REF NO. ICF10064OR

THE INFLUENCE OF DYNAMIC TESTING ON THE J - R RESISTANCE CURVE BEHAVIOUR OF MEDIUM DENSITY POLYETHYLENE

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ABSTRACT

The dynamic fracture behaviour of medium density polyethylene has been investigated using an instrumented drop weight machine. Quasi-static and dynamic J - R resistance curves were obtained on both the parent and weld material. Three point bend specimens were used with a width of 30mm and a thickness of 15mm. All specimens were sidegrooved to a depth of 10% on each side. In the case of the welded specimens the notches were located in the weld centre line. All tests were carried out in accordance with the ESIS protocol on R curve testing of plastics. Dynamic tests were carried out over a range of impact velocities between 0.5 and 1m/sec. Load time data were obtained using a piezoelectric force transducer and displacement was derived from the double integration of the acceleration. Energy to maximum displacement was used to calculate J. Little difference was observed between the parent and the weld materials under both quasi-static and dynamic test conditions. Impact loading significantly reduced the level of the J - R curves for both the parent and weld materials particularly at higher values of Δa. $J_{0.2}$ values were reduced by up to 50%. The results were rationalised in terms of increased constraint resulting from the elevation of tensile properties under dynamic test conditions.

Keywords: Polyethylene, J – R curves, Welds, Dynamic Tests, Quasi-Static Tests.

INTRODUCTION

The increasing uses of polymers in many industrial sectors for a wide range of components and structures has resulted in a need to develop a better understanding of the failure characteristics of these materials. One area of particular concern is the fracture behaviour of medium density polyethylene, due to its widespread use in gas and water transmission, and the requirement to carry out engineering critical assessments (ECA) of components containing defects. One of the principal requirements of an ECA is some value of fracture toughness. Firstly, there is a need to establish test methodologies that allow fracture toughness data to be generated and secondly, to quantify those variables that influence fracture behaviour.

Early work [1] in this area established the J integral method for polymers and J was shown to be a useful parameter for determining the plain strain fracture toughness of high density polyethylene. The multiple specimen method was found to be a reliable technique for generating J-R resistance curves and thus for establishing $J_{IC.}$ More recently standard procedures [2] and protocols [3] for J-R resistance curve determination, which can be used to define J_{IC}, and which go a considerable way towards providing the necessary methodologies have been developed. A reasonable amount of data exists in the literature on specimen size effects [4,5], for example, but there is little work on the influence of a number of experimental variables including temperature, dynamic effects and sidegrooving. In addition the influence of welds on fracture behaviour of these materials needs to be quantified.

EXPERIMENTAL

A length of polyethylene pipe (PE 80) was obtained from the manufacturer. From this material a number of notched three-point bend specimens having a width (W) of 30 mm and a thickness (B) of 15 mm were machined from the pipe wall in the axial direction. A similar length of PE pipe containing a circumferential butt weld, manufactured in accordance with British Gas guidance, was also obtained. From this pipe, specimens were manufactured such that the weld was positioned along the centreline, allowing the notch to be positioned in the centre line of the weld. Sidegrooves with a depth of 10% of the specimen thickness and a 45^o angle were prepared in accordance with the ESIS protocol [3]. Pre-cracks were introduced by tapping a razor blade into the base of the notch to give an (a_0/W) of approximately 0.5.

All the dynamic tests were conducted on a instrumented falling weight impact machine. Tests were conducted at impact velocities in the range 0.5 - 1m/s. Impact forces were measured using a piezoelectric force transducer mounted just behind the striker mass. The displacement during the test was obtained from a double integration of the acceleration. Quasi-static tests were carried out on a 10kN servo-hydraulic test machine using a ramp rate of 1mm/min.

Extraneous displacements, such as roller indentations on the test specimen, were measured by loading an un-notched blank specimen, in a rig with the bottom rollers held together. The resultant load-displacement data was used to determine the energy lost due to this extraneous displacement and was subtracted from the total energy calculated for each specimen. The indentation energy obtained during these tests, however, was negligible, much less than 1% of the total energy (due to the small drop heights used) and was therefore excluded from any subsequent energy calculations. In all cases the energy to maximum displacement (U) was used in the calculation of the fracture resistance, J :

$$J = \frac{\eta U}{B_N(W - a_o)}$$

where

$\eta = 2$ for three point bend specimens
B_N = net thickness of sidegrooved specimens
W = specimen width
a_0 = initial crack length (to the tip of the pre-crack)

In all cases, a nine point average method was used to determine the amount of ductile crack growth (Δa).

RESULTS AND DISCUSSION

A summary of results obtained at 20^oC are given in Table 1, in terms of Power Law fits to J-Δa data and $J_{0.2}$.

Sidegrooving

Sidegrooved specimens exhibited much straighter crack fronts than those obtained in the non-sidegrooved specimens. This was anticipated since the increase in constraint and plain strain conditions promoted by sidegrooving would be expected to produce a more uniform crack front [6]. The effect of sidegrooving on the dynamic J-R curve characteristics of the parent material tested at 20^oC is shown, for example, in Figure 1. It is evident from the reduction in the power law exponent that the shape of the R-curve is significantly affected by using sidegrooved specimens.

TABLE 1
SUMMARY OF J-Δa DATA OBTAINED AT 20°C

Specimen Type	Loading Conditions			
	Dynamic		Quasi-Static	
	Power Law Fit	$J_{0.2}$ (kJ/m²)	Power Law Fit	$J_{0.2}$ (kJ/m²)
Parent	$J = 4.22(\Delta a)^{0.709}$	1.35	$J = 5.244(\Delta a)^{0.849}$	1.34
Parent, Sidegrooved	$J = 3.592(\Delta a)^{0.569}$	1.44	$J = 5.077(\Delta a)^{0.656}$	1.77
Weld	$J = 3.972(\Delta a)^{0.813}$	1.07	$J = 5.751(\Delta a)^{0.930}$	1.29
Weld, Sidegrooved	$J = 3.524(\Delta a)^{0.647}$	1.244□	$J = 5.117(\Delta a)^{0.505}$	2.27

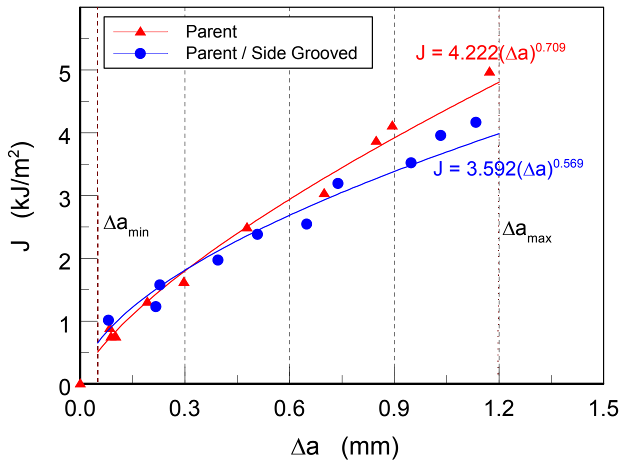

Figure 1 : Effect of Sidegrooving on Dynamic J-R Curve (Parent Material, 20°C)

The toughness exhibited by sidegrooved specimens at longer crack lengths is somewhat lower than non-sidegrooved specimens which is explained by the increase in constraint and crack front straightness associated with sidegrooving [7]. These observations are consistent with data on high density polyethylene [5] which showed that sidegrooving lowered the R curve and reduced the amount of scatter. In this case it was argued that the plastic deformation at the shear lips accounted for a large part of the energy put into the system. Sidegrooving was also shown to promote crack tip triaxiality and reduce crack front curvature. The shape of the R curve for the sidegrooved material reported here is more consistent with what is known about R curve behaviour in polyethylene [5], other polymeric materials [7] and metals [8]. Some earlier round robin work on polyethylene [9] had found that the crack front profile was too curved for valid testing and relaxing the requirements led to inconsistencies in the J-R curves. $J_{0.2}$ values reported here were slightly larger for the sidegrooved specimens. Therefore it is recommended that sidegrooved specimens be used in all cases where significant crack front bowing is encountered.

Welding

Figure 2 shows the J-R curves obtained for non-sidegrooved parent and welded specimens tested under quasi-static loading conditions at 20°C. At the lower end of the curve where crack initiation is important, both the parent and welded specimens exhibited similar toughness characteristics. However, as the crack extension approaches the maximum of $0.1(W-a_0)$, which in this case is approximately 1.2 mm, the welded material appears to be slightly but not significantly tougher.

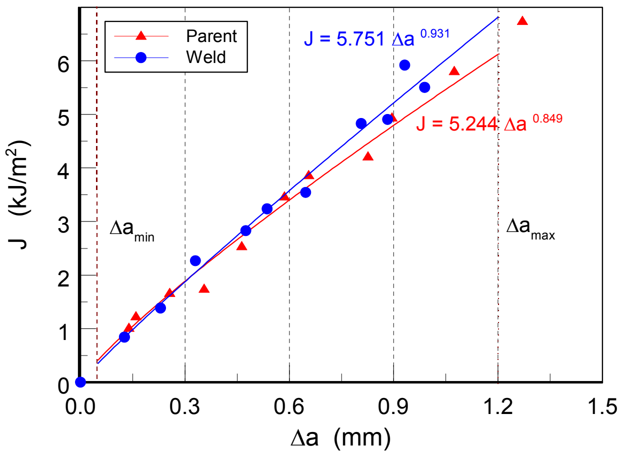

Figure 2 : Effect of Welding on Static J-R Curve (20^{o}C)

Under dynamic loading conditions, the welded material exhibited somewhat lower toughness across the range of crack growth investigated.

For the non-sidegrooved welded specimens significant bowing of the crack front was apparent. In most cases the degree of bowing fell outside that allowed by the protocol and therefore, in this respect, the data were outside the valid range of behaviour.

Impact Loading

The effect of impact loading, at velocities between 0.5 and 1m/s, on the J-R curve characteristics of parent material is shown in Figure 3. Compared to data obtained under quasi-static loading conditions it is evident that impact loading reduces the toughness significantly (predominantly at longer crack lengths), illustrated by a reduction in the power law exponent obtained for the dynamic J-Δa curve. Similar results were obtained for non-sidegrooved welded specimens, underlining the strain rate sensitivity of this material.

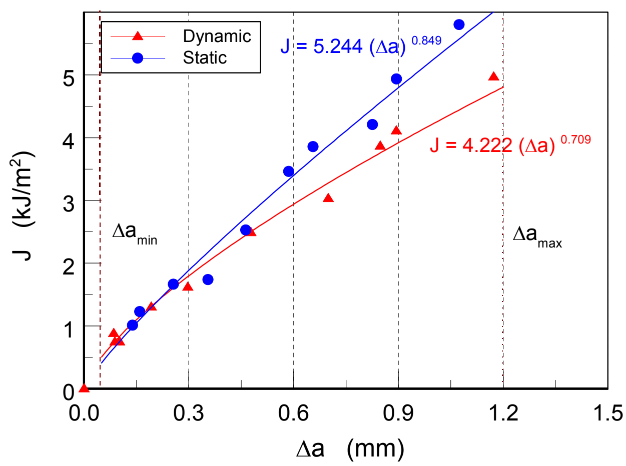

Figure 3 : Effect of Impact Loading on J-R Curve (Parent Material, 20^{o}C)

It should be noted that at shorter crack lengths (<0.3mm), however, toughness remains largely unaffected by variations in applied strain rate, with similar $J_{0.2}$ values being obtained under both static and dynamic loading conditions. Similar fracture surfaces, showing bowed crack fronts, were obtained under both static and dynamic conditions, for non-sidegrooved parent and non-sidegrooved welded specimens.

Results obtained from both quasi-static and dynamic tests performed on sidegrooved parent and sidegrooved weld material, again showed that the effect of impact loading is to reduce the toughness. Lower $J_{0.2}$ results were obtained for both parent and weld material under dynamic loading conditions, with the effect becoming more pronounced at larger crack lengths, as was the case for non-sidegrooved specimens. The reduction in the slope of the R curves under dynamic conditions is consistent with the higher constraint of these specimens resulting from an elevation of the tensile properties.

Temperature Effects

The influence of temperature on the J-R curve obtained for parent material tested under static loading conditions is shown in Figure 4. Similar results were also obtained for welded material. It is clear that a reduction in temperature of 20°C has a significant influence on behaviour. An R curve with a lower slope is anticipated since, at the lower temperature, an increase in tensile properties is expected, analogous to the influence of impact loading discussed in the previous section, and this produces an increase in specimen constraint. Similar trends have been observed in high density polyethylene [4].

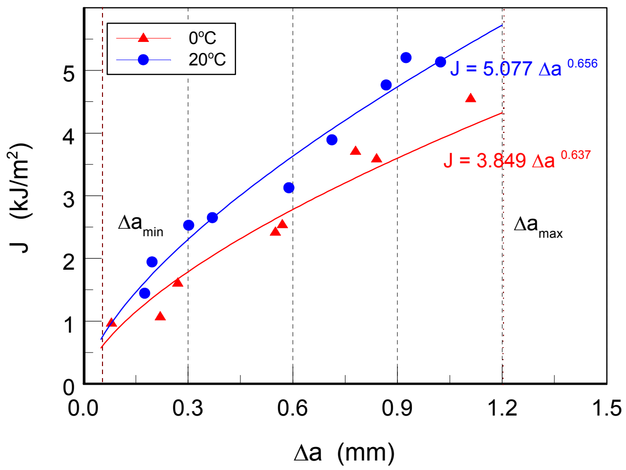

Figure 4 **:** Effect of Temperature on Static J-R Curve (Parent Material)

Under dynamic conditions, little difference between the curves generated at +20°C and 0°C for either the parent material or the welded material, was observed. It was evident from a comparison of the static and dynamic curves obtained at 0°C that there was a small reduction in toughness associated with the dynamic tests, however, a much larger reduction is apparent for the tests conducted at 20°C. It is likely that the constraint changes associated with the reduction in temperature and the impact test rate are not simply additive. Further work in this area is justified to quantify the synergistic effects on constraint of temperature and dynamic rates of testing.

ESIS J-R Protocol

Both the static and dynamic tests were carried out in accordance with the ESIS draft protocol [3] with the exception of pre-crack and ductile crack growth measurement. The protocol recommends the use of a three point average to establish the pre-crack length and a 'subjective' average of ductile crack growth by positioning the cross-hair of a travelling microscope at the centre of the crack front. These methods were thought to be open to error and variability, so a nine point average (as used in other J-integral test standards, e.g. [10]) was considered to be the most appropriate technique to quantify both the original crack length and the amount of ductile crack growth.

The protocol specifies that the difference between the mean crack growth and any measurement point should be less than 30% otherwise sidegrooved specimens must be used. The 'subjective' measurement of ductile crack growth used in the ESIS protocol does not allow this analysis to be carried out and thus a nine point average was used. When this criterion was used to analyse the results reported here for both the sidegrooved and non-sidegrooved specimens, it was found that the majority of the specimens failed to meet this criteria. This was due to a small amount of additional crack growth observed at the edges of the fracture surface adjacent to the sidegrooves. Using a nine point average [10] (i.e. the average of the two near-surface measurements at 0.1B and 0.9B, combined with the average of the seven remaining crack lengths) the majority of the sidegrooved specimens fell inside the 30% validity limit. For the non-sidegrooved specimens, however, the majority of specimens remained outside the 30% limit.

CONCLUSIONS

The data showed that there was little difference in resistance curve behaviour between the parent and the weld material.

Sidegrooving increased the specimen constraint and reduced crack front bowing leading to lower, more conservative, R curves. The shape of the curve for the sidegrooved specimens was more consistent with data obtained for other materials.

Impact loading produced a reduction in the slope of the R curve and lower toughness values, particularly at longer crack lengths. This data was consistent with an increase in specimen constraint resulting from the elevation of tensile properties.

A reduction in test temperature led to a reduction in the slope of R curve and this is likely to be due to the increase in specimen constraint associated with an increase in tensile properties. The effects of impact rate and temperature are not simply additive and further work is needed to quantify the influence of these variables.

The ESIS draft protocol is generally fit for purpose, however, a more rigorous method of determining the amount of ductile crack growth is needed. A nine point average method such as that used in ASTM 1737-96 is suggested.

ACKNOWLEDGEMENT

This work was funded by the Health and Safety Executive. Special thanks are due to Mr H Bainbridge of HSE’s Technology division.

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