for the component composed totally of the base material. To determine the equivalent stress-plastic strain curve, the values of $M(\epsilon^p)$ at a number of plastic strain, ϵ^p , should be found from uniaxial stress-strain data of the two materials. Then P_{Lmis}/P_{Lb} should be found for the values of $M(\epsilon^p)$, as described below.

3.1.1 Weld Metal Cracks

The values of P_{Lmis}/P_{Lb} for **plane strain** SENB specimens can be found in [Ref. 7]. For $M(\epsilon^p) > 1$,

$$\frac{P_{Lmis}}{P_{Lb}} = \begin{cases} M & \text{for } 0 \leq \psi \leq \psi_1 \\ C_1 + C_2 \cdot \frac{\psi_1}{\psi} + C_3 \left(\frac{\psi_1}{\psi} \right)^M & \text{for } \psi_1 \leq \psi \end{cases} \quad (2)$$

where $C_1 = \frac{M + 49}{50}$; $C_2 = \frac{49(M - 1)}{50} - C_3$; $C_3 = 0.3(M - 1)\sqrt{M - 1}$; $\psi_1 = 2e^{-(M-1)/8}$.

For $M(\epsilon^p) < 1$,

$$\frac{P_{Lmis}}{P_{Lb}} = \begin{cases} M & \text{for } 0 \leq \psi \leq 2 \\ \min\left(\frac{P_{Lmis}^{(1)}}{P_{Lb}}, \frac{P_{Lmis}^{(2)}}{P_{Lb}}\right) & \text{for } 2 \leq \psi \end{cases} \quad (3)$$

where

$$\frac{P_{Lmis}^{(1)}}{P_{Lb}} = \frac{M}{1.22} \cdot \left[1.22 + 1.724 \left(\frac{\psi - 2}{10} \right)^2 - 0.944 \left(\frac{\psi - 2}{10} \right)^3 \right]$$

$$\frac{P_{Lmis}^{(2)}}{P_{Lb}} = \frac{9(M-1)}{10} \cdot e^{-(\psi-2)/20(1-M)} + \frac{M+9}{10}.$$

It should be noted that P_{Lmis}/P_{Lb} can be quite sensitive to $\psi=(w-a)/h$ particularly for $2 < \psi < 5$ (which is in the present case), and thus determination of the weld width, h , needs particular attention. **Figure 1** shows schematically how to determine the value of h for under- and over-matched specimens. The hardness profiles suggest that $h \approx 13\text{mm}$ for the over-matched specimens, but $h \approx 4\text{mm}$ for the under-matched specimens. The resulting values of $\psi_o=(w-a_o)/h$ are summarised in **Table 3**.

3.1.2 HAZ Cracks

In the tests, the cracks were placed in the HAZ, 1mm from the fusion boundary (**Fig. 2**). The limit load solutions in such cases are currently not available. In the present analysis, one assumption is made: the crack is assumed to be in the interface of the M3 material and the EB zone (**Fig. 2b**). Such an assumption gives a conservative estimate of the limit load, since plastic deformation in the much higher strength HAZ is neglected. To evaluate the mismatch limit load, P_{Lmis}/P_{Lb} , and thus the tensile data for the equivalent material from eqn. (1), there still remains one problem: the detailed tensile properties of the EB and the associated HAZ are not available. However, the relevant dimensions shown in **Fig. 2b**, together with available mismatch limit load solutions in [Ref. 7], suggest that the specimen can be idealised by bimaterial specimens with interface cracks with sufficient strength mismatch (**Fig. 2c**). The limit load solutions, P_{Lmis} , can be then determined from [Ref.7]

$$P_{Lmis} = 1.06 \cdot P_{L(M3)} \quad (4)$$

where $P_{L(M3)}$ denotes the limit load for the component composed totally of the M3 material.

Once M and P_{Lmis}/P_{Lb} are found at a number of plastic strain values, ϵ^P , the tensile data for the equivalent material can be found, as shown in **Fig. 3a-3b** for weld metal cracks and in **Fig. 3c** for HAZ cracks. For over-matched specimens with weld metal cracks, the tensile data for the equivalent material reduces to that for the weld material (M1). The reason is that for bend specimens with $\psi < 2$, the strength mis-match effect is minimal and thus the mis-matched specimen can be treated as an all-weld-metal specimen. The equivalent material's properties for HAZ cracks are very close to those of the M3 material. On the other hand, for under-matched specimens, the initial value of ψ , ψ_o , ranges from 4.0 to 6.29, and thus the strength mis-match effect is not negligible.

The tensile data for the equivalent material also provide the yield stress, σ_{ye} , and the flow stress, $\bar{\sigma}_e$, for the equivalent material, which will be used in the next sub-section to determine the cut-off, $L_r^{\max}$.

3.2 Define the Failure Assessment Diagram (FAD)

For the level 2 analysis (when both weld and base materials exhibit Lüders strain), the FAD line is constructed by the equation

$$K_r = f(L_r) = \left(1 + \frac{1}{2} \cdot L_r^2\right)^{-1/2} \quad \text{for } L_r = 1 \quad (5-1)$$

At $L_r=1$, the function $f(L_r)$ is taken as discontinuous and reduces to the value of $f(1)$,

$$\begin{aligned} K_r = f(1) &= \left(\lambda_M + \frac{1}{2\lambda_M}\right)^{-1/2} \\ \lambda_M &= \frac{(P_{Lmis}/P_{Lb} - 1)\lambda_w + (M - P_{Lmis}/P_{Lb})\lambda_b}{(M - 1)} \\ \lambda_w &= 1 + \frac{E_w \Delta \epsilon_w}{\sigma_{yw}} \quad ; \quad \Delta \epsilon_w = 0.0375 \left(1 - \frac{\sigma_{yw}}{1000}\right) \\ \lambda_b &= 1 + \frac{E_b \Delta \epsilon_b}{\sigma_{yb}} \quad ; \quad \Delta \epsilon_b = 0.0375 \left(1 - \frac{\sigma_{yb}}{1000}\right) \end{aligned} \quad (5-2)$$

For $L_r > 1$,

$$\begin{aligned} K_r = f(L_r) &= f(1) \cdot (L_r)^{(N_M - 1)/2N_M} \\ N_M &= \frac{(M - 1)}{(P_{Lmis}/P_{Lb} - 1)/N_w + (M - P_{Lmis}/P_{Lb})/N_b} \\ N_w &= 0.3 \left(1 - \frac{\sigma_{yw}}{\sigma_{uw}}\right) \quad ; \quad N_b = 0.3 \left(1 - \frac{\sigma_{yb}}{\sigma_{ub}}\right) \end{aligned} \quad (5-3)$$

The level 3 curve is constructed using the equivalent stress-strain curve, obtained from Section 3.1, by the equations

$$K_r = \begin{cases} \left(\frac{E \epsilon_e}{L_r \sigma_{ye}} + \frac{L_r^3 \sigma_{ye}}{2E \epsilon_e}\right)^{-1/2} & \text{for } L_r \leq L_r^{\max} \\ 0 & \text{for } L_r > L_r^{\max} \end{cases} \quad (5-4)$$

where ϵ_e is the true strain obtained from the uniaxial stress-strain curve for the equivalent material at a true stress $L_r \sigma_{ye}$. The cut-off $L_r^{\max}$ is determined by

$$L_r^{\max} = \begin{cases} \frac{1}{2} \left(1 + \frac{0.3}{0.3 - N_M}\right) & \text{for Level 3} \\ \frac{\bar{\sigma}_e}{\sigma_{ye}} & \text{for Level 3} \end{cases} \quad (6)$$

with the values of $\bar{\sigma}_e$ and σ_{ye} determined in Section 3.1. The resulting FAD option 2 curves are shown in **Figs. 4a-4d** for weld metal cracks and **Figs. 4e-4f** for HAZ cracks.

3.3 Determination of Fracture Toughness, K_{mat}

3.3.1 Weld Metal Cracks

Fracture toughness values for the M1 and M3 materials have been determined from the homogeneous CT specimens (**Table 1**). **Table 4** lists the coefficients of off-set power law fits to the data, together with $J_{0.2}$ initiation values:

$$J(\Delta a) = a_1 + a_2 (\Delta a)^m \quad (7)$$

It should be noted that for validation purposes, the best fit to two data sets is used, instead of the lower one. The resulting fits are compared with the test data in **Fig. 5a**. For the category 3 analysis, the $J(\Delta a)$ data are converted to $K_{\Omega}(\Delta a)$ using

$$K_{\Omega}(\Delta a) = \sqrt{\frac{E \cdot J(\Delta a)}{(1 - \nu^2)}} \quad (8)$$

3.3.2 HAZ Cracks

For the assessment of defects, the toughness of the material where the crack is located should be used. In the present work, the HAZ toughness is taken as that from the composite specimen (M3 material EB welded between M3 plates; 3HE3E3, see **Table 2** and **Fig. 2d**). The resulting resistance curve is shown in **Fig. 5b**, together with the power-law fit given in **Table 4**. Again, the best fit to three data sets is used here. It shows that the toughness of HAZ is very close to that of M1 material.

3.4 Calculation of L_r

The values of L_r are calculated by

$$L_r = \frac{P}{P_{Lmis}(a_j)} \quad (9)$$

The values of $P_{Lmis}(a_j)$ at some discrete values of crack length a_j can be determined from the relevant equations given in Section 3.1; for weld metal cracks, eqn. (2) for over-matched specimens, and eqn. (3) for under-matched specimens; for HAZ cracks, eqn. (4). It should be noted that the change of ψ , denoted by $\psi_j = (w - a_j)/h$, due to changes in crack length a_j should be taken into account to determine $P_{Lmis}(a_j)$.

3.5 Calculation of K_r

For a category 3 analysis in the absence of secondary stresses, values of K_r can be calculated by

$$K_r = \frac{K_I(a_i)}{K_{\Omega}(\Delta a_j)} \quad (10)$$

The fracture toughness $K_{I\Omega}(\Delta a_j)$ was determined in Section 3.3. For SENB specimens, the following expression according to the testing standards is used to calculate the values of the stress intensity factor $K_I(a_j)$

$$K_I = \left[\left(\frac{S}{w} \right) \frac{P}{\sqrt{B \cdot B_N \cdot w}} \right] \cdot g \left(\frac{a}{w} \right) \quad (11)$$

$$g \left(\frac{a}{w} \right) = 3 \sqrt{\frac{a}{w}} \cdot \left[\frac{1.99 - (a/w) \cdot (1 - a/w) \{ 2.15 - 3.93(a/w) + 2.7(a/w)^2 \}}{2(1 + 2a/w)(1 - a/w)^{1.5}} \right]$$

3.6 Results and Discussion

To predict the maximum load, P_{max} , ductile tearing analysis is used. The tearing loci resulting from the analysis are shown in **Fig. 4**. The maximum loads are typically determined when the locus satisfies the tangency condition to the failure assessment curve, as shown in **Fig. 4**. The figure also includes the results (maximum loads) from the experiments (see also **Table 3**). For weld metal cracks, both level 2 and 3 curves are shown for comparison.

For weld metal cracks, the results from the level 3 curves are less conservative, compared to those from the level 2 curve, as expected, which is summarised in **Fig. 6a**. Concerning the level 3 curve, for overmatched specimens, the resulting predictions are conservative only by 10% (**Fig. 6a**). Such conservatism is likely to result mainly from the conservatism in the assessment curve for bend geometries, in particular for materials with Lüders strain. For undermatched specimens, however, the tangency condition occurs beyond $L_r = L_r^{max}$, implying that failure is dominated by complete plastic collapse. Such behaviour can happen in typical laboratory test specimens. As summarised in **Fig. 6**, the conservatism increases up to 20%. However, if the failure assessment curve were extended beyond L_r^{max} , a similar level of conservatism to that for overmatching could be expected. Therefore, the present results strongly support the SINTAP methodology for mis-match.

For HAZ cracks, the results are shown only for the level 3 analysis, showing that the predictions are slightly more conservative than those for weld metal cracks. One possible reason is the conservative estimate of the limit load in the analysis, due to neglecting plastic deformation in the higher strength HAZ (see Section 3.1.2). Another possible source of such higher conservatism is conservatism involved in the J integral estimation for interface cracks [Ref. 8]. It has been shown that, for interface cracks, the J estimation assuming the lower strength material properties provides the conservative result. This aspect is general to interface (HAZ) crack problems, and thus should be looked at further. One test for HAZ cracks failed in an unstable manner just after initiation (see **Table 3**). **Figure 4f** shows that the predicted maximum load is the same as the initiation load, and thus the SINTAP procedure still gives a conservative prediction.

4. CONCLUSIONS

This report addresses experimental validation of the SINTAP procedure for strength mis-matched structures. It uses experimental data for mis-matched specimens with idealised weldments from tests performed at AEA Technology [Refs. 5,6]. Ductile tearing analyses are performed for both weld metal cracks and HAZ cracks, and predicted maximum loads are compared with the experimentally measured ones. It should be noted that plastic collapse is

the dominant failure mechanism for all the tests analysed, and thus the mis-match corrected limit load is a crucial factor in the assessment.

The following conclusions can be drawn from the present validation work, regarding the accuracy of the SINTAP level 3 curve.

- For overmatched specimens with weld metal cracks, the predicted maximum loads are conservative only by ~10%. Such conservatism is likely to result from that involved in the level 3 curve for bend geometries in the presence of Lüders strain. For undermatched specimens with weld metal cracks, on the other hand, specimens failed by complete plastic collapse, and the resulting maximum loads are determined when the tearing locus just touches the L_r^{max} line. The resulting conservatism increases up to ~20%. However, if the failure assessment curve were extended beyond L_r^{max} , a similar level of conservatism to that for overmatching could be expected.
- For HAZ cracks, the conservatism increases to ~30%. Such higher conservatism results from two possible sources. One is a conservative estimate of the limit load, which is rather specific to the present problem. Another source would be a conservative estimate of the J integral for interface cracks, which is general to defect assessment of interface or HAZ cracks.
- In general, the present results strongly support the SINTAP methodology for strength mis-matched structures. It also shows that the assessment of the interface or HAZ cracks gives more conservative results than that of the weld metal cracks. Thus, further investigation on assessment of interface cracks would be required to reduce conservatism.

5. STATUS NOTES

Although the present validation examples provide confidence in the SINTAP procedure for strength mis-matched structures, further validation work is necessary. Experimental data resulting from other sources should be analysed as they become available. Those data may be able to cover fracture-dominated failure cases, whereas the data in the present analysis are dominated by plastic collapse.

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Table 1. Mean tensile data for two base materials and HAZ.

Material	σ_y (MPa)	σ_u (MPa)	Elongation (%)	Reduction in area (%)
M1	738	849	16.4	63.5
M3	497	647	24.7	69.0
HAZ	880*	920*	N/A	N/A

* These values were inferred from the hardness measurements.

Table 2. Information on test matrix.

	Specimen Code	Mis-match ratio (M)		Test specimen* $w(\text{mm}) \times B(\text{mm})$		a/w	No. of Tests
Homo-geneous	M1			CT	40x20	0.65	2
	M3			CT	40x20	0.65	2
Weld Metal Crack	3E1E3	OM	1.48	SENB	40x25	0.45	3
						0.65	3
	1E3E1	UM	0.67	SENB	40x25	0.45	3
						0.65	3
HAZ Crack	3HE3E3	EM		SENB	27.5x20	0.45	2
						0.65	1
	1HE3E1	UM	0.67	SENB	27.5x20	0.45	3
						0.65	3

* All specimens are side grooved by a total of 20%

OM Over-matching; UM Under-matching; EM Even-matching

Table 3. Information on test results of mis-matched specimens.

		a_o/w	$\psi_o = (w - a_o)/h$	Max. Load, P_{max} (kN)
Weld Metal Crack	OM, 3E1E3	0.65	~1.08	26.0, 24.9, 25.0
		0.45	~1.69	60.8, 61.5, 61.5
	UM 1E3E1	0.65	~4.0	22.5, 22.0, 21.5
		0.45	~6.29	55.4, 53.8, 54.8
HAZ Crack	1HE3E1	0.65	~2.14	14.2, 11.8*, 13.9
		0.45	~3.36	31.4, 31.1, 31.0

* Unstable crack growth

Table 4. Information on toughness data used in the present analysis: homogeneous base materials (M1 and M3) and HAZ (3HE3E3). Note that these data are the best estimate, not the lower bound. Moreover, no crack growth correction was applied in the test.

	$J(\Delta a)$ (MPa.m)			$J_{0.2}$ (MPa.m)
	a_1	a_2	m	
M1	0.0944	0.0954	0.7785	0.1216
M3	-0.0271	0.3108	0.4008	0.1360
HAZ, 3HE3E3	0.072	0.1234	0.6200	0.1174

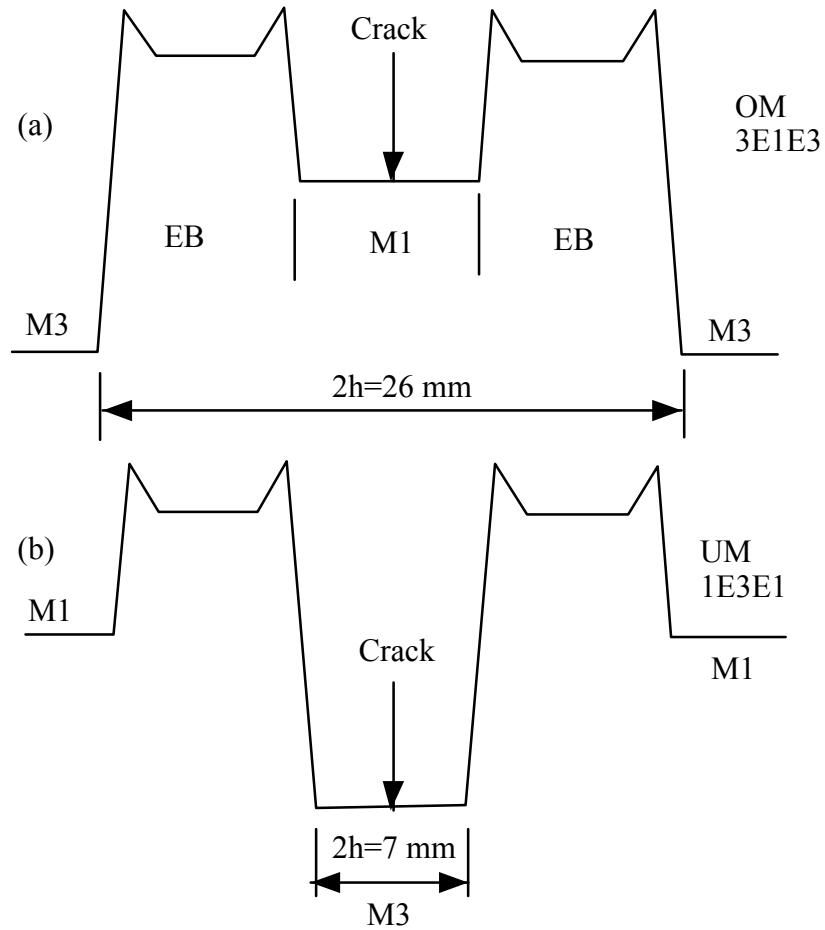


Fig. 1: Schematic figure of hardness profiles in mismatched specimens with weld metal cracks: (a) overmatched specimens, and (b) undermatched specimens. The figure also shows the location of the cracks, and how to determine the value of $2h$.

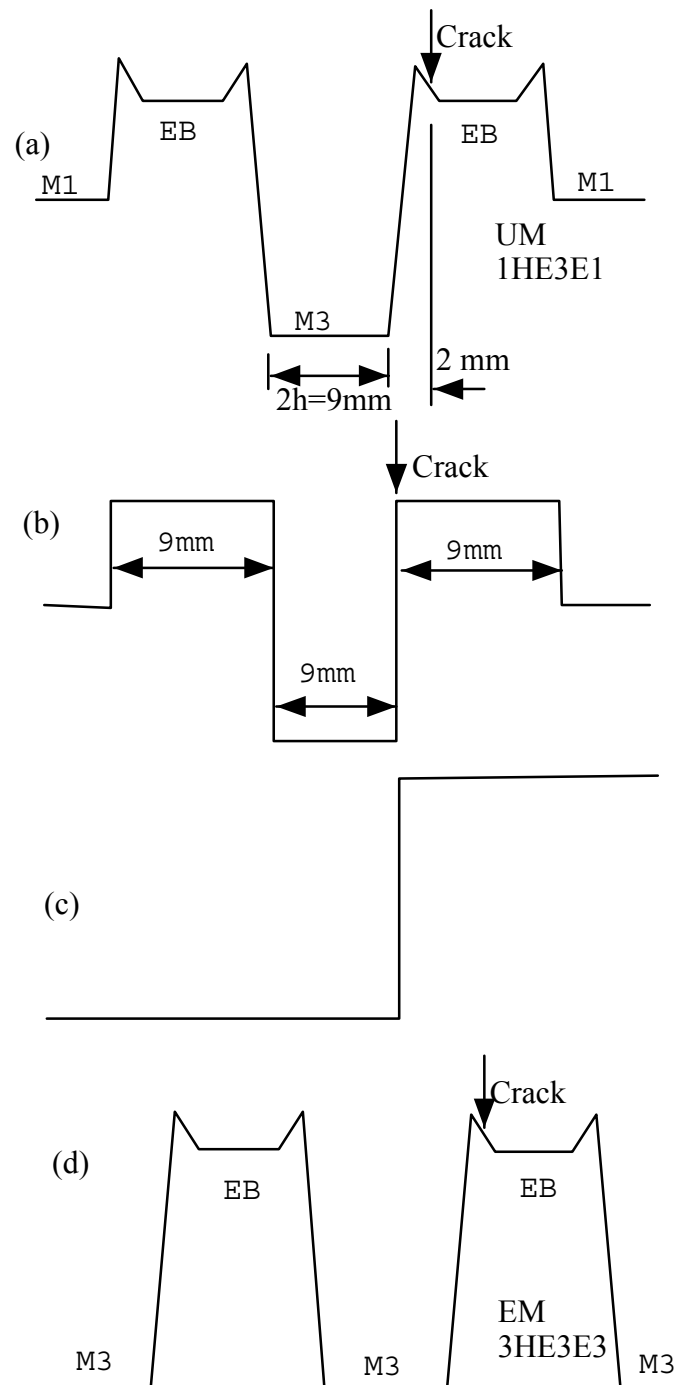


Fig. 2: Schematic figure of hardness profiles in mismatched specimens with HAZ cracks: (a) undermatched specimens; (b) idealisation of undermatched specimens for present analysis; (c) bimaterial specimens equivalent to the specimen (b); (d) evenmatched HAZ specimen for toughness determination. The figure also shows the location of the cracks, and how to determine the value of $2h$.

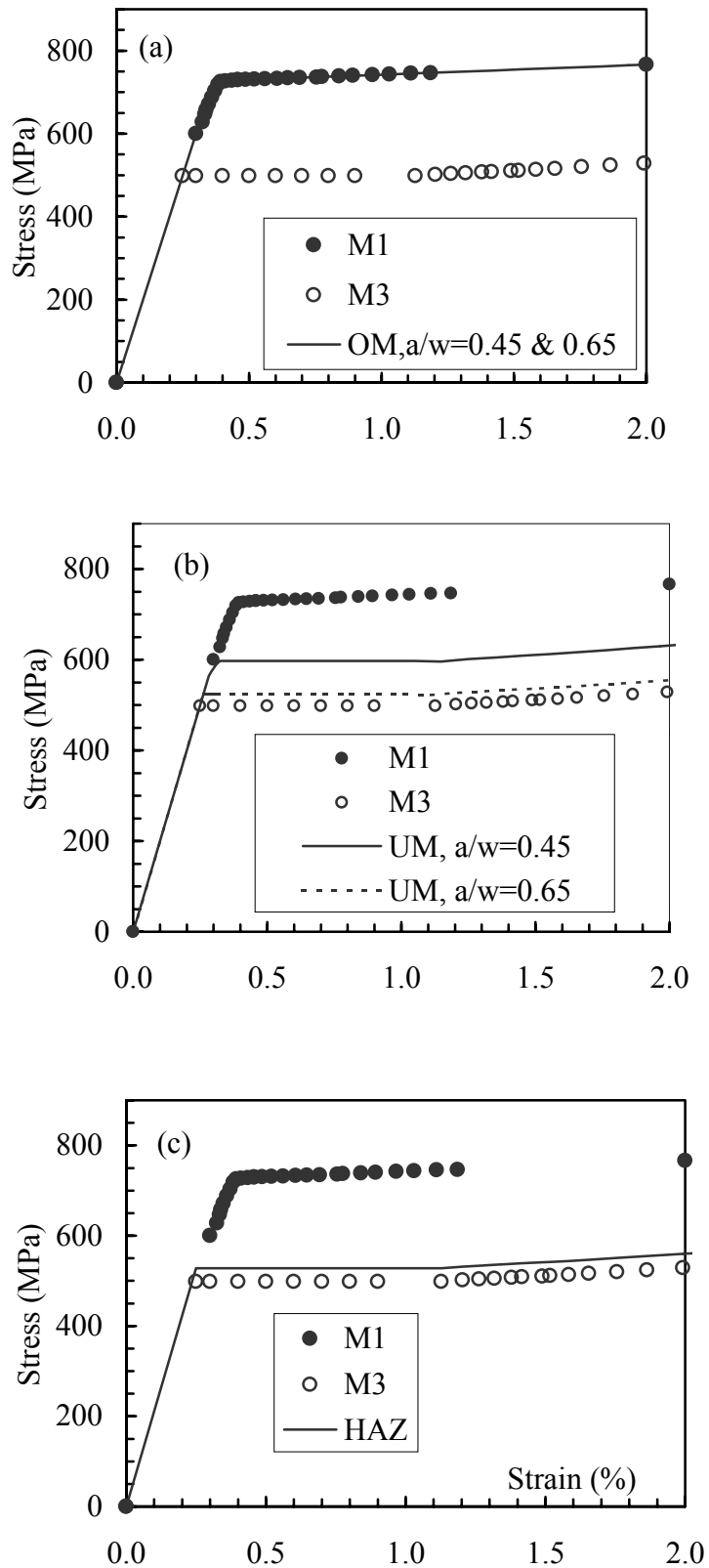


Fig. 3: Tensile properties of base materials and equivalent material; weld metal cracks with (a) over-matching and for (b) under-matching; (c) HAZ cracks.

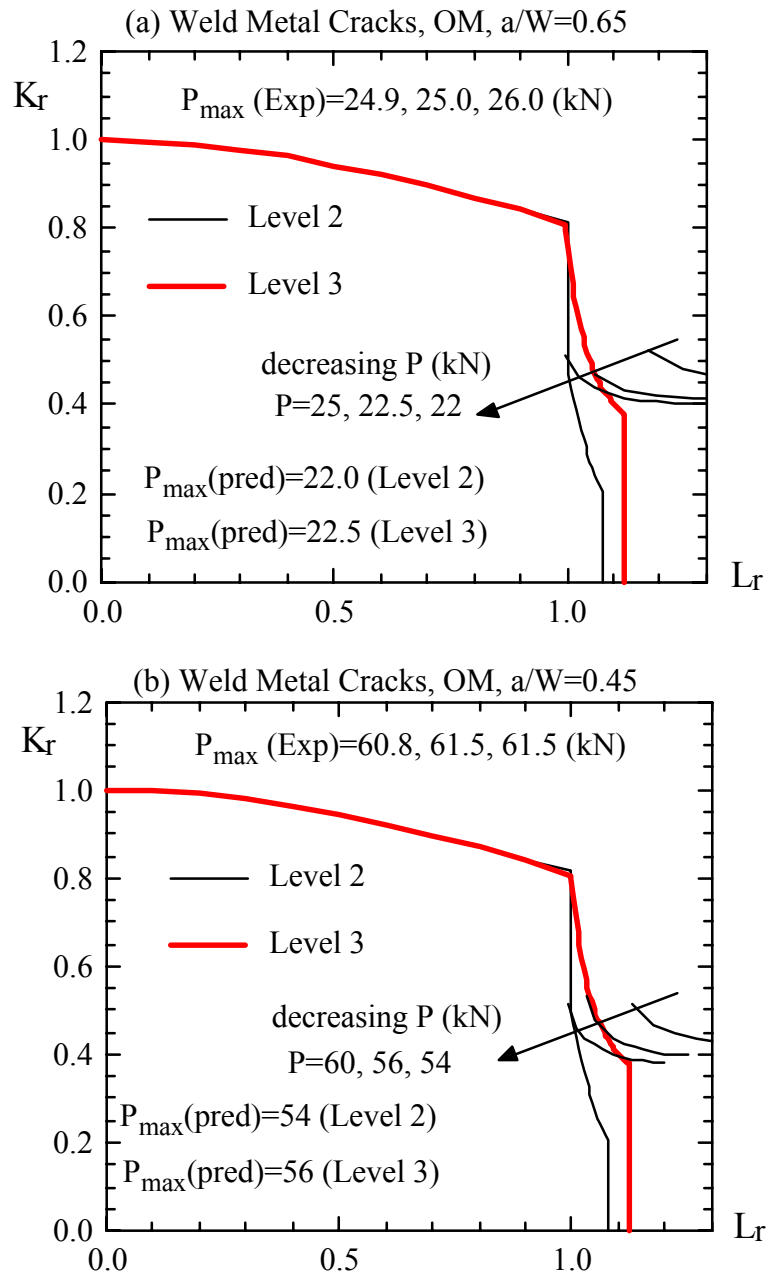


Fig. 4: SINTAP level 2 and 3 FADs and determination of maximum load from ductile tearing analysis. Figures also include experimentally measured maximum load.

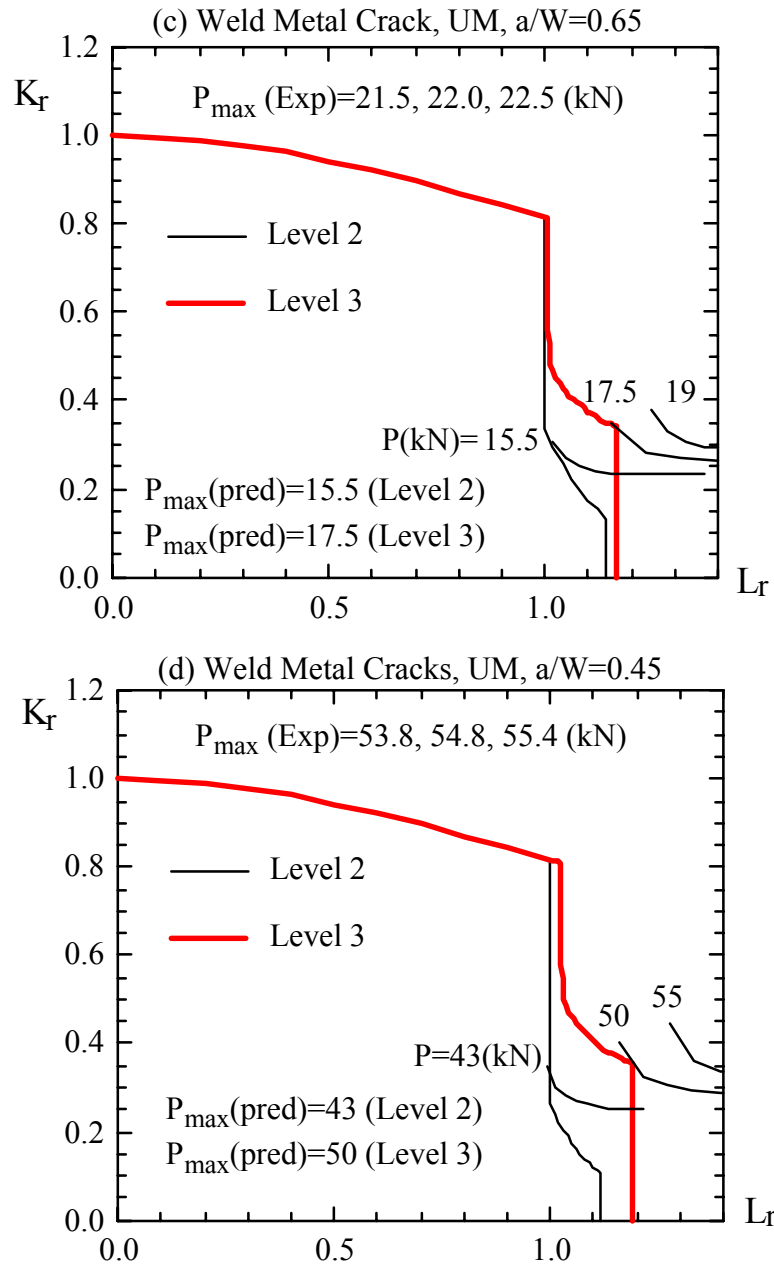


Fig. 4 (cont'd)

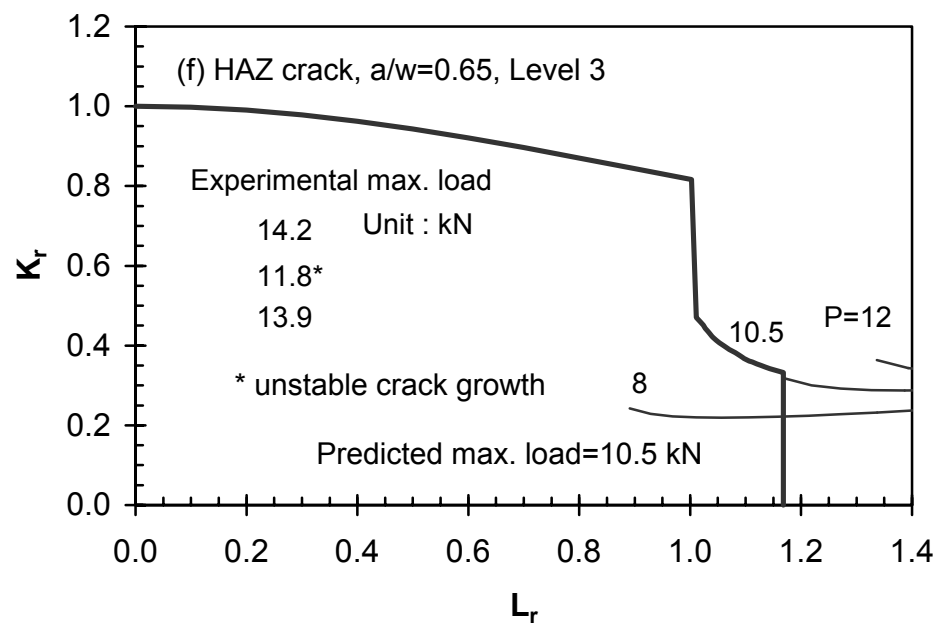
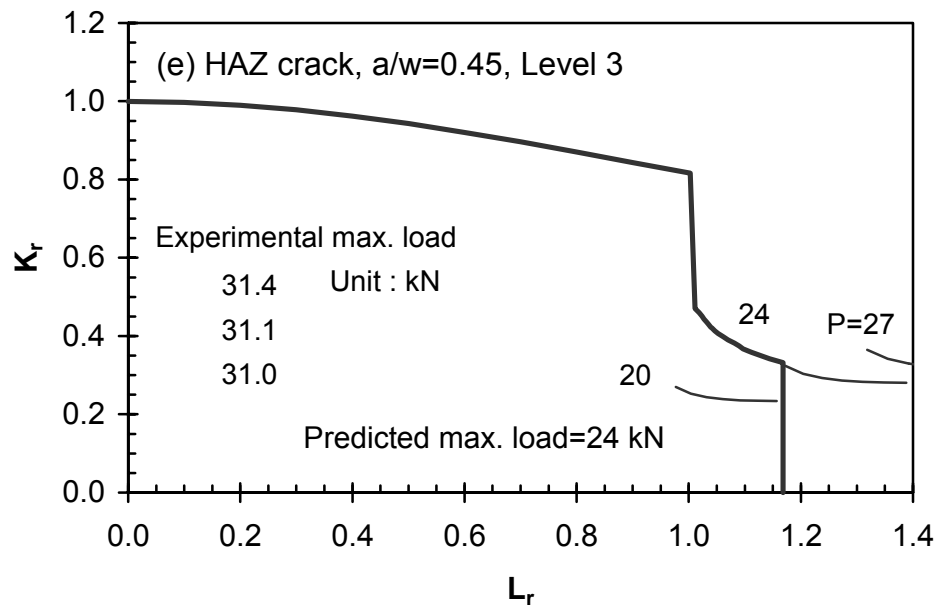


Fig. 4 (cont'd)

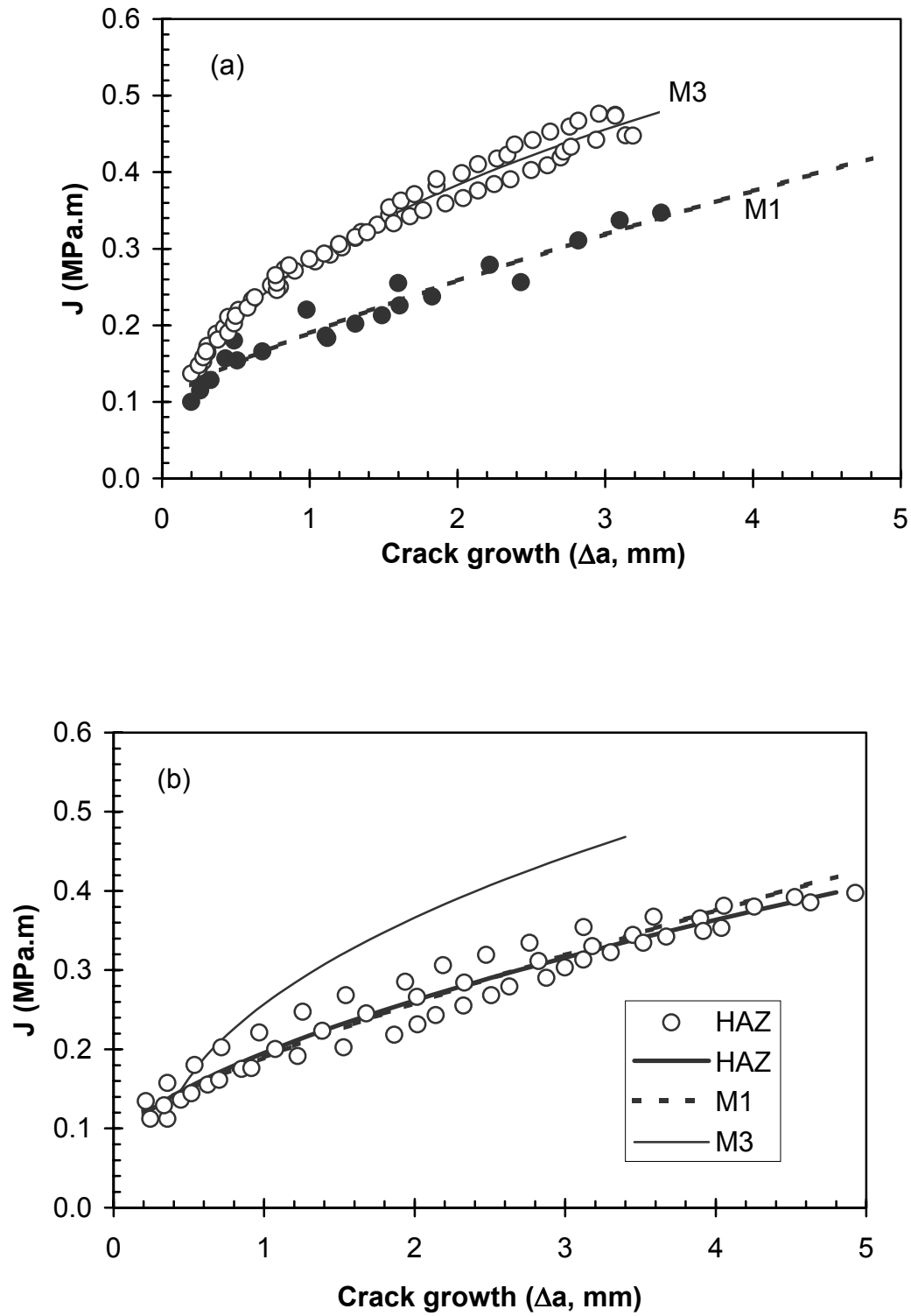


Fig. 5: J-resistance curves of base materials and HAZ. Circles show experimental data and lines show the corresponding off-set power law fits.

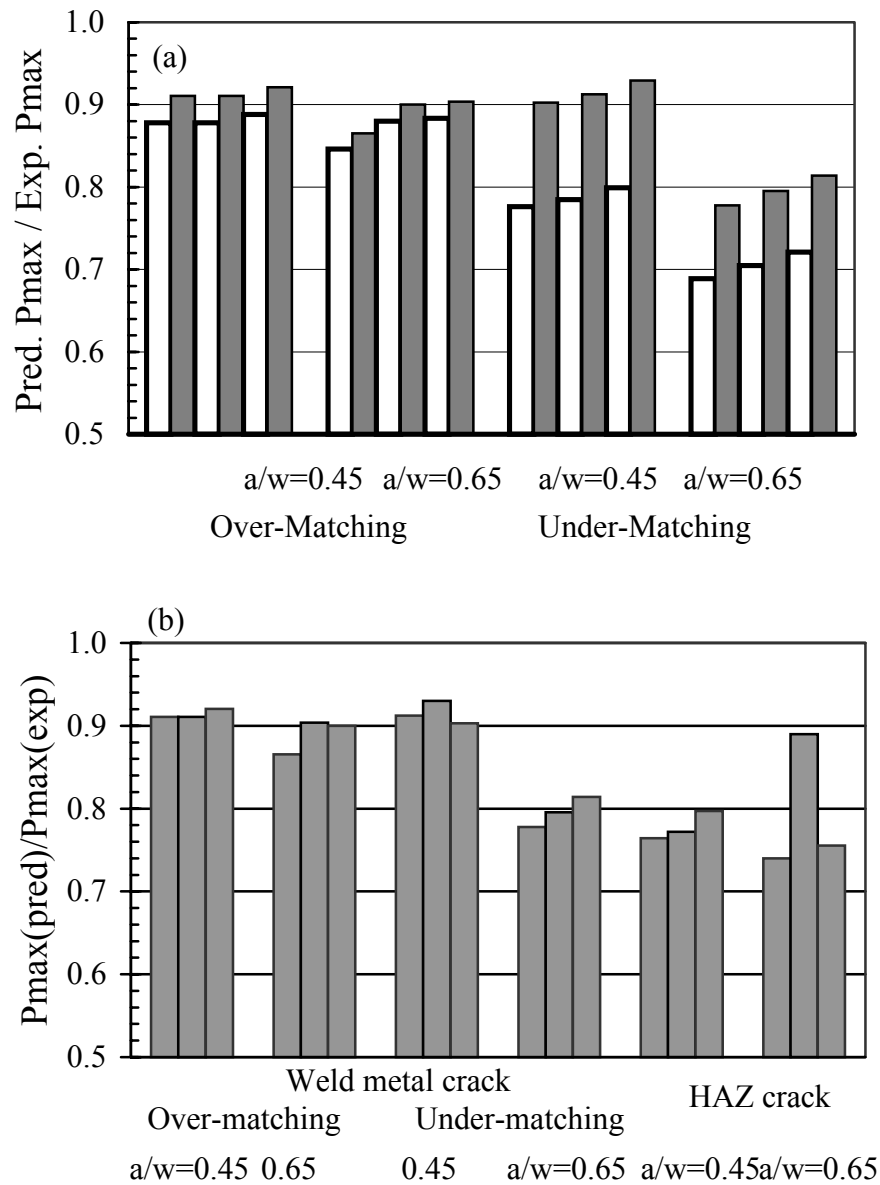


Fig. 6: Comparison of predicted maximum load, $P_{\max}(\text{prediction})$, to experimentally measured maximum load, $P_{\max}(\text{experimental})$; (a) levels 2 and 3 results for weld metal cracks, (b) level 3 results for weld metal and HAZ cracks.

