Investigation on the Fracture Behaviour of Laser Beam Welded Wide Plates

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Abstract
The tensile characteristics of the power beam narrow weld zone differ significantly from those of the base metal (strength mismatch, mis-match ratio, M = σ_Y^{WM} / σ_Y^{BM}). Conventional design rules and defect assessment procedures do not directly address the strength mismatch effect on the narrow laser beam weld joint performance. The through thickness center cracked (a/W=0.1) wide plate specimens notched at the fusion zone and heat affected zone (HAZ) were prepared from 12 mm thick laser beam welded five different C-Mn structural steels. The present study has shown that the guidance on mismatch analysis provided in currently developed European SINTAP procedure can give good results in predicting the laser beam welded wide plate behaviour of a specimen with through thickness crack located in the fused zone.

1. Introduction

The tensile characteristics of the power beam narrow weld zone differ significantly from those of the base metal (strength mismatch, mis-match ratio, M = σ_Y^{WM} / σ_Y^{BM}). Conventional design rules and defect assessment procedures do not directly address the strength mismatch effect on the narrow power beam weld joint performance. It needs to be shown that the guidance on mismatch analysis provided in R6 Appendix 16 [1], ETM-MM [2] and in currently developed SINTAP procedure [3] can give conservative results in predicting the power beam welded wide plate behaviour of a specimen with surface and through thickness crack located in the fused zone. It can be expected that the plastic yielding pattern in and around the very narrow power beam fusion zone has a significant effect on the tolerable defect size within the fusion zone. Because of the close connection between the yielding pattern and weld joint performance, the level of strength mismatching (M) and weld width (2H) are the most important factors if a designed stress concentration, a defect, or a possible overload causes plastic deformation.

It is rational to require a defective power beam C-Mn steel structural weld joint (with fusion zone of high hardness martensitic microstructure) to sustain remotely applied (gross) stresses of the base metal yield strength magnitude. Obviously, the requirement of base metal yielding for safe structural performance implies that the overmatching case (yield strength of weld metal is higher than the base metal, M>1) is desirable because yielding of the base metal (gross section yielding, GSY) can be more easily obtained for very narrow power beam welds even for comparatively longer defects and furthermore, it implies that strain at failure will be plastic. However, the yield strength, weld width (2H) and strain hardening capacity of the fusion zone region as well as defect position/shape/size will affect the yielding behaviour and hence crack path deviation of the power beam weldments. In particular, the interdependence of these variables should be established in order to determine the toughness needed for mis-matched power beam weld joints for safe and economic considerations.

The general purpose of the wide plate test is to verify the assumed relationships between small scale testing and large scale fracture behaviour by using defect containing plates which are more representative of real service conditions. The wide plate test is therefore considered to be a structurally relevant test. The laser beam welded wide plate tests (very limited in number) carried out to date have been exploratory in nature in order to find the major effects and indicate the trend of the results. The wide plate tests in this study were carried out for two main reasons: Firstly to observe the crack initiation and fracture behaviour of narrow laser beam welds; secondly to determine the effect of strength mismatch on failure behaviour by comparing the test results with the failure predictions from SINTAP procedure.

2. Experimental Procedure

The laser welding of 12 mm thick five C-Mn steels (EMZ 355, EMZ 450, RQT 701, Lloyd`s D, Lloyd`s DH) was carried out at the FORCE Institute using Rofin Sinar RF-exited fast axial flow CO_2 laser with a continuous maximum power of 17kW. Fracture tests of laser welded 33 wide plates were carried out at GKSS. Six C-Mn steels and one structural stainless steel plates with various strength levels were investigated. However, the present manuscript reports the results of the two steel grades, namely 355 MPa and 701 MPa yield strength steels. The mechanical properties and strength mis-match levels of each weld are given in Table 1. The macrographs of both weld cross sections are given in Figure 1.

The wide plate specimen geometry is shown in Figure 2. The plates had the following dimensions: thickness, B=12 mm and width, 2W = 200 mm. Small through thickness fatigue cracks (with nominal crack size of a/W=0.1) were produced at the tip of short machined notches in tension. The fatigue cracks were located in the fusion zone (FZ) and HAZ. All of the laser welded wide plate tests (including base plate tests for each material) were conducted at room temperature using 400 ton loading capacity testing machine. The experimental approach used at the GKSS in these tests was to measure the CTOD (with four GKSS made CTOD δ_5 clip-on-gauges at the original fatigue crack tip over a gauge length of 5 mm), CMOD and overall elongation using linear voltage displacement transducer, LVDT (gauge length of 300 mm) as a function of the applied load.

3. Results and Discussion

3.1 Weld Joint Microstructures, Hardness and Tensile Properties

Microstructural examinations showed that the fusion zones of both steels contained martensite and bainite due to rapid cooling rate of the laser beam welding thermal cycle. Extensive microhardness testing was carried out by placing the row of indentations at the top, middle and root regions of the welds, Figure 3.The high hardness levels at the FZ and HAZ regions of all laser welds generally indicate the highly strength overmatching nature of these weld joints.

The tensile properties of both base metals (BM) and fusion zones (FZ) are listed in Table 1. The FZ results are obtained from micro flat tensile specimens (0.5 mm thick) extracted longitudinally to the weld for both FZ and HAZ regions in multiple sets. The mismatch levels (M) is expressed as the ratio of fusion zone yield strength to base plate yield strength. The high strength RQT 701 steel weld joint has a mismatch ratio of only 1.36 compared to the lower strength EMZ 355 steel joint which exhibits the high overmatching ratio of 2.0.

3.2 Wide Plate Deformation and Fracture Behaviour

Generally, the degree of influence of strength mismatch on the deformation and fracture behaviour of the wide plates depends on the mismatch level (M), weld width (2H) and crack size (a/W, H/(W-a)). For very narrow (i.e. small 2H) overmatched wide plates with crack located at the weld zone, the plastic deformation mechanism is expected to cross very easily the weld/base metal interface (mis-match boundary), then penetrating into the base metal. The entire deformation mechanism of the highly overmatched wide plates with large 2H-value and hence the description of the yield loads differ significantly from those for homogeneous base metal specimen analysis. After giving this brief explanation on the deformation behaviour of the wide plates, the experimental observations and results of wide plate tests are discussed below. First of all, the fracture mode for all of the tests was ductile and fracture path deviated generally out of the fusion zone and HAZ into the base metal for both steel grades. The experimental results of all tested wide plates are plotted as following:

- Gauge Length Strain (GLS) vs. Gross Section Stress (GSS)
- CTOD δ_5 vs. Gross Section Stress
- CTOD δ_5 vs. Gauge Length Strain

These diagrams are given in Figures 4 and 5. For each group, comparisons between base metal (BM), fusion zone (FZ) and heat affected zone (HAZ) curves were made. The maximum gross section stress measured for welded wide plates exceeded the yield strength values of the base metals given in Table 1. The amount by which the yield strength was exceeded, as it can be seen in Figures 4 and 5, presents significant safety margin (on the basis of elastically loaded structures) for both steel grades. Similar observations have also been made by the tests conducted at the British Steel on the surface cracked wide plates of identical laser welded steel grades.

In Figure 4a, GLS vs. GSS curves obtained from **EMZ 355 steel** base plate as well as FZ and HAZ notched two wide plate tests. The laser welded plates with overmatching level of 2.0 provide similar or higher stresses for a given GLS. This good performance is much more visible in the CTOD vs. GSS curve, Fig. 7b, and the crack driving force diagram, Fig.4c. In both diagrams, the relationship between local (CTOD) and global (applied stress or strain) parameters with respect to crack are presented. It can clearly be seen that for a given applied stress or strain, the highly overmatched (but microstructurally brittle) laser weld region provides sufficient shielding to both FZ and HAZ cracks and hence the crack tip within the laser weld region opens less than the crack in the base metal. Due to the rapid and easy spread of the plasticity into the base metal, a defect within the narrow but highly overmatched fusion zone can receive a significant protection and hence whole welded structure behaves as a base metal. All three plates clearly exhibit gross section yielding (GSY) behaviour. Higher strength, **RQT 701 steel** laser welded plates, Figure 5, show also similar or superior performance than the base metal plates. This steel grade RQT 701 results did not reveal similar deformation pattern or behaviour as 355 MPa steel due to the differences in Lüder`s plateau behaviours.

The visual observations during the conduction of all above mentioned tests showed that the fracture path distinctly deviates out of the fusion zone or HAZ and the ductile crack growth occurs in the base metal. No brittle crack initation or any sign of pop-in type of brittle fracture was observed and identified in the test records.

Finally, these experimentally derived curves intended to provide basic information on the deformation and fracture behaviour of the laser welded wide plates of different structural steels. It can already be concluded that the strength overmatched laser welded wide plate deformation and fracture behaviour are similar or better than the base metal behaviour. The results have also showed that no significant difference between the GSS levels of base and welded panels (with and without into taking account the properties and geometry of overmatching narrow laser weld zone). Furthermore, the experimental results shown above for both structural steels clearly suggest the recommendation for the use of base plate properties (e.g yield strength) for analysis of structural significance of flaws normal to the applied stress (perhaps independent of overmatch level of laser beam weld zone) as long as the uncracked ligament size (W-a) is significantly larger than the weld width (2H).

4. Defect Assessment Methods Specific for Power Beam Welded Joints

4.1 Mismatch Effect on Defect Assessment Methods

Recently there have been significant efforts to extend the defect assessment methods for homogeneous structures to those for strength mis-matched structures, by incorporating the strength mis-match effect. Resulting defect assessment methods include the modified R6 method [1] and the ETM-MM method [2]. It should be noted that both methods make the common use of the mismatch effect on the yield load (mismatch yield load, F_{YM}), which is the main feature of incorporating the strength mis-match effect, although detailed formulations differ. Noting that both methods share common inputs, such as the SIF K and F_{YM}, consistency between these two methods has been shown within the Brite-Euram project SINTAP (Structural Integrity Assessment Procedure for European Industry), i.e., both methods produce compatible results, provided same inputs are used. Based on these two methods, the unified SINTAP procedure for mis-match has been produced. It provides different levels of complexity, which can be used depending upon the quality and details of the input data available. For the sake of space, detailed equations for the SINTAP method for strength mis-matched structures can not be given here, but can be found elsewhere [3]. The SINTAP mis-match method can be further tailored to the power beam welded joints, by incorporating some specific features specific to power beam welded joints, which is described below.

4.2 Features Specific to Power Beam Welded Joints

There are two specific features to power beam welded joints, which can be summarised as follows:

- The weld width, *H*, is small, typically ranging from 2 to 4 mm, and thus the slenderness of the weld, *(W-a)/H*, is typically large (see Fig. 2). Such small *H* (and thus large *(W-a)/H)* has a significant implication to defect assessment, as will be shown later.
- Power beam welding is usually applied to a thin section, and thus the plane stress assumption would be adequate for plate-like structures, thin shell assumption for pipe components. This is particularly true when global parameters, such as load, global displacement and fracture parameters, are concerned.

4.3 Defect Assessment Methods Specific to Power Beam Welded Joints

As noted, the strength mis-match effect on crack driving force can be most vividly seen by the mis-match corrected yield load. An examination of the mis-match yield load solutions, for plane stress condition and with large *(W-a)/H,* provides two important observations [4]:

- For overmatched joints (typical for power beam welding of structural steels), the plane stress mis-match yield load for welded joints for large *(W-a)/H* is similar to that for homogeneous base plate, regardless of the crack location. Therefore, the behaviour of overmatched power beam welded joints can be assessed assuming the plate is wholly made of the base plates. It is also noted that plane strain mismatch yield load solutions also show the same tendency, which imply that the above statement is valid even for thick components.
- For undermatched joints (typical for power beam welding of aluminium alloys), however, the mis-match yield load for welded joints for large values of *(W-a)/H* is similar to that for all weld plate. Therefore, the behaviour of undermatched power beam welded joints can be assessed assuming the plate is made wholly of the weld metal, and thus the tensile properties of the weld metal are very important.

Thus, for power beam welded joints, the defect assessment methods for homogeneous structures can be used, <u>with a proper choice of material properties depending on the strength mis-match</u>; the base material properties for overmatched joints and the weld metal properties for undermatched joints. In principle, any of exiting defect assessment method can be used, such as the SINTAP homogeneous method [3]. Variables to be updated are as follows:

- For overmatching
  - ¬ The yield and ultimate tensile strength set to those of the base material; $\sigma_Y=\sigma_{YB}$, $\sigma_U=\sigma_{UB}$
  - ¬ The yield load set to that of all base plate, $F_Y=F_{YB}$
  - ¬ The strain hardening set to that of the base material, $N=N_B$
- For undermatching
  - ¬ The yield and ultimate tensile strength set to that of the weld material; $\sigma_Y=\sigma_{YW}$, $\sigma_U=\sigma_{UW}$
  - ¬ The yield load set to that of all weld plate, $F_Y=F_{YW}$
  - ¬ The strain hardening set to that of the weld material, $N=N_W$

4.3 Experimental Validation

Within the ASPOW project, wide plate tests of homogeneous and power beam welded joints have been performed. All wide plates have same nominal dimensions: width of 200 mm, thickness of 12 mm, and the crack length of 20 mm (*a/W*=0.1), Fig. 2. Two different steels were considered: 355EMZ and RQT 701 steels. For each material, homogeneous cracked plate was tested as reported above. Further tests were performed of power (laser) beam welded joints with the crack in the fusion zone (FZ) as well as in the heat affected zone (HAZ). Detailed information on the further test results can also be found in [5].

From test results, the J integral was calculated according to

$$J=\frac{K^2}{E'}+\frac{U_*^{CMOD}}{(W-a)} \quad .$$

The area, U_*^{CMOD}, is measured between the load versus crack mouth opening displacement (CMOD) record and the secant offset line. The stress intensity factor (SIF), *K*, was estimated from [6]. The resulting *J* values are shown as a function of gross section stress, in Fig. 6. It also includes the *J* values estimated according to the SINTAP homogeneous methods, using the base plate properties (Level 3 of the SINTAP method for homogeneous structures [3]). The results in Fig. 6 confirm our conclusion that the defect assessment methods for homogeneous structures can be used for narrow width laser beam welded joints, using appropriate material properties. Moreover, agreement is excellent, regardless of the crack location, within the FZ or in the HAZ, which provides confidence in the use of homogeneous defect assessment methods to power beam welded joints.

5. Conclusions

Large numbers of wide plate tests under tension have been conducted at room tempertaure on 17 kW CO_2 laser beam welds in five different structural steels of different strength levels in order to investigate their deformation and fracture behaviour. This paper has concentrated on only two steel grades. All wide plates (200 mm wide) contained 20 mm long (a/W=0.1) fatigue pre-cracked machine notch located on the fusion zone centerline and HAZ. The experimental results of these tests have provided following conclusions:

1. All of the wide plates of both steels with a high strength overmatched laser weld region, exhibited higher gross section stress levels and exceeded the yield strength of the base metals.
2. All of the laser welded wide plates showed fracture path deviation into lower strength base metal due to high strength overmatching of the fusion zone and HAZ. No brittle fracture inititation or pop-in behaviour was observed or identified. Hence, no detrimental effect of high hardness level of laser weld regions on the performance of structural component-like wide plate behaviour was observed.
3. The strength overmatched C-Mn steel wide plate results suggest that the use of base metal tensile properties in defect assessment procedure may yield safe predictions since deformation behaviour of the welded plates rather similar to those of base metals.
4. The structurally representative wide plate test results clearly demonstrated that the laser welded various ferritic structural steels can provide technically sound weld joint deformation and fracture performance similar or better than the respective base metals.
5. Finally, the defect assessment methods for homogeneous structures can be used for narrow width and highly overmatching laser beam welded joints, using appropriate material properties.

6. References

[1] Appendix 16 in R/H/R6-Revision 3: Allowance of Strength Mis-match Effect, Nuclear Electric (1997).

[2] K-H Schwalbe, Y-J Kim, S Hao, A Cornec, and M Koçak, EFAM ETM-MM 96: The ETM method for assessing the significance of crack-like defects in joints with mechanical heterogeneity (strength mis-match), GKSS Research Centre, Germany, GKSS97/E/9 (1996).

[3] SINTAP, Structural Integrity Assessment Procedures for European Industry, Final procedure (November 1999), Brite-Euram Project No. NE95-1426.

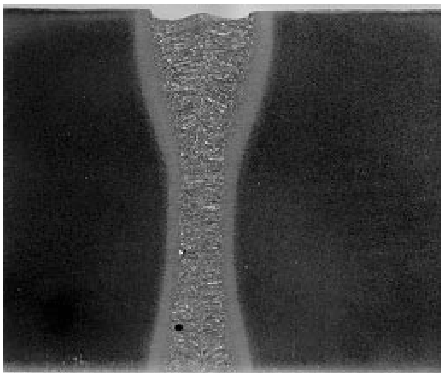
[4] Y-J Kim and k-H Schwalbe, ”Mis-Match Effect on Plastic Yield Loads in Idealised Weldments: Part I-Weld Centre Cracks, Part II-HAZ Cracks”, Engineering Fracture Mechanics (to be published).

[5] M. Koçak et al., ”Analysis of Fracture Behaviour of Laser Welded Wide Plates”, European Symposium on Assessment of Power Beam Welds, February, 4th-5th , 1999, Geesthacht, Germany

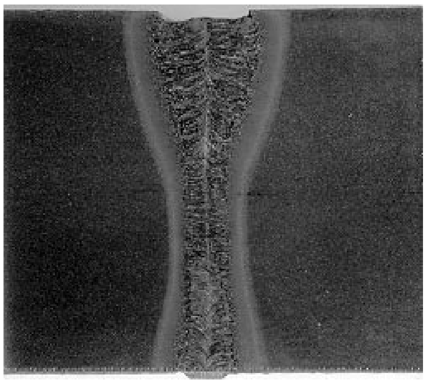
[6] H Tada, P Paris and G Irwin, The Stress Analysis of Cracks Handbook, Paris Production Inc (1985).

Table 1. Mismatch properties of laser beam joints determined by testing of micro flat tensile specimens extracted from fusion zone (values are average of at least 3 specimens).

Material	$R_{p0.2}$ or R_{eL} Yield Strength (MPa)		M Mismatch Factor
	Base Material	Fusion Zone	(M = $R_{p0.2}$ FZ / $R_{p0.2}$ BM)
EMZ 355 Steel	413	830	2.00
RQT 701 Steel	776	1060	1.36



a)



b)

Fig. 1. Macrographs of 12 mm thick 17kW CO_2laser welded steel plates; a) Grade EMZ 355 steel, b) Grade RQT 701 steel

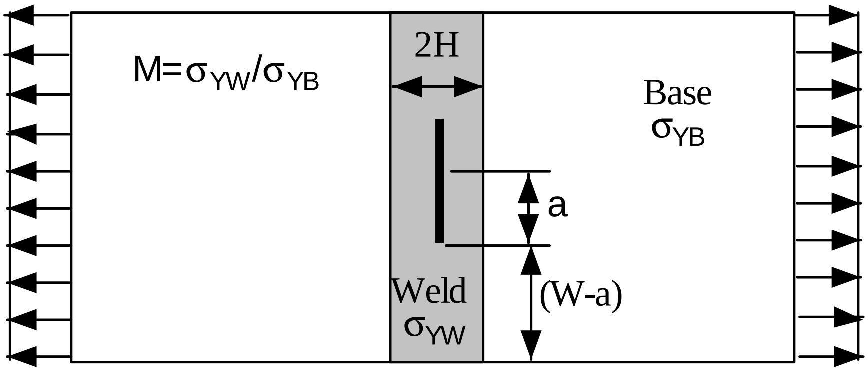
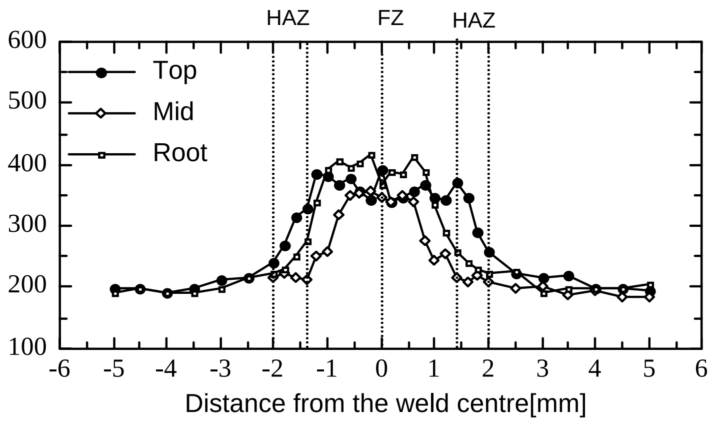
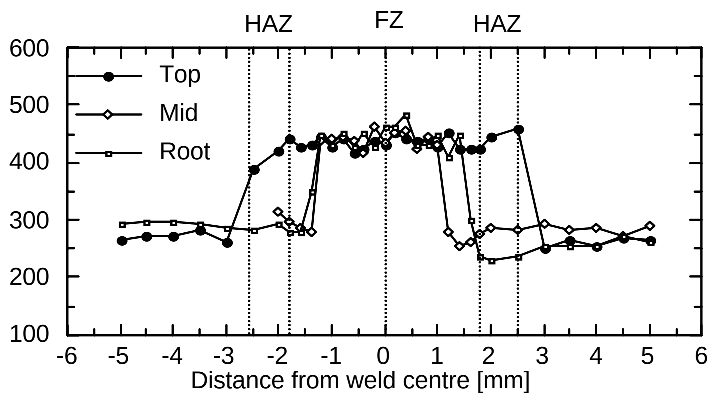


Fig. 2 Schematic showing the dimensions of the laser welded center cracked wide plate: 2H= 3,5 mm, 2W= 200 mm, a/W=0.1, Thickness of 12 mm.



a) EMZ 355



b) RQT 701

Fig. 3 Hardness profiles of the laser weld joints for 355 and 701 MPa steels

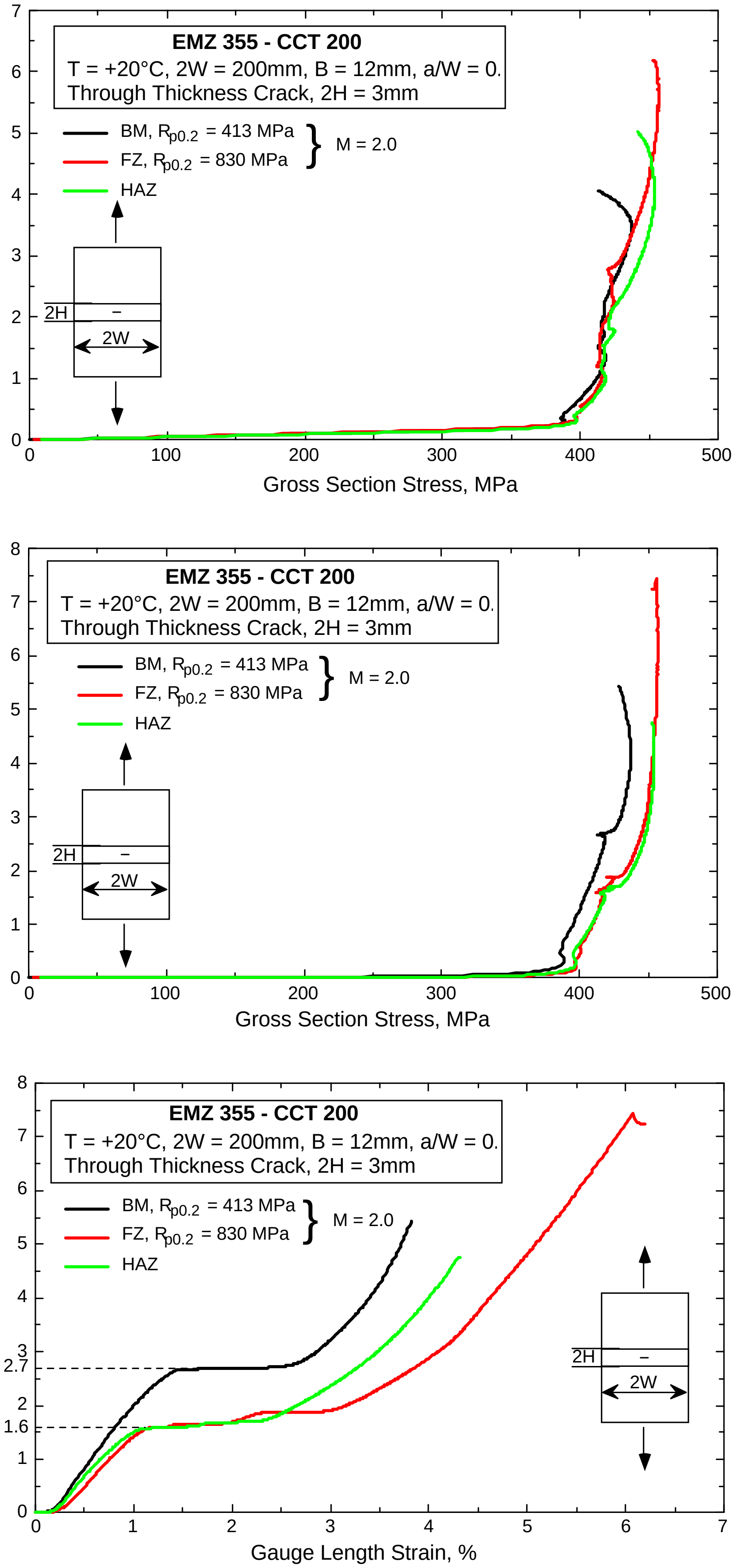
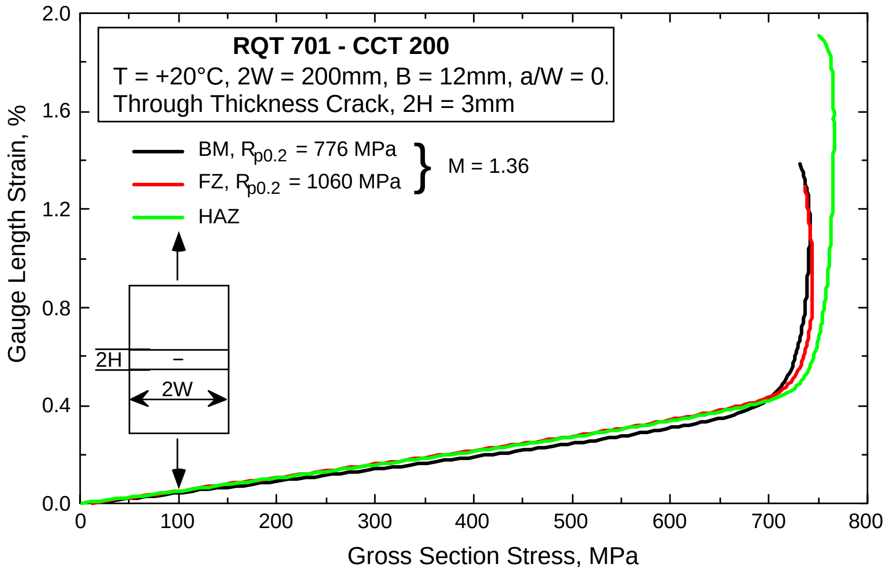


Fig. 4   Stress-Strain, CTOD-Stress and crack driving force diagrams of the 355 MPa steel



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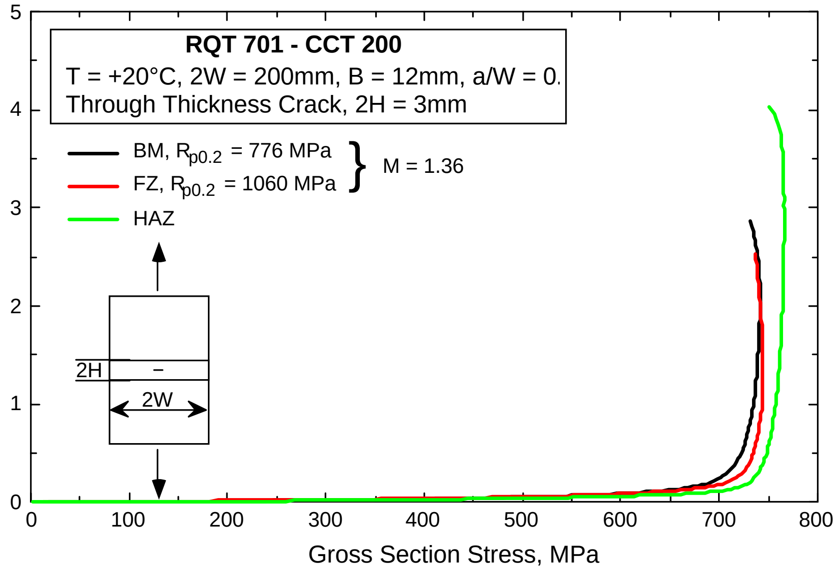

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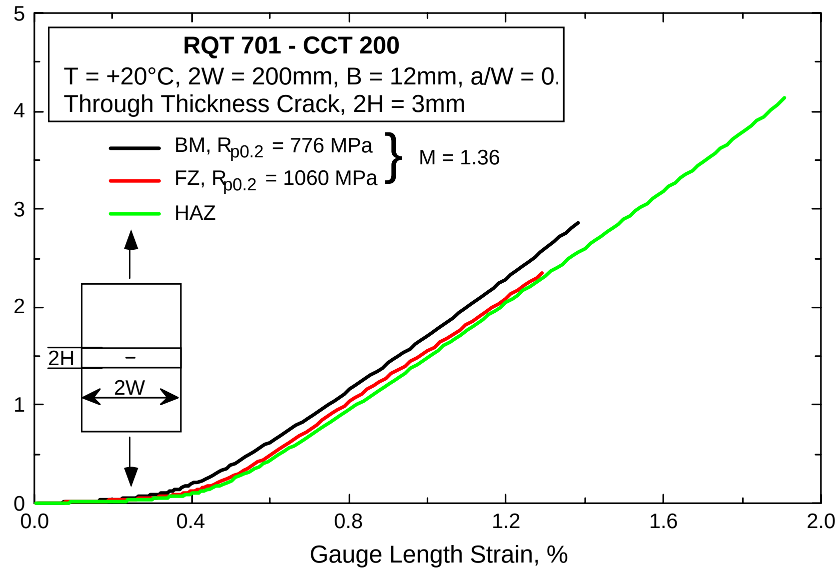
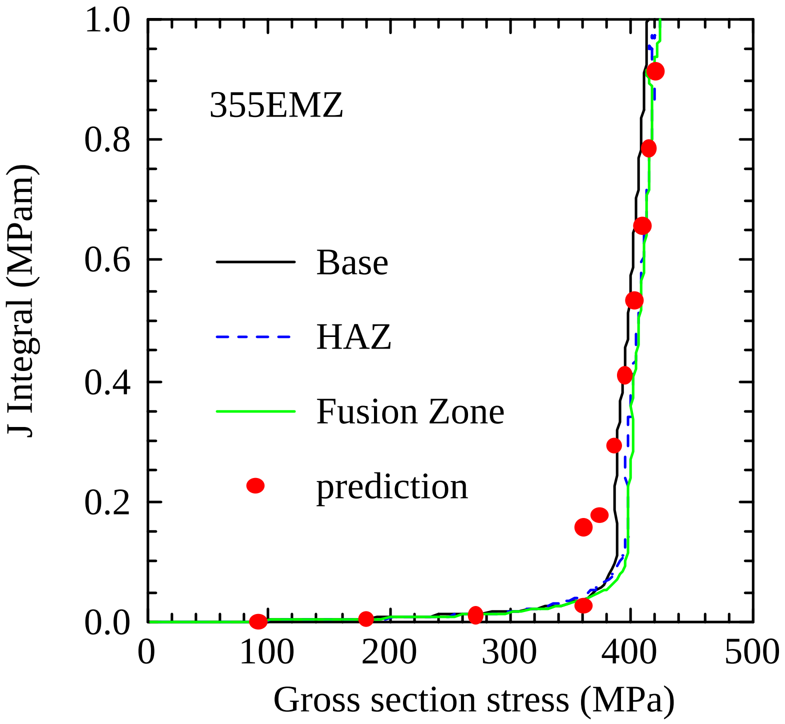


c)

Fig. 5 Stress-Strain, CTOD-Stress and crack driving force diagrams of the 701 MPa steel



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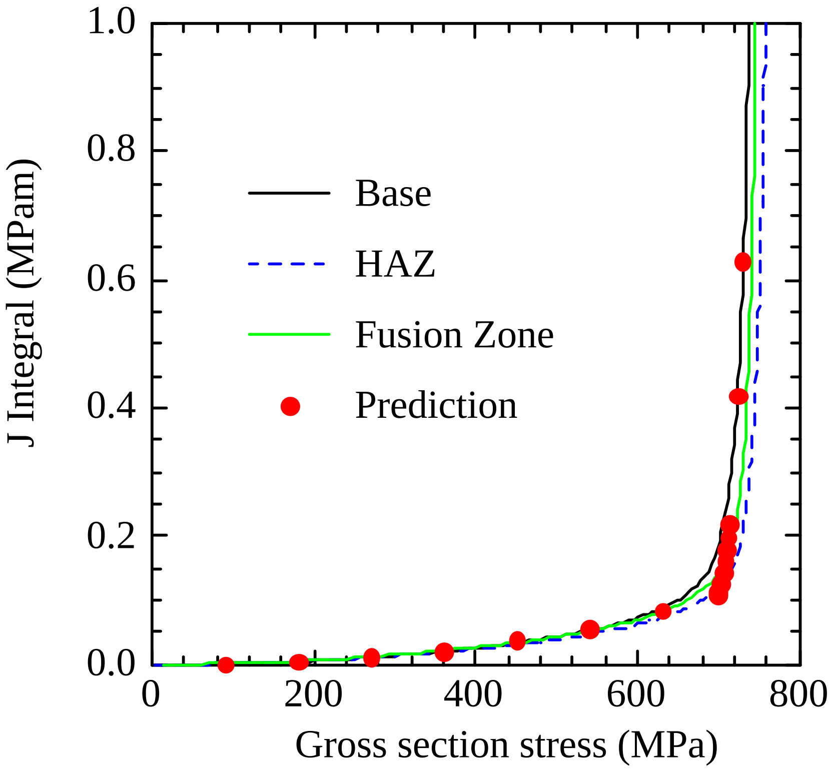

b)

Fig. 6 Comparison of the experimental wide plate results and SINTAP procedure predictions for; a) 355 MPa Steel, b) 701 MPa steel