CHARACTERIZATION OF DUCTILE MATERIAL BEHAVIOUR BY J-R CURVES

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An improved characterization of ductile material behaviour by J-R curves and by derived fracture toughness parameters is a major goal of the activities of EGF Task Group I "Elastic Plastic Fracture Mechanics". The state-of-the-art in applying single specimen tests based on potential drop and partial unloading compliance methods is described and discussed in terms of accuracy and reliability. The quality of test results allows for separation of procedural and material variations, to get down to the problem of geometry dependence of J-R curves, and for updating and finalizing the procedures of ductile failure test standards.

INTRODUCTION

The ductile failure behaviour of steels is characterized by crack initiation after macroscopic plastic deformation and crack tip blunting, by more or less distinct stable crack extension, and by subsequent local or global instability depending on the relevant mechanical and material conditions. These different stages and the underlying mechanisms of void nucleation, growth, and coalescence are described in the framework of elastic-plastic fracture mechanics (EPFM) by J-crack growth resistance curves (J-R curves). They deliver a quantitative measure of the actual fracture resistance of the material in terms of the loading and crack driving parameter J-integral as a function of the increasing crack size. In laboratory tests J is evaluated from the work done on the precracked specimen whereas the corresponding stable crack growth is determined from additional measurements - for instance potential drop or partial unloading compliance - during the test or subsequent evaluation of the fracture surfaces

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of a series of interrupted loading tests. A high degree of
precision is necessary in such measurements to deliver well defined
material curves which allow for further evaluation of material
parameters like initiation toughness J_i, J_{Ic}, $J_{0.2}$ (see
Schwalbe et al. [1]), tearing modulus T, or instability parameter
J_{50}. In applying such results to the assessment of cracked com-
ponents it is important to take into account all details of the
specific structural situation as there are temperature,
orientation, constraint and to have them properly modelled in the
experiments. This problem of transferability can only be solved
by analyses and more complete material characterization; their
interrelation has to be checked in component tests.

The EGF-Task Group on Elastic-Plastic Fracture Mechanics
(Figure 1) is active in these three regimes. Through information
exchange in plenary and specialists' meetings as well as on a
personal basis, coordination of research programs, round robins,
or joint evaluation of large scale tests it is tried to strenghten
European capabilities and efforts for a better understanding of
ductile failure of materials and components.

This report concentrates on material characterization. The
experiences at different member laboratories of the Task Group and
the results of round robin as well as standardization activities
show that computer controlled single specimen J-R curve tests
offer the chance for improved resolution, accuracy, and re-
producibility necessary to separate the influences of mechanical
and material parameters. Possibilities, results, and some problems
are described in the following, when applying such J-R curve pro-
cedures in a temperature range from 100 to 1100 K for different
materials.

POTENTIAL DROP METHOD

The principle of a direct current potential drop (DCPD)
method as used by IWM [2] is shown in Figure 2. A highly
stabilized direct current of about 5 A is fed into the specimen in
the plane of loading and the potential drop φ is measured at two
contact points across the crack. Zero compression is used at begin
of test and the small changes $\Delta \varphi$ during loading (order of mag-
nitude $1 \mu V$) due to deformation and crack growth are amplified and
recorded together with the force F and the load-line displace-
ment V. Initiation of ductile tearing is indicated by a more or
less distinct change of slope of the $\Delta \varphi$-V curve and the further
change of $\Delta \varphi$ in good approximation is proportional to the crack
growth Δa:

$$\Delta a / \Delta \varphi = c \cdot \varrho(T) \cdot I/B^2$$

with $\varrho(T)$ = specific resistance of material as funtion of tempera-
ture T, I = constant current, B = specimen thickness, and c =
geometry dependent constant.

Figure 3 as an example shows the force/potential drop vs. load-line displacement diagram together with the fracture surface of a 50mm thick compact specimen of the steel 20Mn Mo Ni 55 tested at 300°C. The J-Δa curve derived from these measurements using Equ. (1) is shown in Fig.4 (No.7). Also shown are results of additional tests of the same kind which have been interrupted at lower levels of displacement and have been broken open at liquid nitrogen temperature to reveal the actual stable crack growth. Their final J-Δa points (filled symbols No. 1 ...6) and the corresponding PD-derived curves confirm the first single specimen result. In addition Fig.4 demonstrates: Whereas the multiple specimen unloading procedure as standardized in [3] delivers just one J-R curve, which may be hard to be interpreted in cases of larger variations of material properties, several single specimen tests with continous potential drop measurement allow for a statistical assessment of procedural and material scatter. But it is recommended that when using the single specimen procedure one additional specimen should be unloaded after a small amount of crack growth to verify initiation.

The precision and reliability of the DC potential drop method may be assessed from tests as in Fig. 3 and 4:

RESOLUTION: At a current of 10A a maximum change of potential of 5 μV was measured for a stable crack extension of 2.5 mm in a CT50 specimen. Thus a resolution 2 μV/mm results. Figure 3 shows superimposed fast variations of a magnitude of 0.1 μV; there-fore only distinctly larger changes corresponding to Δa > 0.05 mm can be interpreted as real crack growth.

ACCURACY: Besides parameters like current, material, specimen size, test temperature and quality of electronic components the absolute accuracy of a crack length measurement depends on the quality of a linear interpolation as in Equ. (1) and is limited by an uncertain influence of the crack front curvature. The unloading points in Fig.4 deliver $\pm$ 0.1 mm as a rough estimate and this is comparable to the accuracy for an optial crack length measurement on a fracture surface.

REPRODUCIBILITY: The smoothness of the single specimen J-Δa curves in Fig. 4 indicates a reproducibility of the potential and from that of the crack length measurement of better than $\pm$ 0.05 mm. Comparing curves of "identical" specimens it is not possible to separate differences resulting from material or procedural varia-tions. The 7 results in Fig. 4 define a common scatterband which is wider than that for each single test and therefore should mainly be determined by variations in material properties between the specimens.

PARTIAL UNLOADING COMPLIANCE METHOD

The partial unloading compliance (PUC) method as principally sketched in Fig.5 is the preferred single specimen test method for J based material toughness characterization in existing drafted or published standard documents [3,4,5,6]. This method is realized in a computerized test control and evaluation system at IWM [7] the novel and essential features of which are:

- on line evaluation of J-values from load and displacement measurements digitized in a 16 bit A/D converter

- control of test according to predefined parameters and conditions or push-button of the user; the computer supplies control signals to the function generator of the loading machine, the analog closed loop control system of which remains unchanged; in this way a free of doubt definition of parameters in repeated tests is possible.

- from the unloadings the specimen compliance is evaluated by linear regression of the F/V data and from that through known and stored geometry funtions the actual crack length is deduced.

- the J and Δa values are shown on the computer screen and are plotted allowing continous control and -if necessary- immediate change of the test procedure

- the test is finished when reaching preset end conditions or by push-button of the user

- all primary data are stored for later reevaluation

- after finishing the test a preliminary evaluation is conducted and the results are plotted

- for the final evaluation using the real crack length as measured on the fracture surface a specific programme is available which allows to follow different routines for deduction of an analytical description of the J-R curve and of material parameters (J_i, J_{Ic}, T, J_{50},...) with automatic check of relevant validity criteria.

Figure 6 shows a test result demonstrating the performance of the system at $300^{\circ}C$; as for the DCPD method in Fig.4 it may be used to derive a quantitative assessment of the attainable quality of the PUC-method:

RESOLUTION: The first and lowest points of the J-R-curve in Fig.6 show a scatter of $\pm$ 0.1 mm in Δa around the blunting-line which describes a quasi-crack extension by forming the stretch zone.

This indicates a system resolution in the same range, mainly governed by the resolution of the displacement measurement system.

ACCURACY: The difference between the final crack lengths evaluated from the specimen compliance and measured on the fracture surfaces supplies a quantitative measure of the absolute accuracy. This assumes an "effective Young's modulus" to be determined accurately from fitting to the initial fatigue crack-length and using that throughout the evaluation. Figure 6 delivers a difference of about 0.3 mm (equal to 0.5% of crack length) being compatible with the estimated resolution of $\pm$ 0.1 mm.

REPRODUCIBILITY: Figure 7 demonstrates the good reproducibility of the PUC J-R curve generation by results from two tests on identical CT14 specimens with 20% side grooves of the steel X20 Cr Mo V 12 1. As the F/V - diagram for one specimen shows some unloadings have been omitted; from the good agreement for the later part with the second test it can be concluded that there is little or no influence of the small partial unloadings.

COMPARISON OF TEST METHODS

Similar values of the accuracy of crack growth measurements are found from typical J-R curve tests when using the single specimen PD- or the PUC-method. For favourable test conditions, e.g. at room temperature, even better results may be achieved.

But it is only through an independent calibration (length of the starter fatigue crack / initial potential and final crack length / final potential) that the PD-method delivers absolute and accurate crack growth predictions. The PUC-method delivers absolute crack growth results, which are little dependent on the fitted effective Young's modulus and which can be checked against the final crack length on the fracture surface.

The crack lengths and extensions determined by the two methods in principle are different from what is measured on the fracture surfaces of a series of interrupted loading tests. Following the ASTM J_{IC}-standard [3] the stretch zone width is added to the real stable crack extension. But for the single specimen PD-method the stretch zone formation cannot be quantitatively evaluated and Δa (PD) $<$ Δa (ASTM). For the single specimen PUC-method crack tip blunting means an increase of the specimen compliance; but the deduced increase of crack length is not necessarily equal to the stretch zone width and frequently it is found: Δa (PUC) $>$ SZW (fractography). In both cases the differences are small, the order of magnitude being 0.1 mm which is comparable to the measurement accuracy of the two methods. But the differences in principle have an effect on the evaluation of material parameters and should therefore be kept in mind (see [8]).

SPECIFIC PROBLEMS

Crack front curvature

As a consequence of the variation of the stress state over the specimen thickness crack fronts are sometimes strongly bent forward in J-R curve tests. This results in quite different "effective" crack length measurements by the PD- and the PUC-method. Figure 8 is an example from [2] in which both methods have been used to develop a J-R curve. Assuming that for small crack growth because of negligible crack front curvature both methods should deliver the same result the PD-evaluation has been calibrated using two selected PUC-measurements (marked in Fig.8). Then the J-R curves coincide in the beginning but two branches are formed for $\Delta a \gtrless 1.5$ mm.

The crack lengths predicted - 2.5 mm from PUC and 3.0 mm from PD - are different and both do not meet the value of $\Delta a = 3.9$ mm which is found as a 9 point mean value from a fracture surface measurement. To avoid such discrepancies side grooved instead of smooth specimens should be used whereever possible and as recommended by [3]

Negative crack growth

The results of a compliance measurement of the crack length can be influenced by unintentional changes of the loading geometry. This is the background of the standard specification [3] with flat and hardened surfaces for the bolt supports in CT-clevisses. But problems have still been found because under loading the bolts can bend and will induce local plastic deformations which hinder the necessary free rotation of the bolts resulting in an effective decrease of specimen compliance and therefore in an apparant negative crack growth. New grips have been developed [9,7] which use specifically shaped and hardened inserts to maintain line contact between bolts and supports. They have been tested successfully in PUC-experiments at temperatures up to 1100K (see Fig.11).

Measurements at low or high temperatures

When the test temperature is different from room-temperature additional problems arise for the crack length measurement: For the DCPD-method temperature gradients over the specimen result in superimposed thermal voltages. They may be minimized by using appropriate contact wires and thermal insulation of the contact points. In such cases an AC-method is advantageous; but a reference specimen without crack growth should be used in parallel to eliminate the influence of changes of the specific electrical resistance of the material.

For the clipgage in a PUC-measurement an accurate temperature
compensation of the zero-point and of the sensitivity is required.
In addition, the displacement measurement can be disturbed by the
movement of the gaseous or liquid medium for cooling or heating. To
avoid problems a special device was developed (Fig.9 [10]). The
load line displacement is transferred to the load line plane on
both sides of the clevisses through stiff connectors which are
screwed to the specimen front side at positions usually used for the
pair of razor blades to hold the displacement gage. The outer parts
of the connectors are coupled to a pair of LVDT's outside the
cooling bath or the oven by four quartz rods. By a system of
springs guiding the cores and the coils a hysteresis of less than
1 μm over a measurement range of 10 mm is realized for the LVDT-
system. Its performance and the resulting accuracy may be seen from
Fig.10 for a test in a boiling liquid nitrogen bath and from Fig.11
for a creep test at 800°C [11]. The latter technique is now
applied in the round robin exercise of the EGF-Working Party "High
Temperature Crack Growth Measurement".

SPECIFIC RESULTS

One of the activities within the EGF Task Group Elastic-Plastic
Fracture Mechanics was a round robin on crack initiation detection
with M. de Vries being chairman of that specific Working Party [12].
The material used was a plate of steel A 542, mainly CT 25-
specimens were tested. Each participant was free to choose his
own method for measuring a J-resistance curve for the material. Out
of more than 30 labs participating about one third used the PUC-
technique for monitoring stable crack extension. Figure 12 shows
all points measured by 11 of these labs only distinguishing between
smooth and sidegrooved specimens. Negative crack growth that could
be seen in some of the results was simply compensated by shifting
the most negative points close to the blunting line. The points in
Fig.12 show an appreciable amount of scatter. Some participants
claimed to have had no or only little experience with this tech-
nique before and it is assumed that this caused different "levels
of quality" and part of the scatter. But nevertheless a tendency to
steeper resistance curves measured with smooth specimens as com-
pared to sidegrooved ones is obvious. For further evaluation only
results of those tests delivering a resistance curve with enough
points to allow a power law regression $J = C \cdot \Delta a^n$ were
considered. Thus at least part of the tests with some deficiencies
in the performance of the test system were eliminated. The results
of these regressions are plotted in Fig.13 for the smooth and the
sidegrooved specimens. Though the curves are not respresentative
for measurement points of smooth specimens with more than 2 mm of
crack extension, both scatter bands are overlapping even in the
valid region.

In order to distinguish between experimental and material
scatter these curves were analyzed according to the position of the

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specimens in one of three layers across the thickness of the plate. Figure 14 shows the respective curves of the sidegrooved specimens. Obviously the scatter within each subset is less than the total scatterband and the specimens taken from the center layer of the plate tend to develop lower crack resistance as compared to the near surface specimens. These results show that at least part of the scatter seen in the results of this round robin is caused by variations in the material and not by differences or deficiencies in the measurement techniques of different labs. In addition it can be stated that single specimen techniques are able to give information on the amount of material variations in situations where the same variations cause serious problems in evaluating results of a multispecimen unloading series.

CONCLUSIONS

An improved characterization of ductile material behaviour by J-R curves and by derived toughness parameters is a mayor goal of the activities of EGF Task Group I Elastic Plastic Fracture Mechanics. The discussion meetings and the round robin activities within the Task Group have stimulated cooperation and strengthened the work in this field. Single specimen techniques based on potential drop or partial unloading are now available and test results have been cross checked in a large number of European laboratories. The earlier problems of relaxation, negative crack growth, or crack front tunneling are better understood, the reliability of results has been improved by automatization, and the field of application has been extended to low and high temperatures. The high standard of the single specimen methods allows to separate deficiencies of the test procedures and material variations and to attack the problem of geometry dependence of J-R curves. European researchers and laboratories have become not only accepted partners but leading members in ongoing activities to standardize testing of ducticle failure material behaviour.

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        Problems in Nuclear Engineering, Staatl. Materialprüfungsan-
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        Robin", chairman Dr. M. de Vries, ECN, Petten,
        The Netherlands

EGF-TASK GROUP I
ELASTIC-PLASTIC FRACTURE MECHANICS

(J.G. Blauel, K.-H. Schwalbe)

Stress-Strain Analysis   Material Characterization   Component Assessment

WORKING PARTIES

● Numerical Round Robin
(L.H. Larsson)

● R-Curves and Tearing
Instability (I. Milne)

● Crack Growth Round Robin
(M.I. de Vries)

● High Temperature Crack Growth RR
(T. Hollstein)

● Fracture Mechanics Testing Standards
(K.-H. Schwalbe)

Jan. 1986

Figure 1 Organizational structure of EGF Task Group I "Elastic-Plastic Fracture Mechanics
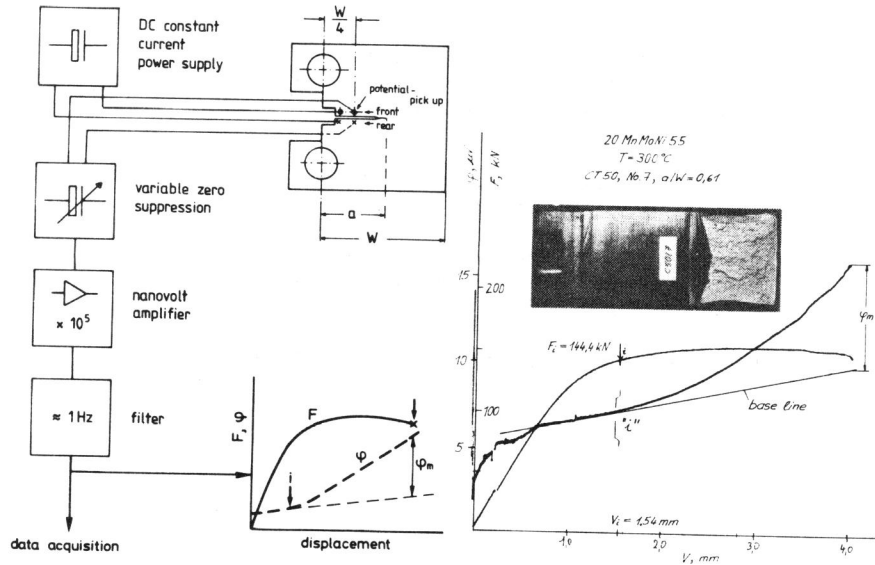
Figure 2 Principle of DCPD-method for J-R curve measurement

Figure 3 Example for experimental diagram with initiation point "i"

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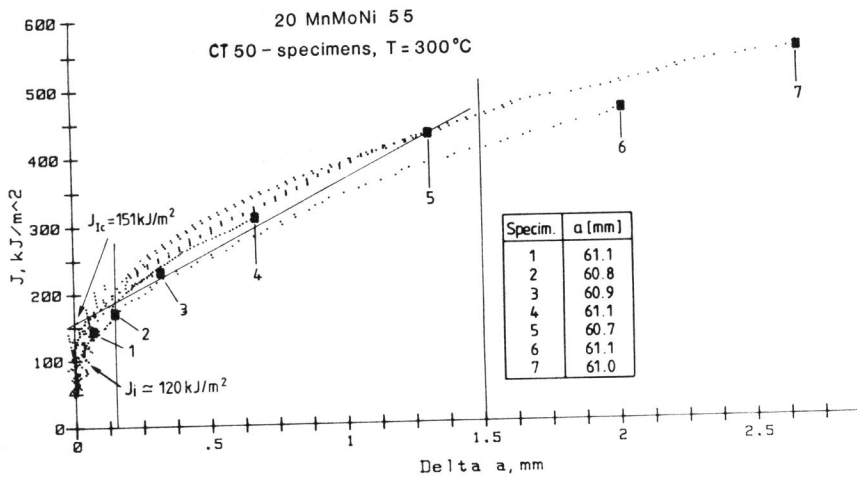
Figure 4 J-R curves of a series of seven specimens: interrupted load points confirm the J-R curves derived from DCPD
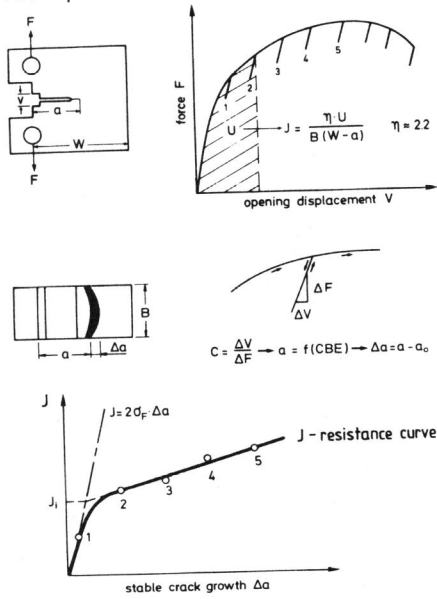
Figure 5 Principle of partial unloading compliance technique
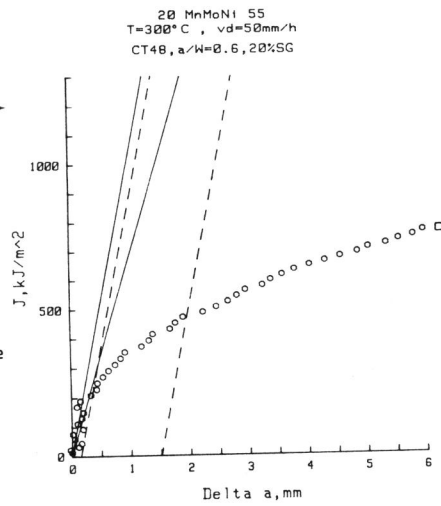
Figure 6 J-R curve, RPV-steel at 300°C, ◘=Δa(final) on cracksurface

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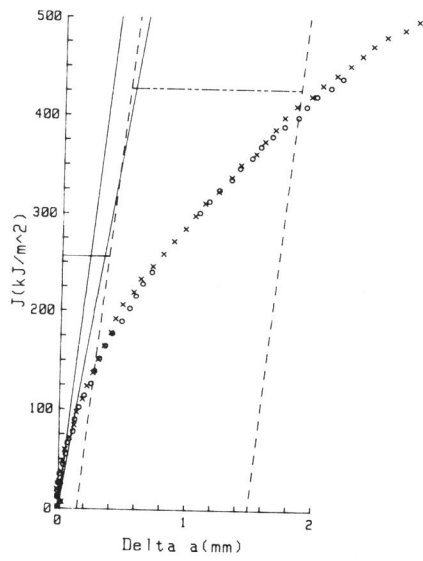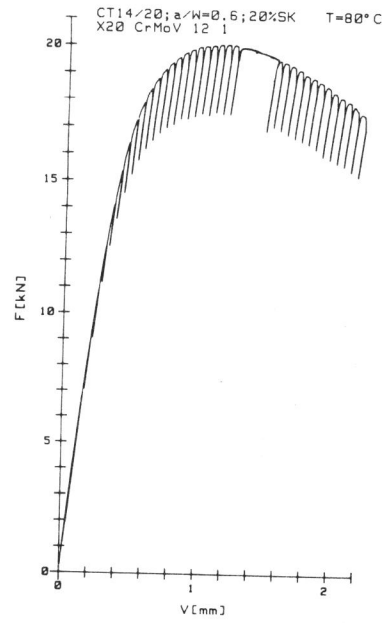
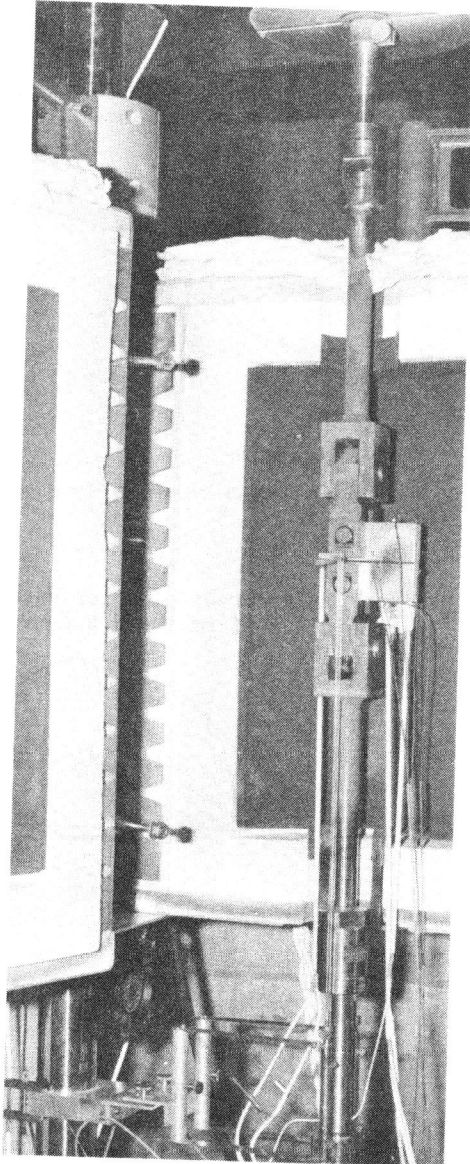Figure 7 Example demonstrating reproducibility of J-R curve measurement and negligible influence of partial unloadings

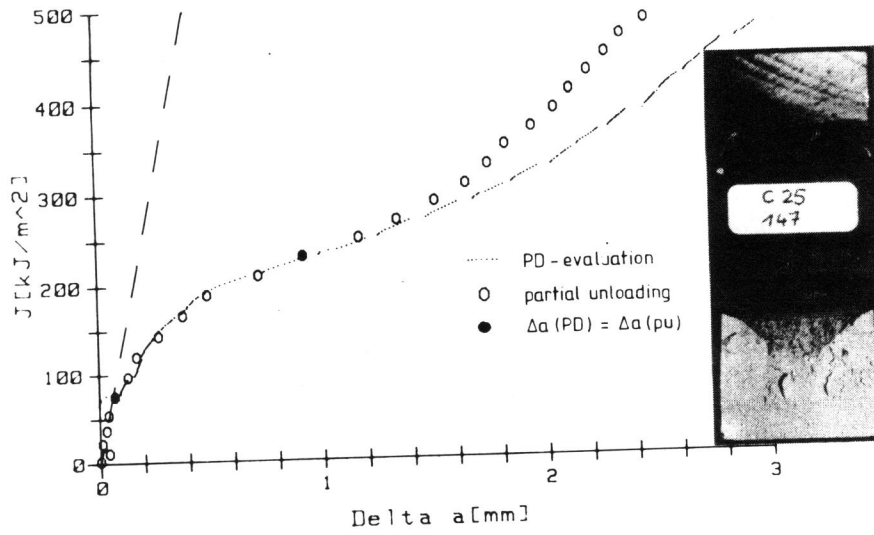Figure 9 High temperature clevis system and load line displacement measurement by two spring guided external LVDT's

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Figure 8 Effect of crack tunneling on the J-Δa curves evaluated from DCPD and PUC measured simultaneously in one test
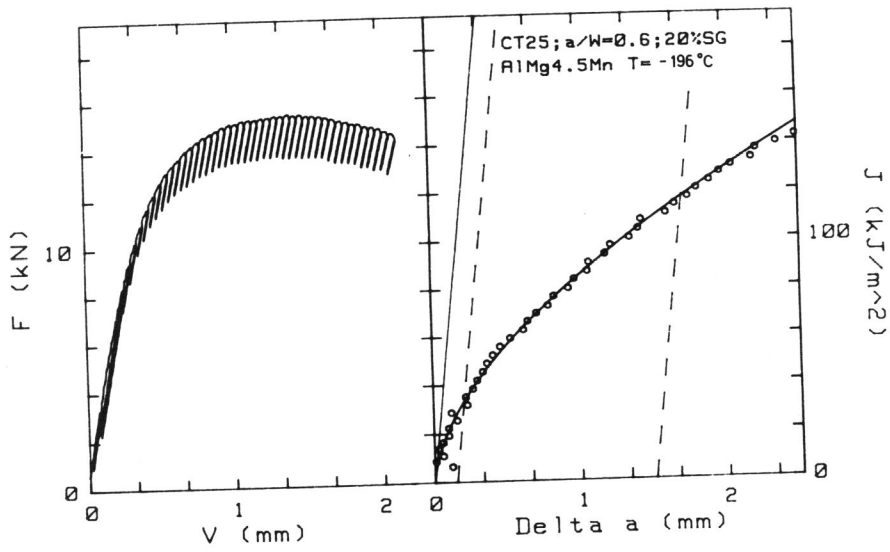
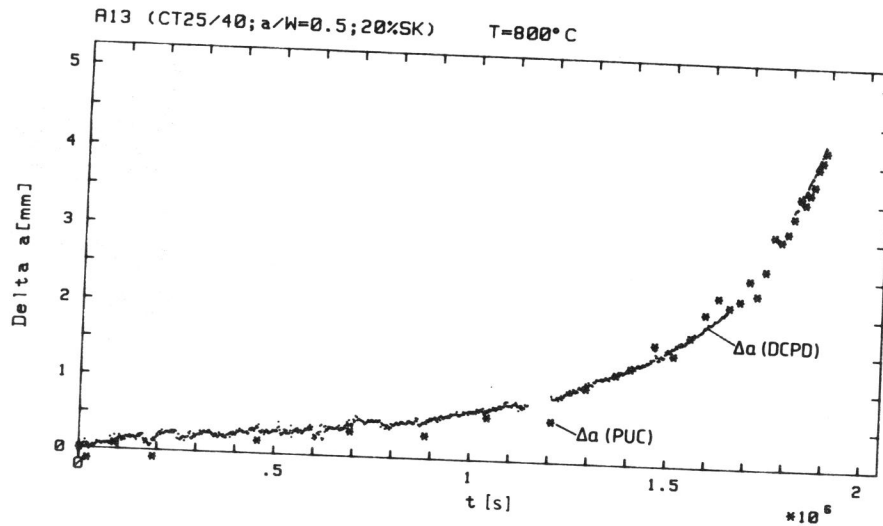Figure 10 Example of force vs. displacement diagram of a partial unloading test at -196°C; aluminium alloy weld metal

A13 (CT25/40; a/W=0.5; 20%SK)   T=800°C

Figure 11 Example of crack growth measurement by DCPD and PUC by the arrangement of Fig.9 at 800°C; Incoloy 800 H

A542   23°C
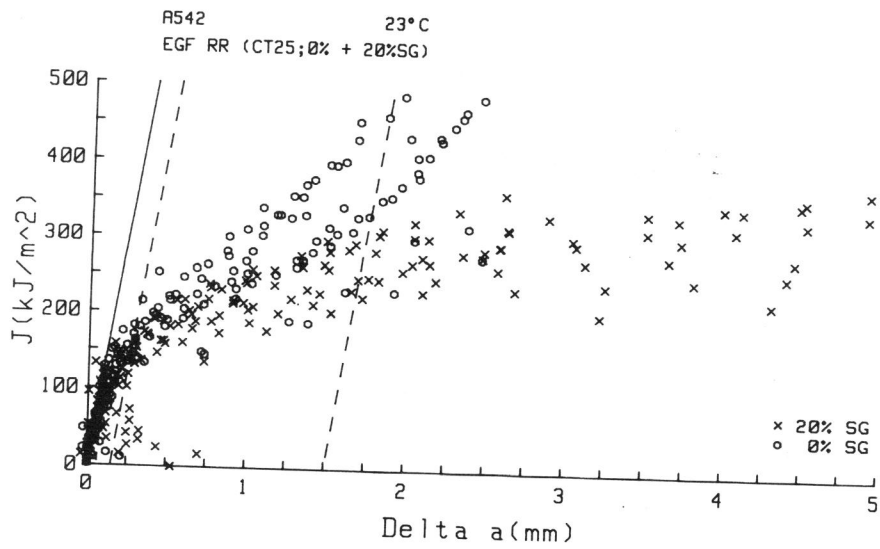EGF RR (CT25; 0% + 20%SG)

x 20% SG
o 0% SG

Figure 12 J-Δa points measured by 11 participants of EGF round robin with smooth and sidegrooved specimens; steel A 542
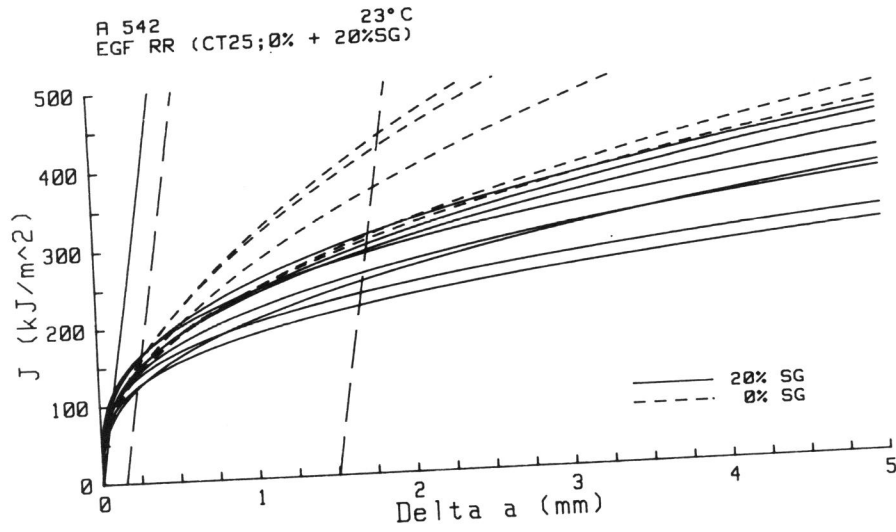
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Figure 13 Regression curves $J=C \cdot \Delta a^n$ for 13 of the specimens of Fig.12; overlapping broad scatterbands of the two subgroups
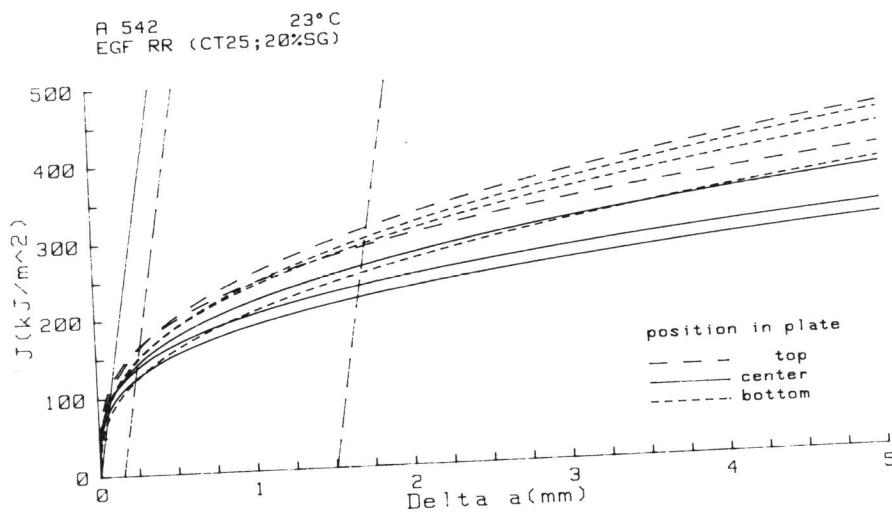

Figure 14 Regression curves of all sidegrooved specimens of Fig.13; narrow scatterbands for comparable positions in the plate