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Fracture Toughness Testing of Sub-Sized and Weld-Reconstructed Specimens

REFERENCE Bicego, V., Lucon, E., and Ragazzoni, S., **Fracture toughness testing of sub-sized and weld-reconstructed specimens**, *Defect Assessment in Components – Fundamentals and Application*, ESIS/EGF9 (Edited by J. G. Blauel and K.-H. Schwalbe) 1991, Mechanical Engineering Publications, London, pp. 765–780.

ABSTRACT Mechanical tests on specimens directly sampled from plants are experiencing increasing popularity as a useful non-destructive method to assess integrity of components operating at high temperatures. Mainly due to limitations in material availability, several problems exist in obtaining valid data from the tests, and non-standard test procedures have to be considered and validated. An activity in this field was recently started at CISE under ENEL–DSR sponsorship: LEFM, EPFM, and Charpy tests were performed on a number of steels, utilising two different types of non-conventional specimens, namely Electron Beam welded composite and sub-sized specimens. Two different reconstruction geometries were considered for the composite specimens, and a miniature disc-shaped ($D = 16$ mm) geometry for the sub-sized specimens. EPFM test techniques included multispecimen procedure, unloading compliance, and potential drop.

Agreement between results of EPFM tests on composite and on standard specimens was found. On the other hand large discrepancies were observed in Charpy data and in LEFM data for one particular reconstruction geometry, the reasons seeming attributable to inaccurate welding: excessive heat embrittlement of the material in the core of the small Charpy specimens, and large residual stresses in the crack tip zone of the composite CT specimens.

Introduction

Among the various approaches to the integrity assessment of critical components operating at elevated temperatures, mechanical tests on specimens directly sampled from the component represent a convenient solution as information regarding the real plant material in the actual damaged state is obtained. Among the several mechanical tests two types are particularly important: creep tests (usually accelerated creep rupture tests) suitable for residual life estimation when the life limiting factor is creep, and fracture toughness tests for analysis of integrity of thick components during thermal transients. A typical feature of testing material sampled from plants is the need to preserve the integrity of components for further operation. In this sense the mechanical characterisation can be considered to be obtained non-destructively. Of course, individual specimens are to be destroyed as a result of testing, but the components from which specimens are sampled retain the capability to work, eventually, after some weld repair or at reduced operating conditions of temperature and pressure. In order to be non-destructive in this

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sense, it is of course important to be able to derive valid test data from limited material sampling. Two techniques may be considered.

(a) Miniature specimens (**1**).
(b) Composite specimens (**2**) – i.e., specimens in which the plant (precious) material is a minor part (usually the gauge length region, the crack tip region, etc.) while other parts are made of a different (non-precious) material without affecting the values of the parameters to be measured, which must remain characteristic of the precious material only (typically these non-important parts are specimen extremities, clamping parts, screwed ends, etc.). Usually the connection of the different parts to form the final composite specimen is achieved by welding.

In order to get reliable test data from such specimens several problems have to be solved in advance:

- theoretical validity of the parameters which are to be measured, e.g., existence of *K* and *J* fields in front of cracks in small and in composite specimens;
- role of volume statistics;
- effects of specimen processing technique, e.g., roles of HAZ and residual stresses in weld-reconstructed specimens;
- adequacy of conventionally available experimental facilities for testing non conventional specimens (e.g., when suitable extensometers are not available for too small specimens).

An activity specifically addressed at setting up procedures for fracture toughness testing of material removed from plant components was started in 1987 in CISE laboratories, in the frame of an ENEL/DSR (Italian Electricity Board, R and D Division) project aimed at high temperature components integrity assessment. Both specimen types, namely miniature size and weld-reconstructed, were utilised, and a discussion of test results is the subject of this paper. As far as weld-reconstruction philosophy is considered, good results had already been obtained at CISE in impact tests on Charpy 'V' (CV) and precracked Charpy 'V' (PCCV) specimens, with specimen ends attached to core regions by resistance butt welding. Interest has recently been put in the alternative technique of electron beam (EB) welding, potentially quite convenient in focusing the weld into a very net area and thereby limiting the extent of heating of adjacent regions; in addition, the technique is suitable for welding thick pieces. Results obtained in impact tests, static LEFM tests (*K* determination) and static EPFM tests (J_{Ic} determination) using EB welded specimens are presently discussed. In case of sub-size specimens, the interest was restricted to J_{Ic} tests.

In the type of activity here referred to, the objective was primarily to derive, from considerations over experience and results gained from tests performed with only moderate degree of sophistication in the techniques adopted, impressions regarding the directions for future activity. Namely, depending on the degree of success already obtained in these tests and on the extent of the difficulties which have been encountered and still need to be solved, it will be decided whether additional efforts merit being pursued.

Materials and experiments

Four types of steels were considered: SA333 Gr6 steel and AISI 304 stainless steel for piping, 1CrMoV forging rotor steel and SA533B pressure vessel steel, with chemical compositions and main mechanical characteristics given in Table 1. As in this phase the aim was to set up and verify test procedures more than to characterise serviced materials from plants, the tests were performed on materials in the as-received state of fabrication.

The essence of the job was to carry out a number of comparisons between test data obtained from standard specimens and data from weld-reconstructed and sub-size specimens. The test matrix is shown in Table 2. Charpy impact tests were made on composite specimens of SA333 Gr6 steel, for which conventional specimens test data were already available for comparison. Specimens of AISI 304, 1CrMoV, and SA533B steels were utilised in fracture toughness tests for K_{Ic} and J_{Ic} determination. Test temperatures were chosen depending on brittle or ductile behaviour requested in the different types of tests performed: well below the FATT (FATT = fracture appearance transition temperature) in K_{Ic} tests and well above the FATT in *J* integral tests; no K_{Ic} tests were made on AISI 304 steel.

For the EB welded specimens, the 1 inch thick compact tension geometry was considered. Two reconstruction geometries were considered, one with the additional (i.e., non-important, non-precious, easily available) material in the front position, called 'F-type' in Fig. 1(a), and a second type having the additional material welded around a cylindrical core of the actual test material,

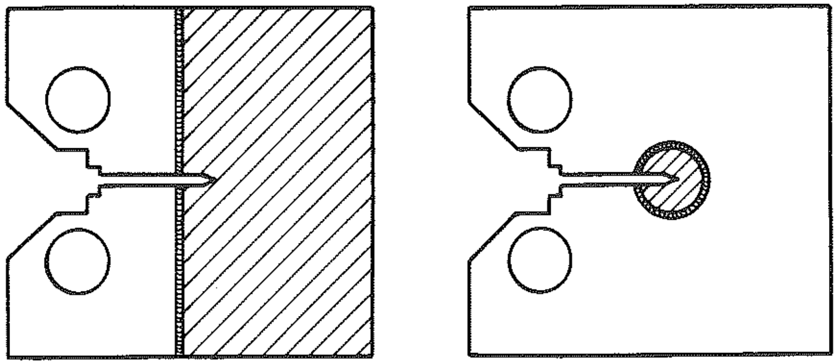
Table 1 Chemical composition (weight percent) and mechanical properties of the experimental materials

Material	*C*	*Si*	*Mn*	*P*	*S*	*Cr*	*Mo*	*Ni*
AISI 304	0.03	1.00	2.00	0.045	0.030	18.00	0.50	8.00
SA533B Gr.B Cl.1	0.21	0.23	1.43	0.006	0.011	0.08	0.50	0.62
1CrMoV	0.33	0.22	0.77	0.009	0.006	1.25	1.18	0.06
SA333 Gr.6	0.30	0.10	0.29	0.048	0.058			

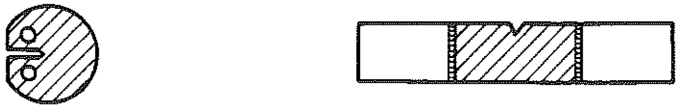
Material	T (°C)	$\sigma_{ys,\,0.2}$ (*MPa*)	σ_{uts} (*MPa*)	*FATT* (°C)
AISI 304	RT	193.2	516.8	
SA533B Gr.B cl.1	−150	612.2	777.6	−8
	RT	449.9	597.6	
1CrMoV	+150	610.5	751.5	+96
SA333 Gr.6	RT	298.8	448.1	−31

Table 2 Test matrix

Material	*Specimen type*	*LEFM tests*	*EPFM tests*	*Impact tests*	*Residual stresses determination*
AISI 304	1TCT conventional	—	2 (RT)	—	—
	1TCT 'F-type'	—	2 (RT)	—	—
	1TCT 'C-type'	—	—	—	—
SA533B	1TCT conventional	2 (−150°C)	2 (RT)	—	—
	1TCT 'F-type'	2 (−150°C)	2 (RT)	—	2
	1TCT 'C-type'	2 (−150°C)	—	—	2
1CrMoV	1TCT conventional	2 (−150°C)	2 (+150°C)	—	—
	1TCT 'F-type'	2 (−150°C)	2 (+150°C)	—	—
	1TCT 'C-type'	—	—	—	—
SA333	CV reconstructed	—	—	3 (RT)	—
	PCCV reconstructed	—	—	3 (RT)	—
1CrMoV	1/2TCT	—	5 (+150°C)	—	—
	Miniature disc-shaped	—	8 (+150°C)	—	—



Compact-tension F-type Compact-tension C-type



Miniature disk-shaped Weld reconstructed Charpy-V

Fig 1 Types of specimen considered; 'precious' material is shaded

which therefore completely surrounds the crack tip region **(3)**: 'C-type' (C = core) in Fig. 1(b). (Actually, the distinction between additional material and true test material is essential in real applications of this technology, to characterise material sampled from components. In the case of setting up and verifying experimental procedures, e.g., against undesired effects of residual stresses, thermal sensitisation of crack tip zone etc., the distinction is less important and in fact the two parts of the present specimens, i.e., the additional material and the core material, were from the same heats). During EB welding, no specimen cooling was provided. Initially with the C-type specimens, cases of weld cracking all around the cylinder surface during post weld cooling in the room air were found, indicating that positive residual stresses were acting. To oppose such stresses, cylinder diameters (16.25 mm) overdimensioned with respect to the diameters of the holes in the plates (16.00 mm) were utilised. Insertion of the cylinders was made easy by cooling the cylinders in liquid nitrogen before insertion into holes. In terms of a simplified two-dimensional model from **(4)**, a compressive hydrostatic stress field is created, with a radial component of 170 MPa. The actual extent of the residual stresses near the crack tip region was measured on the F-type and on the C-type reconstructed specimen, in the loading and in the crack growth directions, using the destructive technique consisting of progressive layering the specimen by spark erosion, while registering the strains so relaxed **(5)**. Stresses were measured all along the thickness when using specimens in which the notch had not yet been machined, and only on the lateral surface when using notched specimens (the reason being related to details of the idealised models in the stress evaluation procedure based on measured strain values **(5)**; discussing such features is beyond the scope of this paper).

For the miniature specimens the disc-shaped (DS) compact tension geometry of ASTM E399 was considered, with minimal material consumption for a fixed sample volume. These specimens had a diameter of 16 mm, typical of sample irradiation facilities in nuclear reactors and also typical of dimensions of 'carrots' of materials when sampling thick components; the thickness B was 6 mm, and the width W 12 mm, Fig. 1(c). From preliminary analyses it was argued that LEFM conditions did never exist down to liquid nitrogen temperature when testing miniature specimens with $D = 16$ mm of AISI 304 and SA533B, while the situation for 1CrMoV was doubtful. It was therefore decided to perform only J integral tests on the miniature specimens and to use the 1CrMoV steel having the highest probability of providing valid data according to ASTM E813, while with specimens made of the other steels a sufficient 'J capacity' was doubtful.

Tests were performed on a servo-controlled 100 kN machine. Test procedures for the weld-reconstructed specimens were conventional, and are not mentioned, except saying that the unloading compliance (UC) technique was used for single-specimen derivation of J–R curves; details may be found elsewhere **(6)**. In the miniature specimen tests a problem arose due to the small dimensions which made difficult the use of clip gauges for load point displacement measurements. The problem was solved by utilising an indirect method, namely recording the actuator displacement values and correcting them for machine compliance. The degree of accuracy of this technique was previously checked in tests of conventional dimensions and turned out adequate according to ASTM E813 for most materials and test conditions **(7)**. As a matter of fact, the accuracy was adequate for multi-specimen J–R curve derivation, but of course not for single-specimen J–R curve derivation via the UC technique; therefore the multi-specimen procedure was systematically applied in J integral tests on the miniature specimens. More recently, however, the reversing direct current electrical potential drop (RDCEPD) method was implemented at CISE laboratory for crack length determinations in various types of mechanical tests **(8)**; the degree of accuracy of this technique for single-specimen J–R curve derivation with miniature specimens was checked in some recent tests on the miniature DS specimens of 1CrMoV.

Results

Weld-reconstructed specimens

In all cases the welds proved to be of sufficient strength, as no cracking along the welded surfaces was observed during the tests performed.

Results of the fracture toughness tests under LEFM conditions for specimens of the normal type (i.e., made from a single piece, not from two welded pieces) and the welded types are compared in Fig. 2. For the two materials investigated the toughness data of the normal specimens are close to the F-type specimens data; on the other hand the C-type specimens of SA533B show much higher values of apparent toughness. In addition due to the large fracture loads no valid K_{Ic} results could be obtained for the C-type specimens; this same difficulty arose in one of the four other tests on normal and F-type specimens; the K values in Fig. 2 are therefore from the equivalent energy method.

The J_{Ic} data from the different tests on normal and F-type specimens are compared in Fig. 3. Here again the agreement is good. Such data come from reductions over well overlapped J–R data, see for example Fig. 4 for the SA533B steel.

Residual stresses in the load direction measured in an unnotched F-type and in an unnotched C-type specimen of SA533B near the region where the crack tip should be present are shown in Fig. 5. Surface values measured on notched specimens are also reported (similar trends were found for the stress component in the crack growth direction, but they are not presently reported for the sake of brevity). It should be appreciated that the measured residual stress field for the C geometry is tensile in the mid-thickness region and compressive near to the surface. The maximum stress is quite large; a change of sign in the residual stress field near the lateral surface of the C-type specimen occurs when the notch is machined. In the F-type specimen the stresses are lower.

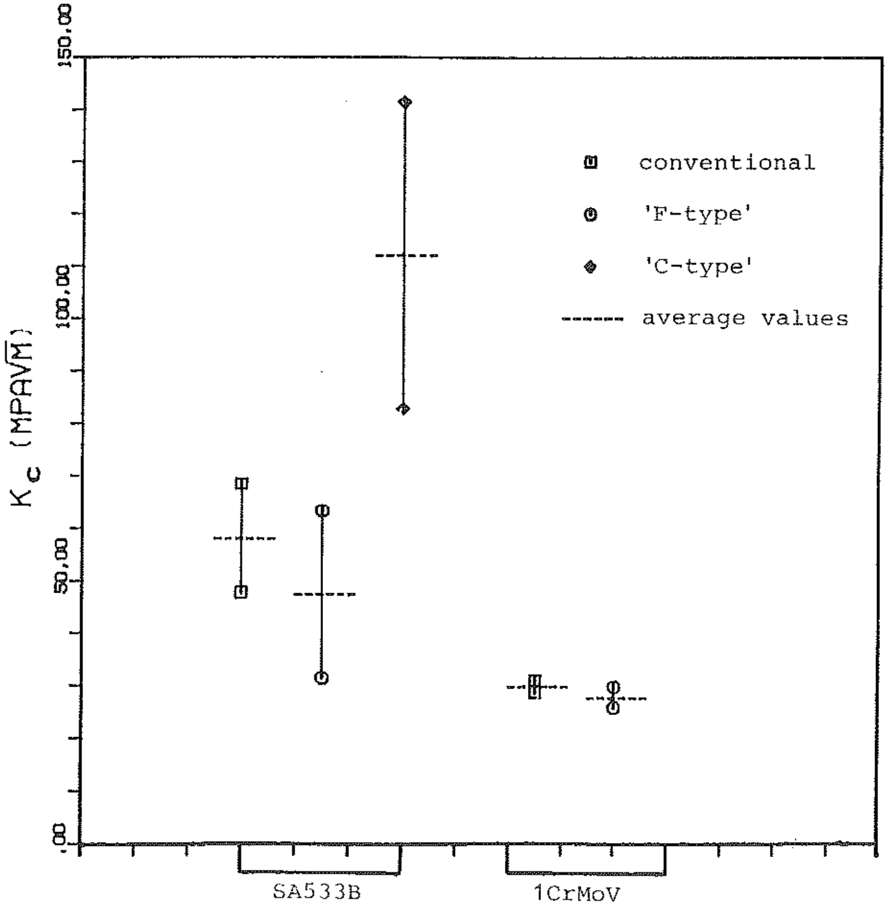


Fig 2 Comparison of LEFM test results for different types of specimens

The results of the impact tests, simple and instrumented, on normal and EB reconstructed Charpy specimens are finally shown in Fig. 6: the discrepancy between normal and composite specimens is quite large.

Miniature specimens

Two aims were pursued: first, to demonstrate that J integral data obtained via a multi-specimen technique from tests on the miniature size DS specimens reproduce data from tests on conventional specimens; second, to assess the applicability to miniature specimens of the RDCEPD technique for single-specimen J–R curve derivation. For the former scope, a number of tests utilising 1/2 inch CT specimens of the 1CrMoV steel were performed and the

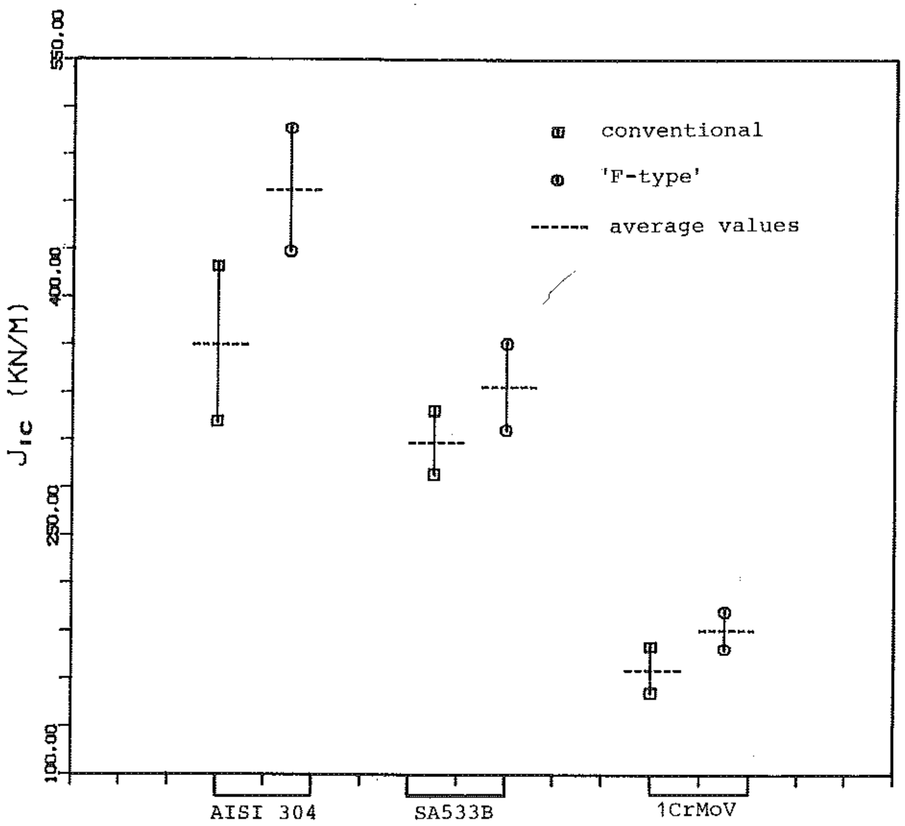


Fig 3 Comparison of EPFM test results for different types of specimens

results are compared in Fig. 7 with the data from the tests on the miniature specimens of the same steel. These latter data come from two distinct groups of tests: one in which the RDCEPD technique was utilised and one in which it was not. This distinction is inessential when data are treated according to the multi-specimen philosophy, as in Fig. 7; but the two groups have been explicitly identified in Fig. 7 for a different reason. The two groups of tests were performed at different times (a year in between) and a number of machine loading elements had been substituted by different pieces in the meantime (rods, bolts, pins, etc.). The machine compliance was different between the two groups of tests and in fact two experimentally determined compliance calibration curves were used to evaluate load point displacements according to the previously mentioned indirect method. An error in the calibration curve is cause of systematic deviations of all the J data based on that calibration; therefore the distinction between the two sets of data in Fig. 7 was to manifest the effect of this variability in calibration determination over the test points for the sub-size specimens.

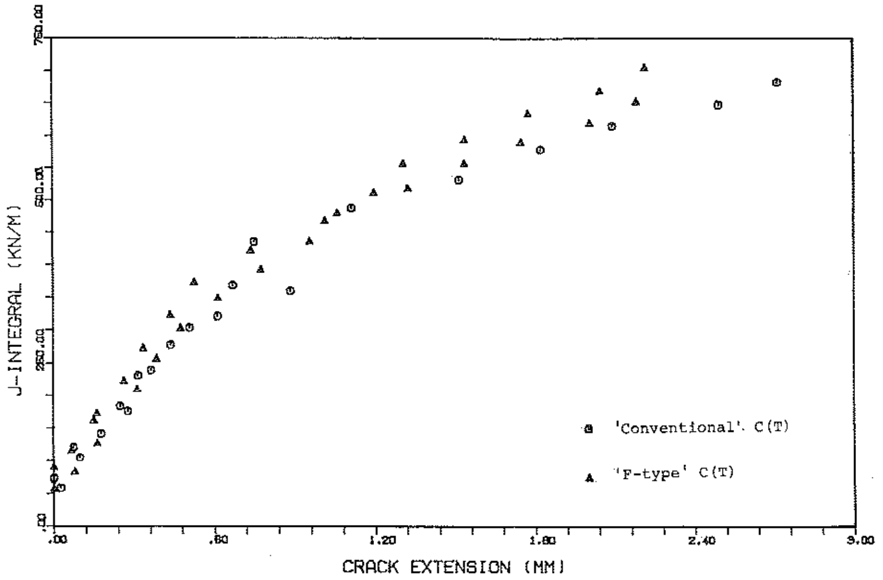


Fig 4 *J–R* curves obtained with the unloading compliance method on different types of SA533B specimens

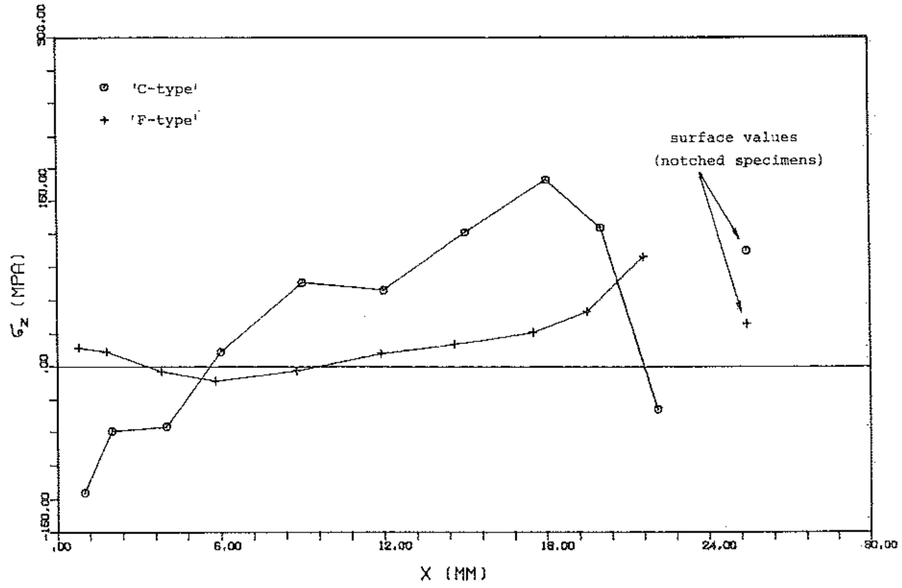


Fig 5 The residual stresses measured in the load direction

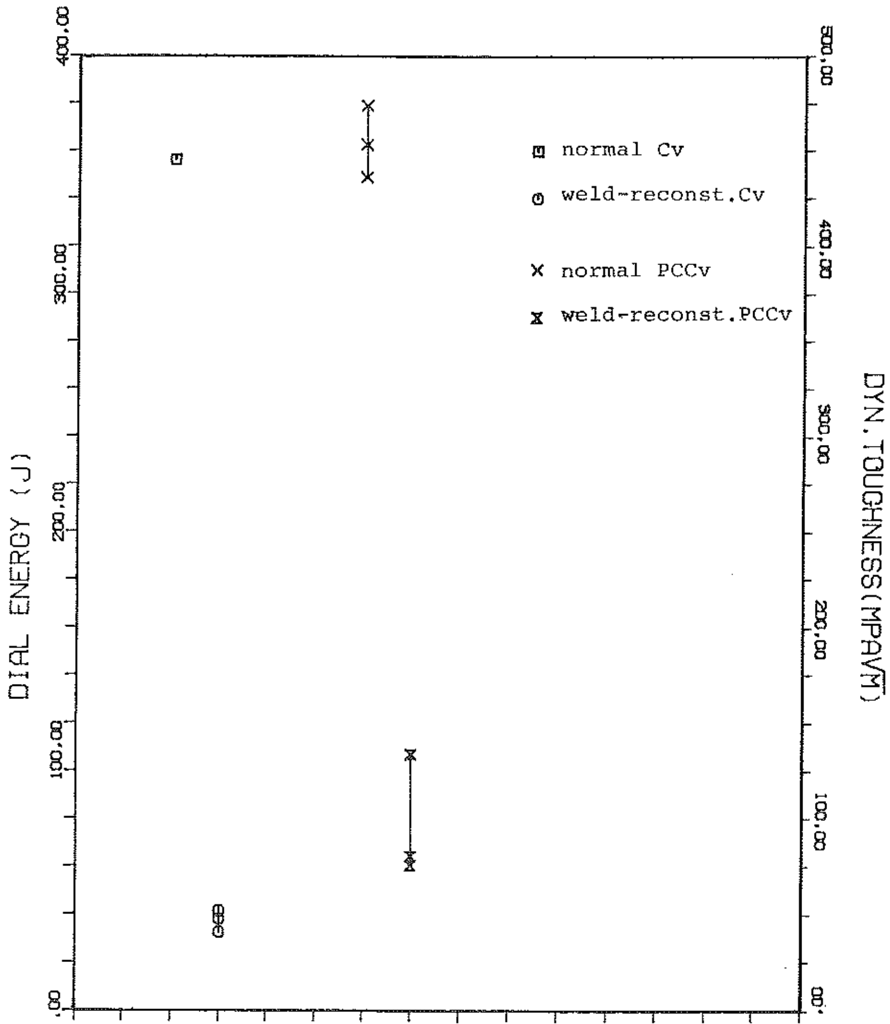


Fig 6 Comparison of impact test results from normal and reconstructed specimens

As far as the degree of accuracy of the RDCEPD method in single-specimen derivation of *J–R* curves is of concern, this analysis is shown in Fig. 8 in terms of *J–R* curves, and in Table 3 in terms of *J* data. Comparisons between values of final crack extensions measured from fractography and values obtained from RDCEPD technique are also shown in Table 3.

Discussion

Due to the limited amount of tests performed in each particular condition, in general it can be said that definite conclusions cannot be derived for all the

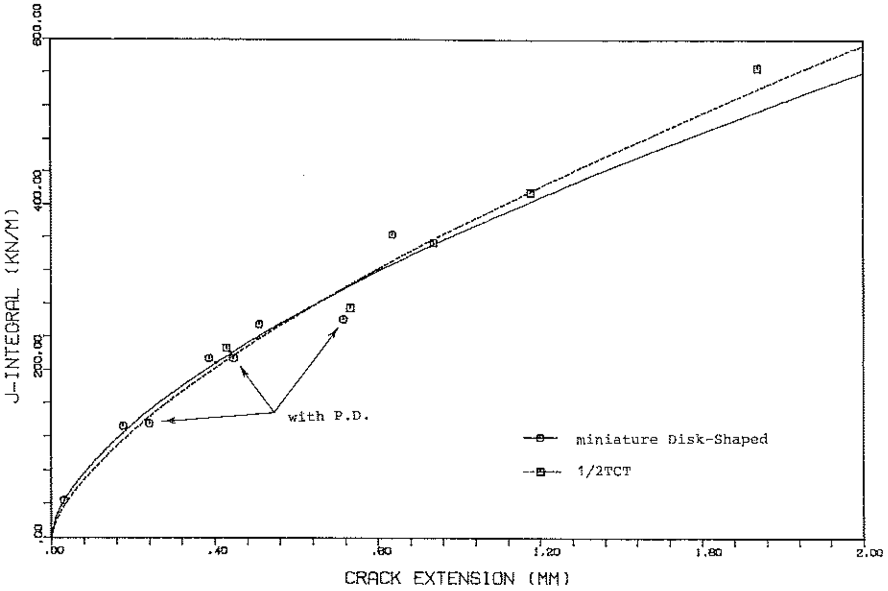


Fig 7 EPFM test results obtained from standard 1/2TCT and miniature disc-shaped specimens

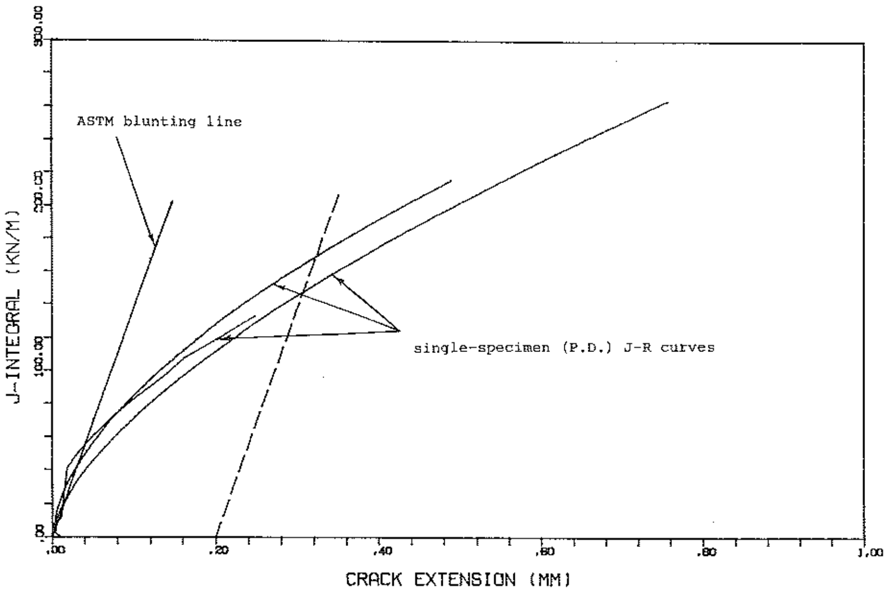


Fig 8 *J–R* curves obtained with the RDCEPD method on miniature disc-shaped specimens

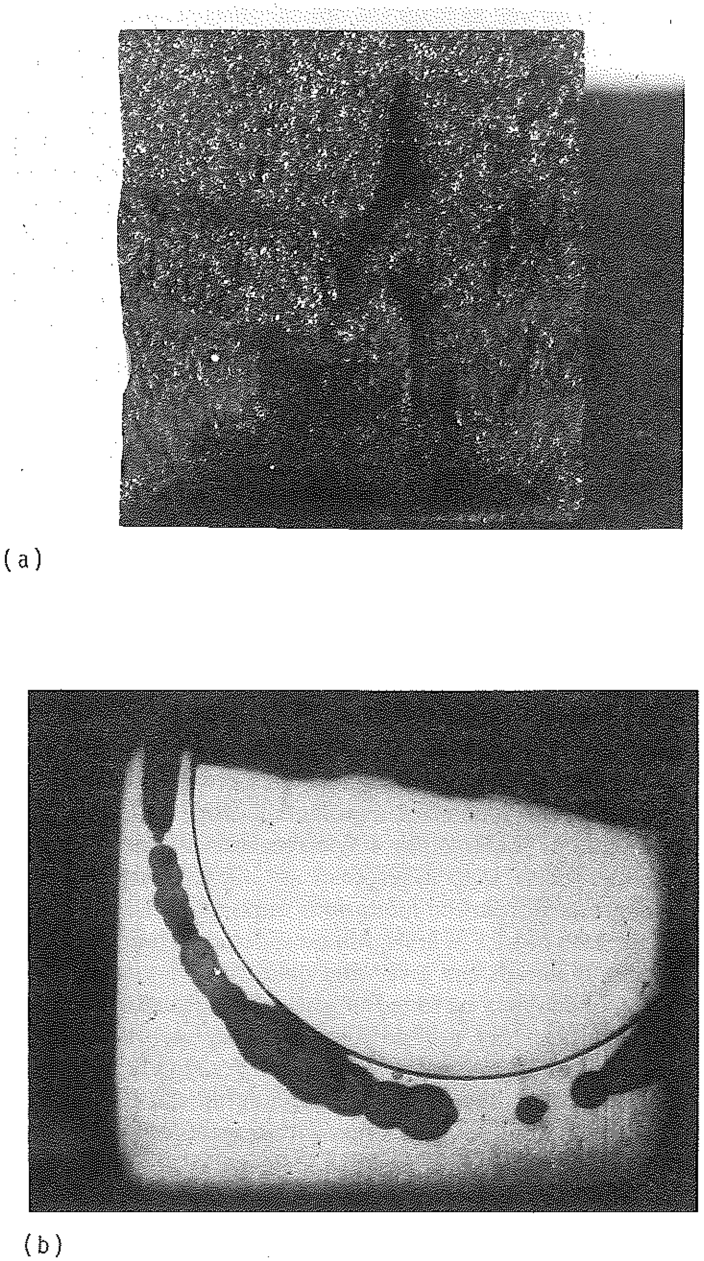
Table 3 **Analysis of accuracy of test results via the RDCEPD method**

	Multi-specimen	*Single-specimen (RDCEPD)*
J_{Ic} (kN/m)	190.50	147.41 150.00* 169.04
	Measured	*From RDCEPD*
Δa_{fin} (mm)	0.72 0.24 0.45	0.76 0.25 0.49

* Estimated value, from a prematurely ended test.

cases considered. This seems particularly the case with the experiments aimed at clarifying the possible use of reconstructed specimens obtained via EB welding for fracture toughness evaluations.

Results obtained in the LEFM tests seem to indicate that the C-type weld reconstructed specimens were inadequate in providing correct K data, representative of the core material. Surely a main problem was the presence of large residual stresses: in the centre region of the crack tip, from which crack initiation should first occur in a LEFM test under plane strain condition, the residual stress in the load direction was tensile. In fact, considerable tunnelling was observed in post-test fracture surface examination, Fig. 9(a). The attempt to introduce a pre-compressive state by over-dimensioning the core diameter to oppose the tensile residual stress in the mid-thickness region cannot be commented. It is even difficult to say if the cause for the fairly high values of the apparent fracture toughness of the C-type specimens was the residual stresses field along the crack tip. Non-linear behaviour was found in the initial portion of the load–displacement curve in a K test of a C-type specimen, followed by a sort of pop-in possibly due to early crack initiation at a region of high tensile residual stress followed by difficult crack initiation in other parts where residual stresses were in compression. Perhaps a problem even more important was the poor quality of the EB weld; evidence of erroneous orientation of the beam was found, leading to non-welded surfaces, Fig. 9(b). On the other hand the situation for the LEFM tests on the F-type reconstructed specimens was significantly better. Reliable fracture toughness data were obtained in this latter case, together with moderate residual stresses. Unfortunately the economy of test material provided by the F geometry is not much. Results seem therefore to suggest the usefulness of a better consideration of conditions which can improve the EB welding procedures for C-type specimens in order to reduce internal stresses and to provide complete welding of the surfaces. The possibility of relieving the residual stresses via a post-weld heat treatment and/or applying a correction to the load value used in the K evaluation formula (as reported in (3)) should be considered. From the types


(a)

(b)

Fig 9 **SA533B, C-type reconstruction: (a) crack tunnelling after a J_{Ic} test; (b) side cross section, wrong fusion line**

of results obtained as well as from the optical observations performed at a low magnification it seems that material embrittlement produced by heat diffusion towards the crack tip region during EB welding is not a problem for the 1 inch thick CT weld-reconstructed specimens considered; in contrast, the fairly low impact energies found in the composite Charpy specimens with respect to the standard specimens with respect to the standard specimens are indicative of considerable embrittlement of the core material. Of course, when such small volumes of material are considered, a better control of the EB welding process would be needed: reduced diameter of the welding beam, lower intensity or, even simpler, water cooling of the centre part of the Charpy specimens.

EPFM tests on F-type specimens do not present particular problems, as J–R curve data and J_{Ic} values have been found close to those of conventional (large) specimens. EPFM tests on the C-type specimens had not been planned when starting this experiment, even if these latter tests might be perhaps even more promising than the K_{Ic} tests. The presence in the C-type specimens of zones with different values of the elastic modulus, E (core material, weld zone, HAZ, additional material), disturbs the K field, with a perturbation which is of about the same proportion than variations in E **(3)**. Provided that the yielded region is confined in the core part of a C-type specimen in an EPFM tests, this perturbation becomes negligible, as it affects (slightly) only the (small) elastic part of J. Also, the role of the residual stress field should be less critical in EPFM tests on C-type specimens than in LEFM tests. This point merits further consideration.

Derivation of reliable J–R curve data and of J_{Ic} values from tests on miniature DS specimens with 16 mm diameter has proved successful. In this case use of a sophisticated version of a potential drop technique allows further saving of amount of material, as single-specimen J_{Ic} derivation is possible. Perhaps the main obstacle to widespread use of miniature specimens for fracture toughness tests is from the limitations imposed by the fracture mechanics theory itself. In case of LEFM tests, not considered in the present experiments, only very brittle materials can give valid data from very small specimens, and in this case a problem may be found in getting accurate displacement values as the indirect technique here utilised loses accuracy at low values of displacement. In the case of EPFM tests a sufficient J capacity of the specimens is needed, and in fact the present tests were made on the 1CrMoV steel having lowest toughness and highest flow stress with respect to SA533B and AISI 304, conditions which favour good J capacity. As generally sufficient J capacity is a less stringent requirement than sufficient K capacity, miniature specimens are primary candidates for J_{Ic} testing. A typical difficulty in getting valid data according to ASTM standard practices E813 (J_{Ic}) and E1152 (J–R curves) is the limited range of crack extension data which must be considered. Often it becomes necessary to include invalid data from the initial portion of the J–Δa diagram to get a satisfying analytical determination of the J–R curve, so that J_{Ic} is found by interpolation instead of back-extrapolation; in certain cases it may be necessary even to moderately extrapolate in advance. Current test standards do not take care of the specific problems of testing very small specimens as requirements are stated taking in mind specimens of conventional dimensions, typically B, bo and $W > 20$ mm. For example, when applied to the present miniature specimens, use of the exclusion line through $\Delta a = 1.5$ mm fixed by ASTM E813 allows valid J–Δa data up to $\Delta a_{\max} > 0.4\ W$ to be taken, which is seven times beyond the extension of the J controlled region in the specimen ligament **(9)**. This is physically meaningless and would demand a more restrictive recommendation. In other cases recommendations should be put in different ways in order to be less prohibitive for tests on very small specimens.

Conclusions

In many circumstances the amount of material available for conventional fracture toughness testing is insufficient. This happens typically when material availability is limited by the need not to destroy the component from which specimens have to be taken, and in testing pipe material with insufficient wall thickness. In the present study an analysis was attempted of the experimental problems which arise when utilising non-standard specimens of two types: specimens with normal dimensions obtained by welding smaller portions via high energy electron beam heating, and miniature specimens.

Results obtained in toughness tests on weld-reconstructed specimens for three steels have indicated that several problems have yet to be solved. In particular, good results have been obtained only for a reconstruction geometry (called F-type) which has only a modest material saving advantage with respect to a normal single-block specimen. However, at least for pipes with a certain range of wall thickness, this technique seems effective. The second type of reconstruction geometry considered, C-type, is potentially more advantageous in avoiding material waste, as the key part is the small kernel at the crack tip. However in the present case the EB welding was imperfect and caused excessive residual stresses. A deeper study of this technology is needed at CISE in order to get reliable fracture data. Finally, the impact tests on Charpy specimens revealed consistent heat embrittlement caused by the EB process in the fracture zone; here water cooling seems the most natural remedy.

The different solution provided by testing miniature-size disc-shaped specimens should be preferred whenever theory can predict that such specimens made of a certain material are suitable for obtainment of valid toughness data: in practice the K fields or the J fields must exist at the crack tip. From an experimental viewpoint technical problems do not really exist. The present study has demonstrated that it is even possible to use a single-specimen procedure based on a potential drop method for the derivation of reliable J_{Ic} data. Perhaps problems of fitting existing test standard practice recommendations to certain peculiarities of miniature specimen tests should prompt further considerations.

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Influence of Notch Acuity on the Temperature Dependence of Fracture Mechanics Values

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ABSTRACT Fracture mechanics tests with different kinds of specimens have been performed to study the influence of specimen geometry and notch acuity on the fracture mechanics transition curve of three steels (Fe 510, FeE 690, FeE 885). Tests on specimens containing a blunt notch with a notch tip radius of 0.1 mm instead of a fatigue crack lead to an increase of the J_{i} values of 30–50 percent. The slope of the transition curve remains unchanged. The transition temperature T_{i} is shifted about 10 K to lower temperatures with decreasing notch acuity. The use of J_{c} and J_{i} values obtained from notched specimens for a failure prediction of wide plates containing notches with identical notch-tip radius as used in the small scale specimens leads to unsafe predictions. This result may be explained by differences of the local constraint although the notch acuity was equal. Finite element (FE) calculations with refined meshes for calculation of meaningful local stresses and strains will answer this question.

Introduction

A fracture mechanics based failure analysis (K, CTOD, or J analysis) requires the knowledge of material values describing the response of the material to the actual loading situation in the structure. The conservatism of the final statement about the safety of a structure strongly depends on the quality of the simulation of the constraint in the small scale specimen used for the evaluation of material values.

The influence of several geometry parameters like specimen thickness B, width W, overall dimensions, specimen type, side grooving and crack length a_0 on fracture mechanics material values and on crack resistance curves has been investigated by several authors **(1)–(5)**. In all cases fatigue cracks have been used to simulate a very severe loading situation. This seems to be quite reasonable due to the fact that fatigue cracks are often found in real structures. The assessment of components containing small notches instead of fatigue cracks often leads to very conservative estimations of tolerable defect sizes, loads, or minimum service temperatures, resulting from low material values due to a higher constraint in the prefatigued specimens compared to the notched component.

The investigations presented in this paper should show the influence of using notches instead of fatigue cracks, sidegrooving and specimen thickness on the J integral material values and the assessment of wide plate test results.

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