Applications of EPFM to Welding: Current Trends

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ABSTRACT

Discontinuities introduced by welding are of geometrical, metallurgical and mechanical nature. Proper assessment of the fitness of a welded joint to perform satisfactorily in service must take this fact into account. In this paper the main problems posed by the application of EPFM to welding are considered along with some recent results and special techniques developed to overcome these difficulties.

KEYWORDS

Elastic plastic fracture mechanics; welding defects; engineering critical assessment.

INTRODUCTION

Since the introduction of the CTOD concept in 1961 by Wells and Cottrell, elastic-plastic fracture mechanics (EPFM) methodology has been steadily growing in its applications to practical engineering problems. In particular, during the last ten years new concepts and techniques have evolved and a marked increase in the utilization of EPFM in the design and in the assessment of structural integrity of welded components could be observed.

Welding represents today the most popular method for joining metals. For this reason the success of fracture mechanics as an engineering tool is to a great extent tied to its ability to predict the fracture behaviour of welded joints. However, the application of EPFM to welding is neither straightforward nor completely free from drawbacks. Problems usually related with the application of fracture mechanics to welding stem from the fact that a welded joint is a complex, inhomogeneous and anisotropic metallurgical system due to the presence of:

- ○ Geometrical discontinuities (cracks, pores, undercut, misalignment, etc.)
- ○ Brittle metallurgical microstructures in the weld metal (WM) and in the heat affected zone (HAZ) of the base plate.
- ○ Local residual stresses of yield stress or near yield stress magnitude.

Thus the discontinuities introduced by welding are of geometrical, metallurgical and mechanical nature. It must be noted that generally (and wrongly) only geometrical discontinuities are considered since these are the ones usually detected by conventional NDT techniques. However, proper assessment of the fitness of a welded joint to perform satisfactorily in service must take also into account the other types of discontinuities, that is metallurgical and mechanical. In this respect, a distinction must be made between tests for general assessment of welded joints fracture toughness and those for specific assessment of the toughness associated with known or postulated defects (Squirrell *et al.*, 1986).

In this paper the main problems posed by the application of EPFM to welding are described along with some recent results and special techniques developed to overcome those difficulties. In particular, the following points are considered:

- Present status of the "engineering critical assessment" approach.
- EPFM in welding procedure qualification.
- Fracture significance of mechanical and metallurgical discontinuities introduced by welding.
- Applications of EPFM to welding consumables development.

ENGINEERING CRITICAL ASSESSMENT

The derivation of acceptance levels for defects in welds is based on the concept of "fitness for purpose", which may be defined as the right level of material and fabrication quality for each application, with regard to the risks and consequences of failure (Wells, 1983). This means that no single acceptance level for defects can be established for welded components irrespective of service loads, materials involved, environment, etc. According to the "fitness for purpose" concept, allowable defect sizes must be derived either in the light of previously documented experience, stress and environmental combination or after giving proper consideration to the particular conditions under which the component will have to perform satisfactorily for the whole of its intended life. This constitutes the basis of "engineering critical assessment" (ECA) which today is firmly rooted in fracture mechanics concepts. In the last years, several national documents concerning the application of fitness for purpose requirements in welding have been published. In this respect, the International Institute of Welding (IIW) holds the opinion that the level of fracture mechanics calculations, the performance of workshop quality control programmes in welding fabrication and the performance of advanced non-destructive methods of examination of welds have reached a stage permitting widespread application of fitness for purpose criteria in welding (IIW, 1987).

Among the documents concerning with the application of EPFM to ECA assessment of defects significance, the following can be mentioned by virtue of their outstanding importance:

- ○ PD6493:1980 (BSI, 1980).
- ○ Appendix A — API Standard 1104 (API, 1983).
- ○ IIW Doc. 1141-87 (IIW, 1987).

WELDING PROCEDURE QUALIFICATION

Since the introduction of ECA for weld defects, there has been some arguments concerning the convenience of conducting fracture mechanics evaluations at the stage of welding procedure qualification (Cotton, 1980; IIW, 1984). The argumentation pivoted on the fact that the setting of arbitrary levels for minimum values of fracture toughness without reference to the requirements of the specific fabrication should be discouraged since nothing is known at that stage about the size and location of potential cracks. Nevertheless, a general assessment may be justified provided a notch size, position and specimen geometry can be used which is most likely to give a lower bound measure of fracture toughness (Squirrell *et al.*, 1986). This is usually achieved by means of the three point bend or compact specimens notched in the through thickness direction as shown in Fig. 1. Fracture toughness determination must include testing of the heat affected zone (HAZ) of the base plate as indicated by Fig. 2. This may imply the test of several specimens in order to identifiy the lowest HAZ fracture toughness for the relevant service conditions. Figures 3a and b show specimen and notch location for weld metal (WM) and HAZ testing according to Appendix A of API Standard 1104. For each welding procedure, both the WM and HAZ must satisfy minimum CTOD requirements before the fitness for purpose acceptance criteria can be employed. The welding procedure may be qualified to a fracture toughness requirement of either 0.005 inch minimum or 0.010 inch minimum according to the applicable acceptance criteria.

The most widely used EPFM test for measuring fracture toughness of welds in ECA schemes, is the CTOD test. However, at the time of writing this paper, ASTM Committee E24 is working on a draft test method for fracture toughness testing of weldments that takes other standard parameters such as J_{IC} into consideration (ASTM, 1988) which probably will result in a wider use of alternative EPFM testing methods. Fracture toughness assessment of welds usually involves testing of full thickness specimens at the relevant (generally minimum) service temperature. The oft-quoted reason for testing specimens of the same thickness as the structural member is to reproduce at the tip of the fatigue crack in the test specimen a plastic constraint that is equal to or greater than that of the structural member. In the case of testing weldments, there are also other important reasons that justify the use of full thickness specimens.

FRACTURE SIGNIFICANCE OF MECHANICAL AND METALLURGICAL DISCONTINUITIES INTRODUCED BY WELDING

A multipass weld is made by successive layers of deposited molten metal which upon solidifying and subsequent cooling apply a complex thermal cycle on previously deposited weld metal and base plate material. Figure 4 shows the resulting distribution of microstructures along the cross section axis of a multipass manual metal arc weld (Herrera *et al.*, 1986). It can be seen that the weld is composed of columnar grain, coarse grain and fine grain zones. The metallurgical inhomogeneity may result in a steep gradient of fracture toughness along the axis of the weld and the obvious way of detecting the area with the lower toughness is to have the fatigue crack tip probing all the different microstructures during testing, which can be achieved by the use of full size specimens. Another reason which calls for the use of full thickness specimens in fracture toughness testing of welds is the requirement to include the root run region within the sampled material. This is due to the fact that the root run region of multipass welds is the site of mechanical and metallurgical phenomena that may lead to a local deterioration of fracture toughness and ductility. This degradation in mechanical properties is related to dynamic strain ageing effects which occur when carbon-manganese or low alloy steels containing interstitial carbon and nitrogen are subjected to plastic strain in the 100-300°C temperature range (USSC, 1971; Li and Leslie, 1978). As mentioned above, this can have some influence on mechanical properties of multipass welds, since the root run is in this case simultaneously subjected to plastic deformation and thermal cycles imposed by subsequent layers. Most of our basic knowledge on dynamic strain ageing comes from experiments conducted on wrought material under controlled thermo-mechanical treatments. The situation is different with welded joints. In this case thermal cycles and deformation at the root run produced by the welding procedure are in general only roughly estimated. Charpy-V tests conducted by Cochrane *et al.* (1976) on manual metal arc welds made on 40 mm thick plate, using different electrodes and base metals, showed that samples machined from the root region exhibited a toughness degradation which completely overrides the effects of the deposit and base metal chemistry. Experiments conducted by Otegui *et al.* (1983) showed the reduction in toughness experienced by all weld metal sub-size Charpy-V specimens when 6.5% plastic strain is imposed at 250°C to promote dynamic strain ageing under controlled conditions, Fig. 5. As a consequence the properties of the weld metal at the root are generally the poorest and therefore tend to control the fracture toughness of the joint as a whole when through thickness testing is employed. Using a three clip gauge measuring technique and a simple geometrical model, Otegui *et al.* (1986) were able to estimate the amount of plastic strain at the root run of multipass welds. Figures 6 and 7 show effective strain-time plots as experienced at the root region of 19 mm (single-V) and 50 mm (double-V) thick multipass flux cored arc welds respectively. The centre 60% of the specimen is associated with higher triaxial stresses which promote fracture initiation in this region (Squirrell *et al.*, 1986). This is the case with the root run region in double-V preparation welds when using full size specimens. Nevertheless, as can be judged from Fig. 6, there are no reasons for root properties to be better in a single-V preparation weld. However, in this case because the root lies on the surface of the plate it is not subjected to the maximum triaxial stresses developed at the central portion of the specimen. In this state, the root rarely plays a part in controlling the fracture properties of the joint. The combined effect on through thickness CTOD values of a change in specimen thickness (from 19 mm to 50 mm), weld preparation (from single-V to double-V) and external restraint, is shown in Fig. 8 (Otegui *et al.*, 1986). These results correspond to weld metal deposited using in both cases the same electrode and welding parameters, showing the drastic reduction in fracture toughness that may result from changes in plastic constraint at the locally embrittled region of the fatigue crack tip of the test piece.

When modeling the behaviour of root cracks or any other surface or shallow cracks in single-V welds, the testing of full thickness specimens may not be adequate. In these cases it is better to use square section surface notched bend specimens as shown in Fig. 9. The object of using a shallow notch is to reproduce the conditions existing at the tip of a surface defect. This brings about another problem related with fracture toughness testing of welds, specially in those cases where a low a/W ratio must be used, say less than about 0.3/0.4, for instance in assessing root regions of single sided welds or in evaluating HAZ, toe cracks, etc. The use of shallow notches, although more realistic than deep notches relative to actual weld defects, makes the determination of J and CTOD values difficult because yielding ceases to be concentrated in the ligament and starts to occur remote from the crack. This problem is aggravated by the fact that yield stress of weld metal usually overmatches that of parent material. Although in this case it is not possible to define a plastic factor for the specimen, the problem can be solved eliminating the effects of remote plasticity. This can be achieved by obtaining J from measurements made only within the weld as is the case when J is estimated from a load versus notch mouth opening displacement record. In this case the plastic deformation which occurs remotely from the notch will not contribute to clip gauge displacement. This method, originally proposed by Sumpter and Turner (1976) and modified by Dawes (1979) has particular potential in the testing of structural steel weldments with the advantage that it is fully compatible with standard J and CTOD testing procedures. Herrera *et al.* (1986) using a multispecimen technique estimated J values according to ASTM E813-81 procedure for WM and HAZ of three multipass manual metal arc welds and one submerged arc weld in a Q.T. microalloyed steel at different temperatures using standard and square section side grooved bend specimens, and compared the results with those corresponding J_v values obtained with the clip gauge technique. The results are seen in Figs. 10a and b, which show a good agreement between the ASTM and clip gauge methods for bend specimens. The observed departure from linearity for large values of crack extension is due to a correction for crack growth introduced by the Sumpter-Turner procedure but not by the ASTM method. This technique allows for the extension of the use of J to the ductile to brittle transition range since all the advantages associated with geometry dependent critical CTOD values can be realised in the equivalent J_v tests by interpreting the CTOD test results in terms of J (Dawes, 1982). This could be achieved by introducing an equivalent fracture notation, that is J_c for cleavage fracture of the specimen without prior ductile crack extension, J_u for cleavage fracture after some stable tearing and J_m for the attainment of a maximum load plateau, reserving the designation J_i for the initiation of ductile crack extension as determined for example by the multiple specimen technique. The extension of J into the ductile-brittle transition range is justified by the lack of a simple relationship between CTOD and J integral values, (Herrera *et al.*, 1986), due to the variability exhibited by the plastic constraint factor m that relates those parameters (Perez Ipina and Toloy, 1986).

One problem frecuently associated with the testing of weldments in the fracture transition temperature range is the occurrence of a pop-in in the load-displacement record. The structural significance of the pop-in is a matter of concern. If it can be attributed to an arrested brittle crack in the plane of the notch, the result must be considered as a characteristic of the material tested. However this is not always easily determined from the fracture surface appearance. One way of solving the problem, at least from the experimental point of view is to treat the pop-in according to the accompanying change in secant slope as proposed by the draft ASTM method for CTOD testing.

The local mechanical discontinuity introduced at a weld by residual stresses is also a source of problems. These become apparent when fatigue precracking specimens for fracture mechanics testing. The presence of residual stresses results in an uneven shape of the fatigue crack tip that results many times in the invalidation of the test. The problem of straightness of the fatigue crack front can nevertheless be coped with by using a lateral compression technique that has been widely covered in the literature (Towers and Robinson, 1982). A more difficult problem posed by the presence of residual stresses concerns the best way to introduce them in ECA of weld defects. The usual procedure when dealing with as-welded joints is to assume residual stresses of yield stress magnitude superimposed to service loads. However, there is evidence that at least in high strength weldments, residual stresses may be of less than yield stress magnitude (Masubuchi, 1977). This is a problem that still waits for a better understanding since the stress level acting on the plane of a defect strongly determines its admissible size.

APPLICATION OF EPFM TO WELDING CONSUMABLES DEVELOPMENT

The use of full size specimens in order to obtain a realistic assesment of weld fracture properties constitutes a powerful mean to assist in the development of new welding consumables. Previous considerations showed that the standard Charpy-V test, although more economical than fracture toughness testing, is unable to give anything but comparative information on aspects such as susceptibility to strain ageing damage, microstructure induced property gradients, influence of dilution, stress triaxiality, heat input, etc. The absorbed energy obtained by Charpy tests is the strain energy which occurs as a result of the deformation of the specimen up to fracture initiation and during fracture and this energy does not correspond to the stresses/strains in the vicinity of the notch tip (Toyoda and Satoh, 1983). That is, absorbed energy obtained by a Charpy test is not necessarily a characteristic parameter of the fracture toughness of welds. It is not suprising that EPFM is being increasingly used as a laboratory tool in the formulation of welding consumables to obtain complementary information relevant to the actual service conditions under which the new product will have to perform. Thus besides the standard Charpy-V test used to rank all-weld metal toughness, fracture mechanics testing of typical production type single-V or double-V joints will give additional information on the consumable characteristics. In this respect, not only the value of fracture toughness is to be considered but also the rupture mode gives valuable indication on the way the product will behave in service. Figure 11 illustrates the application of CTOD test in the determination of the optimum Mn content for a high strength AWS E11018-M type electrode (Surian *et al.*, 1987). The figure shows "as welded" average CTOD values along with the yield strength of the weld metal of production type single-V joints. Maximum CTOD values were obtained in this case for 1% Mn. It can also be seen that fracture toughness rapidly deteriorates for Mn levels beyond 1.5% as fracture mode changed from ductile tearing to cleavage which established an upper limit to the Mn content in this type of consumable.

CONCLUSIONS

The application of EPFM concepts and techniques to welding engineering is now a well established practice. However, as has already been discussed, this application must be done giving regard to the peculiarities that distinguish a weldment from a wrought product. Mechanical and metallurgical discontinuities introduced by the welding process are not always apparent but must be taken into consideration if proper assessment of fracture properties is to be done. Once those factors are accounted for, fracture mechanics testing of full size specimens gives the most realistic and reliable information on how the weldment is going to perform when in service. Some further developments, like the extension of the use of J to cope with the transition range, a better understanding of the structural significance of the pop-in and of the role of residual stresses on the fracture process, are desirable.

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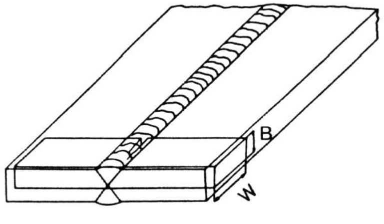


Fig. 1. Obtainment of specimen for testing weld metal

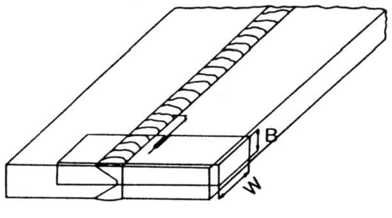


Fig. 2. Obtainment of specimen for testing HAZ

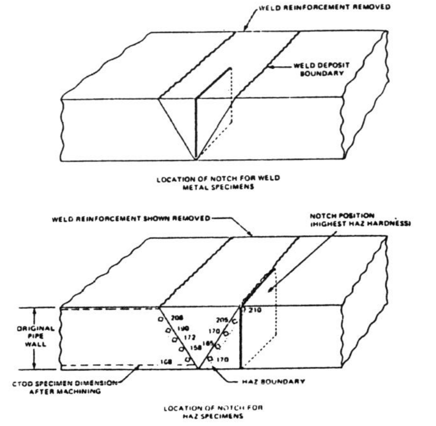


Fig. 3. Location of notch according to API 1104

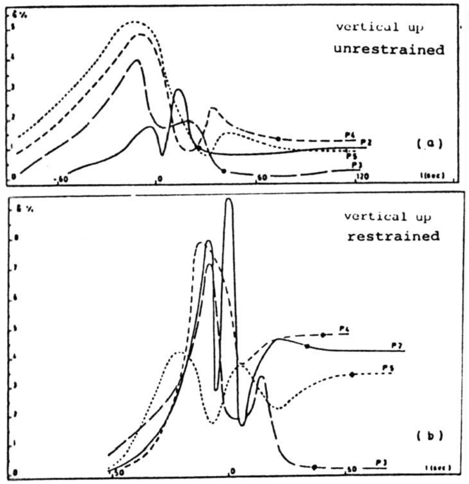


Fig. 6. Effective strain-time plots corresponding to 19 mm thick welds.

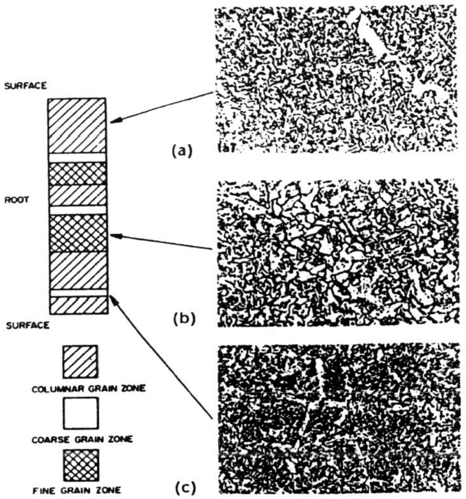


Fig. 4. Weld metal microstructures. Nital etch. Columnar grain zone. 742x; (b) fine grain zone. 742x; (c) coarse grain zone. 364x.

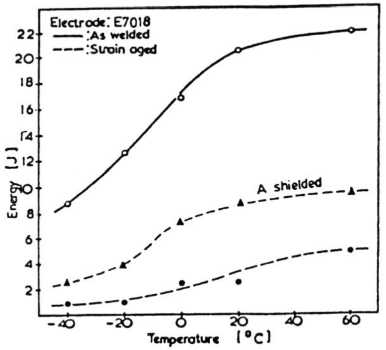


Fig. 5. Influence of dynamic strain ageing on weld metal toughness.

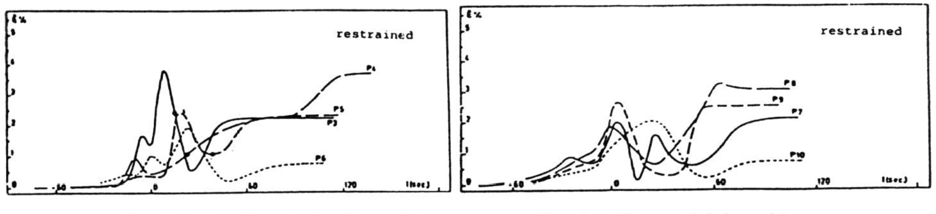


Fig. 7. Effective strain-time plots corresponding to 50 mm thick welds.

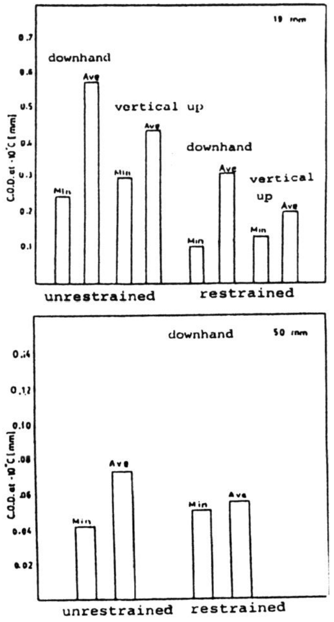


Fig. 8. COD test results.

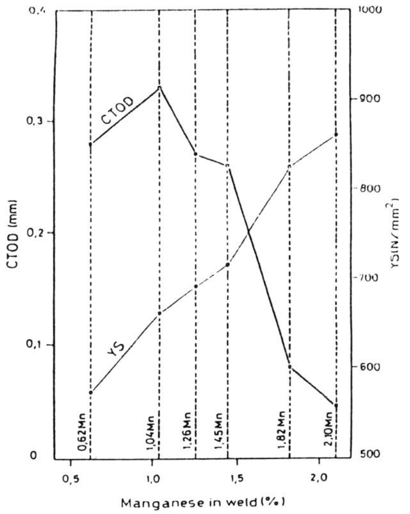


Fig. 11. Effect of manganese on the yield strength and CTOD values of weld metal of single V-joint. As welded.

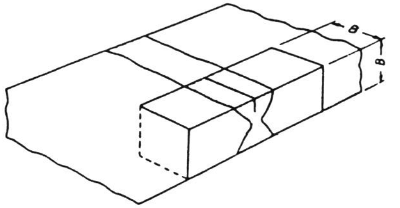
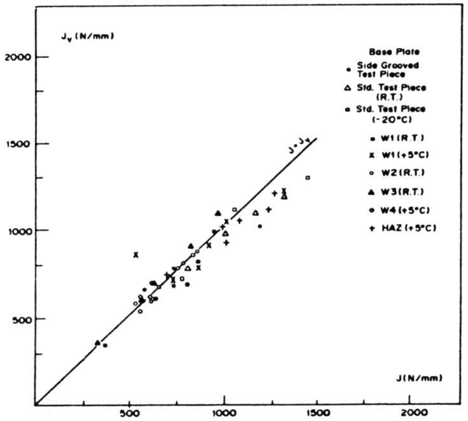
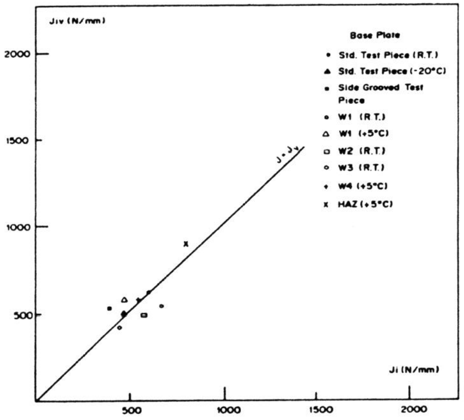


Fig. 9. Typical examples associated with standard specimen designs: surface notches.



(a) J–J_v relationship.



(b) J_i–J_{iv} relationship.

Fig. 10: J-J_v relationship for points with crack growth (a) and at initiation (b).