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By

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SUMMARY

Dimensional changes and the development of cracking in the Charpy V-notch impact test have been studied using a low energy blow technique. Notch opening, angle of bend, notch root contraction and lateral expansion are shown to be proportional to the energy of the low blow which does not cause complete fracture and to be relatively independent of temperature over the range -10°C to -70°C but dependent on material. When complete fracture occurs the same lateral expansion/energy relationship still holds for brittle fractures but gradually breaks down as the plasticity of the specimen increases. This is due to an appreciable energy increment involved in forming the shear lips on the sides of the specimen without corresponding increase in lateral expansion. The lateral expansion after complete fracture is shown to be independent of the number and magnitude of blows taken to fracture.

The development of cracking at the notch root has been studied by direct examination of the surface with a low powered binocular microscope after successive low energy blows and by sectioning specimens after various amounts of deformation. Two main stages of crack initiation were identified which were relatively independent of temperature. In contrast the propagation of these initiating cracks was markedly temperature dependent.

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1. INTRODUCTION

The behaviour of specimens during the Charpy V-notch impact test is difficult to assess because of the instantaneous nature of the test. Techniques must rely, therefore, on rapid response instrumentation or on modifying the test procedure in such a way that time is available for observations to be made without affecting specimen behaviour. Three techniques have been used:-

1. The slow bend test. Evidence suggests, however, that the ductile - brittle transition of structural steels is displaced to lower temperatures when the slow bend test is used as opposed to the impact test, (1).

2. The instrumented Charpy test which enables the load-time diagram to be measured. The velocity of crack propagation can also be determined using a high speed camera, (2). This technique, however, requires the use of sophisticated and costly equipment and does not permit the development of cracking at the notch root to be observed.

3. The low blow Charpy test. This permits deformation and fracture to be studied without the use of additional equipment. The validity of the technique depends upon specimen behaviour being unaffected by variations in impact velocity. HARTBOWER (3) has demonstrated the general validity of the technique and has shown that variations in impact velocity in the range 1.2-4.9 m/sec. have no effect on test performance.

The aim of the present work was to study the behaviour of Charpy V-notch specimens using the low energy blow technique. This involved measuring changes in notch opening, angle of bend, notch root contraction and lateral expansion after both single and multiple low energy blows and relating these to the development of cracking at the notch root as observed by direct examination of the surface with a low powered binocular microscope and by sectioning specimens after various amounts of deformation.

2. MATERIALS

The materials used were two mild steel weld metals which will be designated A and B and QT35 steel in the following conditions:-

(a) as received

(b) water quenched from 1025°C, tempered 1 hour at 550°C

(c) water quenched from 1025°C, tempered 1 hour at 650°C

(d) water quenched from 1025°C.

The composition of the QT35 steel is shown in table 1. No analysis was made on the weld metals.

C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
0.15	1.04	0.011	0.032	0.16	1.12	0.74	0.40	0.06	0.08

Table 1: Composition of QT35 Steel

3. PROCEDURE

All tests were carried out on standard 10mm square Charpy V-notch specimens.

3.1 Single low blow tests

Specimens of weld metal A and QT35 parent material were given single blows in the range 7-81J (one blow per specimen) in a Losenhausen impact testing machine with the additional weights removed. This was achieved by raising the pendulum to the required height and releasing it by hand. The notch opening, notch root contraction, and lateral expansion were then measured by means of a linear traverse using a microscope with micrometer attachments. Angles of bend were measured by drawing the outline of the specimens on a piece of paper and measuring the angle with a protractor. This method was expeditious and enabled angles to be measured to within 0.5°. Weld metal A was tested at 20°C, QT35 at -10°C and -70°C. The minimum blow required to produce a crack visible to the naked eye was noted.

3.2 Multiple low blow tests

Specimens of QT35 in conditions (a), (b) and (c) described above were given a succession of low impact blows of about 7J nominal capacity (with the additional weights removed) in the temperature range 20°C to -100°C. After each blow the lateral expansion was measured and the surface of the notch root was was examined for cracks using a low powered binocular microscope at a magnification of 50. Although cracking could probably be detected earlier at higher magnifications this was not possible because of the difficulty in focusing at the bottom of a deep notch. However, it might be expected that the observable crack length would be a function of the total actual length. The lateral expansion corresponding to various stages of cracking was noted. The low blows were repeated until the complete length of the notch root was cracked.

3.3 Full blow tests

After the single and multiple low blow tests described above were completed the deformed specimens were fractured at the same temperature at which the low blows were carried out using the full capacity blow (294J) and the energy absorbed was recorded and the lateral expansion measured. Standard tests on undeformed specimens were carried out for comparison.

In order to get accurate and consistent measurements of lateral expansion it was necessary to fit the broken specimen together in a vice and measure the maximum lateral expansion by traversing from one side of the specimen to the other using a microscope with micrometer attachments. This need arises because the final fracture does not, in general, pass through the points of maximum lateral expansion on each side of the specimen and, moreover, the maximum lateral expansion on each side of the specimen may be located on different halves of the broken specimen. This finding agrees with that of ORNER and HARTBOWER (4).

3.4 Supplementary tests

Additional tests were carried out on weld metal B and on QT35 in the water quenched condition using the following sequence of blows:-

1. single low blow plus full capacity blow.

2. multiple low blows plus full capacity blow.

3. full capacity blow.

In each case the lateral expansion at fracture was measured in order to provide further comparison on the effect of the number and magnitude of blows taken to fracture on lateral expansion.

A limited number of specimens were sectioned after various low blows in order to relate the stages of cracking observed at the surface with the development of cracking through the depth of the specimen.

4. RESULTS

4.1 Single low blow tests

Fig. 1 shows that notch opening, angle of bend, notch root contraction and lateral expansion increase linearly with energy absorption in the single low blow tests on weld metal A and QT35 parent material. The minimum blows required to produce visible cracking at the notch root, table 2, show that these relationships are not affected by the onset of cracking at the notch root.

Material	Minimum blow for visible cracking (J)
Weld metal A	30
QT35 (-10°C)	30
QT35 (-70°C)	27

Table 2: Minimum low blows required to produce visible cracks at the notch root.

The energy values in fig. 1 have not been corrected for losses which arose mainly from rebound of the pendulum after impact. These losses varied between 1.4 and 2.7J regardless of the magnitude of the low blow and would, therefore, not affect the linearity of the relationships shown in fig. 1. The relationships for QT35 were different from those of weld metal A indicating a dependence on structure but the relationships were essentially the same at -10°C and -70°C indicating a relative independence on temperature over this range.

4.2 Multiple low blow tests

In the multiple low blow tests cracking at the surface of the notch root occurred in a number of stages. After the first blow short fine cracks lying parallel to the length of the notch were formed. These were difficult to identify because of the poor surface appearance of the notch root. Occasionally more well-developed cracks lying perpendicular to the length of the notch appeared at this stage but these were ignored since they did not appear to influence the subsequent development of cracking along the notch root. In the second stage short well-developed cracks formed along the notch root, the sides of which could be clearly resolved under the microscope. With increasing deformation the cracks grew laterally to form a more or less continuous crack extending over the greater part of the notch root. The end of the third stage was taken arbitrarily to coincide with the formation of a crack extending over half of the length of the notch root. In the fourth stage lateral extension continued until the crack reached the sides of the specimen. The distinction between the third and fourth stages was considered necessary since crack extension became more difficult after the central length of the notch had cracked. This is probably due to a change from plane strain conditions at the centre of the notch length to plane stress conditions near the sides. In the fifth stage the crack propagated through the depth of the specimen causing complete fracture.

The extent of cracking observed on central longitudinal sections after stages 1-4 of cracking at the surface is shown in figs. 2 and 3 respectively for a ductile and a brittle fracture. In both cases there was no evidence of cracking after stage 1 as shown in figs. 2(a) and 3(a) although some surface indentations can be observed which are presumably the fine cracks described after the surface examination. The ductile fracture exhibited a fine shear crack at approximately 45^{o} to the principal stress after stage 2, fig. 2(b), which corresponds to the initiating shear cracks described by HARTBOWER (3). This crack opened up during stage 3 and initiated a crack normal to the principal stress, fig. 2(c). This corresponds to the second stage of crack initiation described by HARTBOWER (3). During stage 4 the crack opened up considerably and limited propagation normal to the principal stress occurred, fig. 2(d).

The brittle fracture exhibited a number of different features from the ductile fracture. After stage 2 the initiating crack, which was quite extensive, was mainly normal to the principal stress although a short initiating shear crack can be observed at the surface in fig. 3(b). During stage 3 the crack opened up and propagated a considerable distance normal to the principal stress, fig. 3(c). This process continued during stage 4 as shown in fig. 3(d). The ductile fracture exhibited much more "crack opening" than the brittle fracture.

The results of multiple low blow tests on QT35 steel in three heat treatment conditions are shown in fig. 4. Here lateral expansion corresponding to stages 2-5 of cracking are plotted against temperature. Stage 1 was omitted because of the uncertainties involved in crack detection. Stages 2 and 3 are relatively independent of temperature, while stages 4 and 5 are markedly temperature dependent.

4.3 Full blow and supplementary tests

The lateral expansion of specimens fractured using only the full capacity blow and those fractured with the full capacity blow after previous single and multiple low blows are compared in table 3. The small variations between the three groups are random and generally less than 10% and are considered to reflect the normal scatter associated with notch-impact tests. It seems reasonable to conclude, therefore, that specimen behaviour is not influenced by the number and magnitude of blows taken to fracture and would thus appear to vindicate the procedure.

The relationship between lateral expansion and energy absorption after fracture was similar to the relationship prior to fracture for relatively brittle materials as shown in fig. 5 for QT35 in the the water quenched condition. With more ductile materials, however, energy absorption during the final stages of the test increased at a greater rate than lateral expansion as shown in fig. 6 for QT35 parent material. This can be attributed to an appreciable energy increment involved in forming the shear lips and separating the final ligament without a corresponding increment in lateral expansion. The increasing deviation from the lateral expansion-energy relationship prior to fracture with increasing energy absorption is a manifestation of this.

Material	Test Temp. (°C)	Type of blow	No. of Tests	Average lateral expansion (mm)	Deviation from standard test
Weld metal A	20	Standard	5	1.65	-
"	20	Double	9	1.52	-8%
"	20	Multiple	6	1.63	-1%
Weld metal B	20	Standard	2	2.23	-
"	20	Double	9	2.15	-4%
"	20	Multiple	5	2.33	+5%
QT35, as received	-10	Standard	1	1.85	-
"	-10	Double	3	1.71	-8%
"	-10	Multiple	2	1.70	-8%
QT35, as received	-70	Standard	3	0.88	-
"	-70	Double	3	0.77	-12%
"	-70	Multiple	1	0.79	-10%
QT35	20	Standard	2	1.40	-
WQ 1025°C	20	Double	3	1.43	+2%
Temp. 650°C	20	Multiple	3	1.53	+9%
QT35	20	Standard	2	1.03	-
WQ 1025°C	20	Double	3	1.09	+6%
Temp. 550°C	20	Multiple	3	1.05	+2%
QT35	20	Standard	4	0.47	-
WQ 1025°C	20	Double	4	0.46	-2%
	20	Multiple	4	0.44	-6%

Table 3: Comparison of lateral expansion at failure between standard and low blow tests.

5. DISCUSSION

The validity of the low energy blow approach for studying deformation and fracture in the conventional Charpy test depends upon specimen behaviour being unaffected by the differences in impact velocity between the two procedures. HARTBOWER (3) demonstrated that variations in impact velocity within the range 1.2-4.9 m/sec. does not affect impact performance and this is approximately the range of impact velocities used in the present work. Table 3 shows that, within the normal scatter associated with notch impact tests, the lateral expansion after complete fracture is independent of the number and magnitude of the blows used, i.e. is independent of impact velocity. This being so, it is reasonable to assume that the intermediate stages involved in fracture will be also independent of impact velocity.

The low energy blow procedure, therefore, offers a unique opportunity for studying behaviour in the Charpy test without the need for additional equipment apart from that required for optical examination and measurement of lateral expansion. Two variations in the procedure are available. Either the test can be carried out using a single specimen for each temperature by impacting it with successive low energy blows or a series of specimens can be used for each temperature with each specimen receiving a different low energy blow. In both cases a continuous record of specimen behaviour is not obtained but the steps between each point in the test can be kept small by using small increments in energy, preferably around 7J (5ft. lbs.). The single low blow tests are less time consuming and the effective energy absorbed by the specimen can be estimated by noting the distance of rebound of the pendulum which is considered to be the main source of energy loss. However, this procedure is more expensive in terms of the number of specimens required. The multiple low blow procedure, on the other hand, is more economical in terms of the number of specimens required, but can be more time consuming especially with tests not carried out at room temperature since the specimen has to be examined and taken back to test temperature between successive blows. It was also found that other sources of energy loss arose in the multiple low blow tests as was apparent from the observation that the increments in lateral expansion decreased with successive blows of the same nominal energy. The linear relationship between lateral expansion and energy absorption in the single low blow tests (fig. 1(d)) indicates that if all the energy of the pendulum, after allowance has been made for rebound, is absorbed by the specimen then the successive increments in lateral expansion should also be similar. This extra source of energy loss may be due to the fact that the specimen, which has been bent by preceding blows, has a much reduced contact with the machine anvil or else work hardening has increased the energy required to cause further plastic deformation. Whatever the explanation the successive energy blows are not additive and in order to convert lateral expansion values into energy values it is necessary to establish the correlation between the two parameters using a series of single low blow tests. However, it has been well established that lateral expansion and energy values in the Charpy test are approximately equivalent (5, 6) so that for purposes of studying specimen behaviour the conversion to energy values is not really necessary.

The results shown in fig. 1 indicate that notch opening, angle of bend, and notch root contraction are alternative parameters by which progress of the test can be measured. However, notch opening and angle of bend become indeterminate when the specimen breaks in two and so do not permit the test to be studied to the end. Notch root contraction is more difficult to measure accurately and reproducibly than lateral expansion as can be seen from the greater degree of scatter in fig. 1(c) compared with fig. 1(d). Consequently lateral expansion measurements are the most satisfactory for following progress of the test up to and including the final stage of fracture.

Two main stages of fracture initiation can be identified. The initiation of shear cracks at approximately 45^{o} to the principal stress followed by the initiation of cracks normal to the principal stress. These cracks form in the central part of the notch length where the stress system is most severe and correspond to the two stages of initiation described by HARTBOWER (3). Propagation can also be described as a two stage process. In the first stage the initiating crack extends laterally to the sides of the specimen and at the same time limited propagation through the depth of the specimen occurs. This is followed by the final process of fracture through the full depth of the specimen. The two stages of initiation are relatively independent of temperature but the propagation stages are markedly temperature dependent and reflect most of the temperature dependence displayed by the standard Charpy test. Previous attempts to measure the energy for initiation have shown this to be independent of temperature over a wide range (3, 7).

RARING (8) using slow bend tests on Charpy V-notch specimens has observed that the start of crack propagation through the depth of the specimen coincides with the maximum load in the load-deflection diagram and at this point a crack extending over the entire length of the notch root was observed. The present results indicate that for impact rates of loading at least some propagation through the depth of the specimen occurs before cracking has extended over the entire length of the notch root.

The single low blow tests (fig. 1) have shown that deformation in the Charpy test, as measured by notch opening, angle of bend, notch root contraction, and lateral expansion occurs uniformly during most of the test, even after cracks have initiated and extended along the entire length of the notch root. A comparison between these results and values of lateral expansion and energy at fracture explains the limited success achieved in the past in attempting to relate lateral expansion at fracture with energy absorption (1, 5, 6, 8, 9, 10). Such relationships, although generally linear, have been characterised by a good deal of scatter. This scatter, which was also observed in the present tests after the specimens had been completely fractured can be explained by the fact that during the final stages of fracture when the sides and final ligament break there is an energy increment without a corresponding increase in lateral expansion. The observation that the final fracture does not pass through the points of maximum lateral expansion on either side of the specimen indicates that the lateral expansion is not affected at this stage.

A number of features observed in the present work suggests a close similarity in behaviour between 10mm square Charpy and crack opening displacement (COD) specimens. The linear relationship between notch opening and notch root contraction observed in the present tests is analogous to the linear relationship between COD and notch root contraction reported for the COD test (11, 12). In fact the COD of a test specimen has been shown to be directly proportional to the notch opening as measured at the surface by means of clip ganges (11). The present results suggest, therefore, that the linearity between COD and notch root contraction in the COD test could be extended to include angle of bend, lateral expansion, and energy absorption. The choice of parameter would appear to be relatively unimportant in theory and to be dictated by the practical considerations of ease and accuracy of measurement. The essential difference between Charpy and the COD tests, apart from the obvious ones of strain rate and notch profile would thus appear to be in the point during the test at which fracture behaviour is assessed. In the COD test this is done at the point of instability whereas in the Charpy test the assessment includes the unstable part of fracture.

The relative ineffectiveness of small cracks produced in the early stages of the Charpy test indicates that fatigue cracking should have little influence on test performance. This has been substantiated by the work of ZENO and LOW (13). BURDEKIN (11) has also shown that fatigue cracking of 10mm square COD specimens has only a marginal effect on test performance. In addition it would seem likely that the production of a uniform fatigue crack at the notch root would be difficult to achieve since cracking would be expected to occur first in the more severely stressed region at the centre of the notch length.

6. CONCLUSIONS

The low energy blow technique is a valid method for studying behaviour in the Charpy test. Using this technique the following observations were made:-

1. Prior to fracture, notch opening, angle of bend, notch root contraction, and lateral expansion increase linearly with energy absorption.

2. In the brittle regime the lateral expansion-energy absorption coordinates after fracture follow closely the relationship prior to fracture. With increasing plasticity the lateral expansion-energy absorption coordinates after fracture deviate more from the relationship prior to fracture due to an increasing energy increment used in forming the shear lips and separating the final ligament without a corresponding increase in lateral expansion.

3. The final fracture does not, in general, pass through the points of maximum lateral expansion on either side of the specimen indicating that lateral expansion ceases before fracture is complete.

4. The lateral expansion at fracture is independent of the number and magnitude of blows taken to fracture.

5. Cracking at the notch root occurs very early in the test and progresses in a series of stages. Two main stages of initiation can be identified viz. the formation of shear cracks at approximately 45°C to the principal stress followed by the formation of cracks normal to the principal stress. These initiating cracks form in the central length of the notch root where the stress system is most severe. Two main stages of propagation can also be identified viz. the extension of the initiating cracks to the sides of the specimen coupled with limited propagation through the depth of the specimen followed by propagation through the full depth of the specimen.

6. The initiating stages of fracture are relatively independent of temperature.

7. The propagation stages of fracture are markedly temperature dependent and reflect most of the temperature dependence displayed by the standard test.

7. ACKNOWLEDGEMENT

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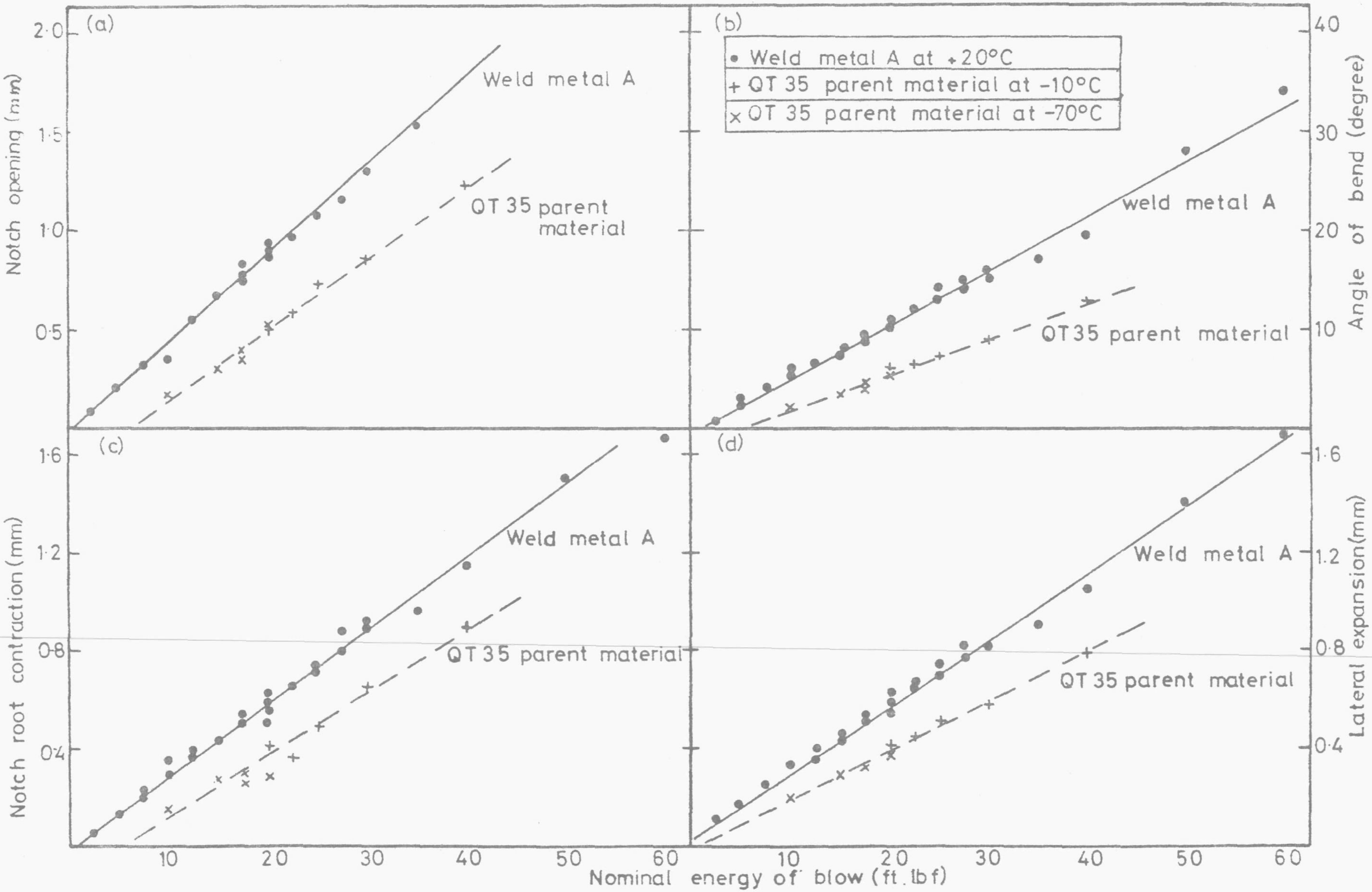
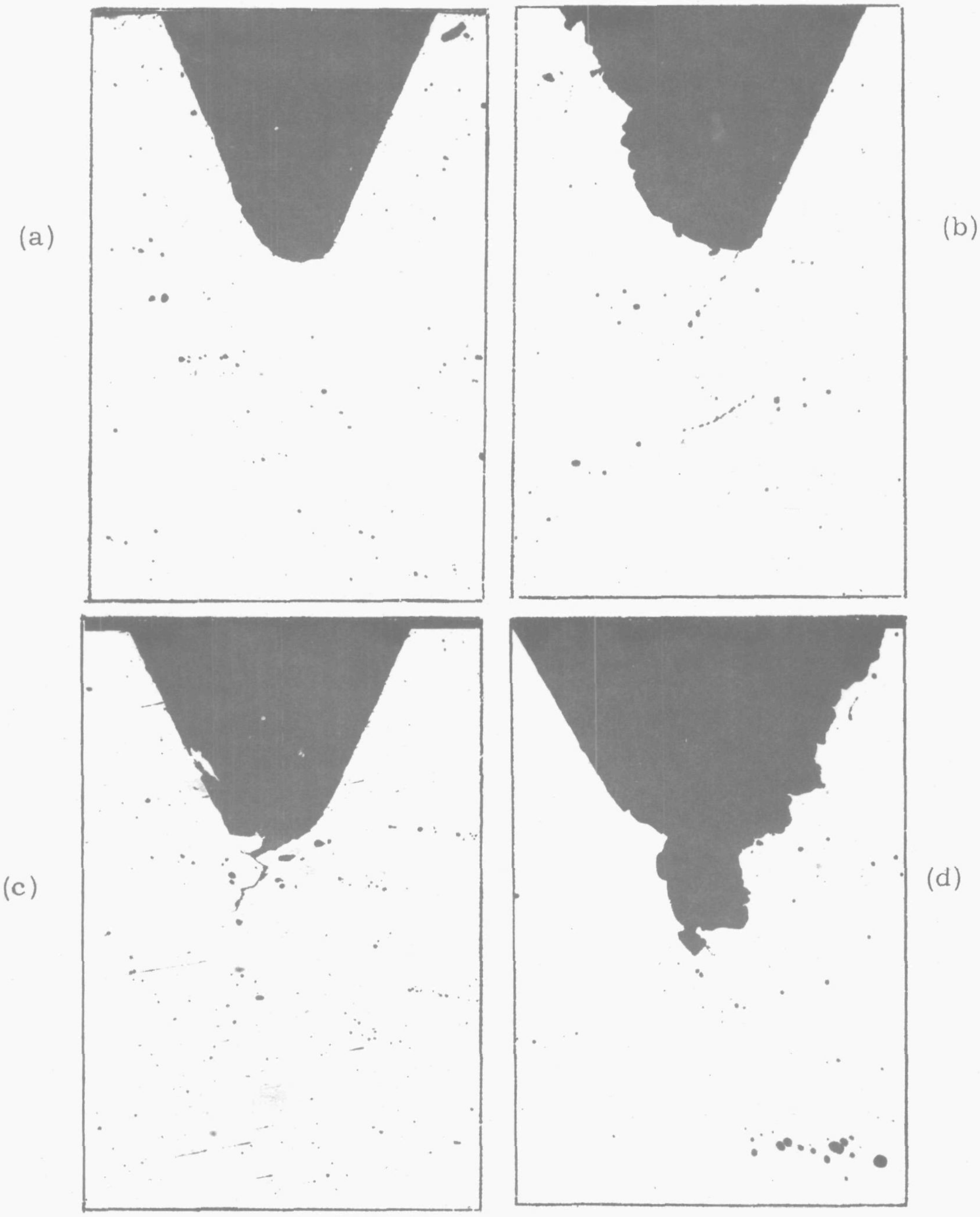
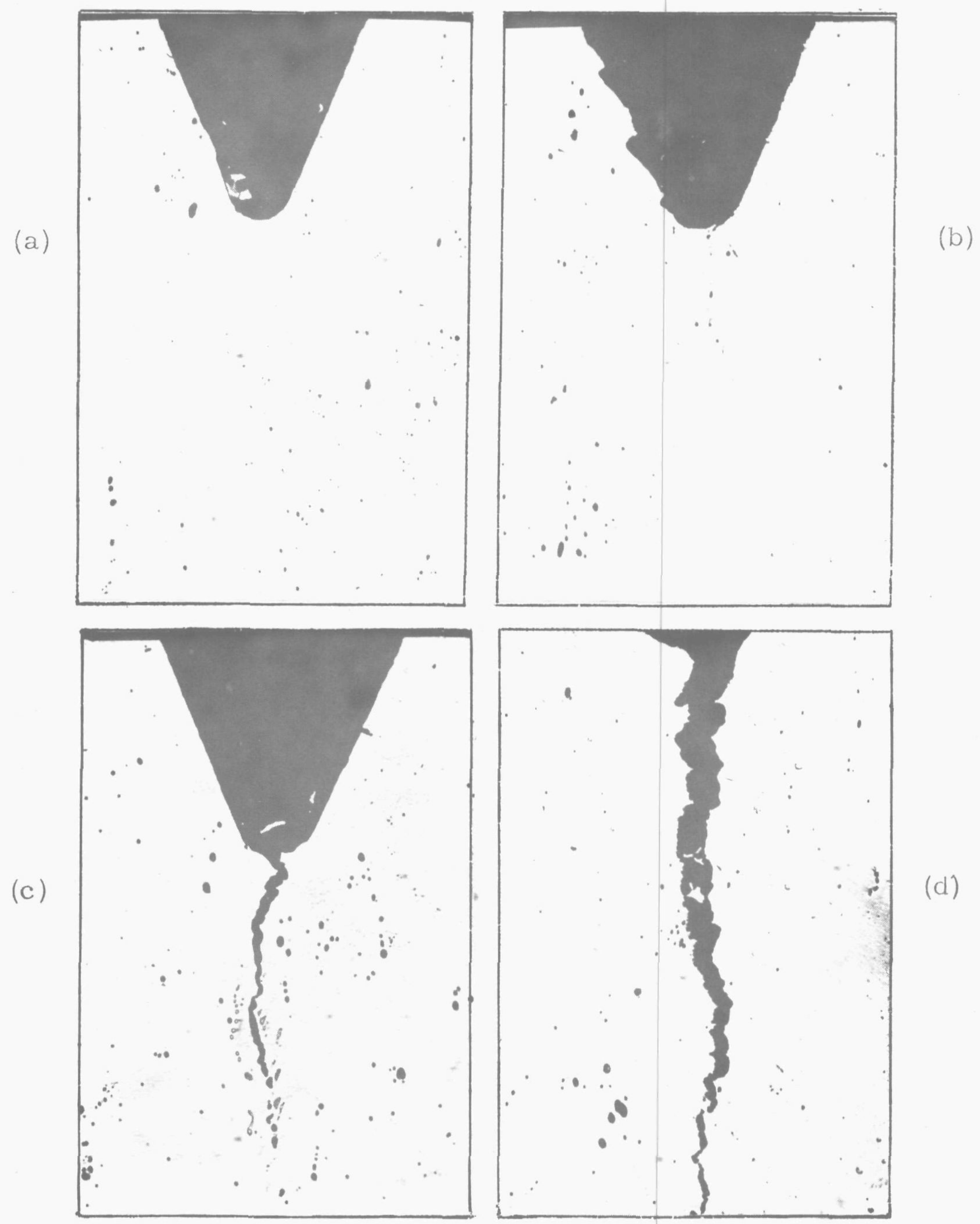


FIG. 1. RELATIONSHIP BETWEEN NOMINAL ENERGY ABSORPTION AND (a) NOTCH OPENING (b) ANGLE OF BEND (c) NOTCH ROOT CONTRACTION AND (d) LATERAL EXPANSION FOR SINGLE LOW ENERGY BLOW TESTS.



(a) Stage 1 - 20.3J(15 ft.lb.) blow
(b) Stage 2 - 33.9J(25 ft.lb.) blow
(c) Stage 3 - 40.7J(30 ft.lb.) blow
(d) Stage 4 - 67.8J(50 ft.lb.) blow

FIG. 2. EXTENT OF CRACKING OBSERVED ON CENTRAL LONGITUDINAL SECTIONS OF A DUCTILE FRACTURE AFTER VARIOUS SINGLE LOW ENERGY BLOWS. x 20



(a) Stage 1 - 13.6J(10 ft.lb.) blow
(b) Stage 2 - 20.3J(15 ft.lb.) blow
(c) Stage 3 - 27.1J(20 ft.lb.) blow
(d) Stage 4 - 33.9J(25 ft.lb.) blow

FIG. 3. EXTENT OF CRACKING OBSERVED ON CENTRAL LONGITUDINAL SECTIONS OF A BRITTLE FRACTURE AFTER VARIOUS SINGLE LOW ENERGY BLOWS. x 20

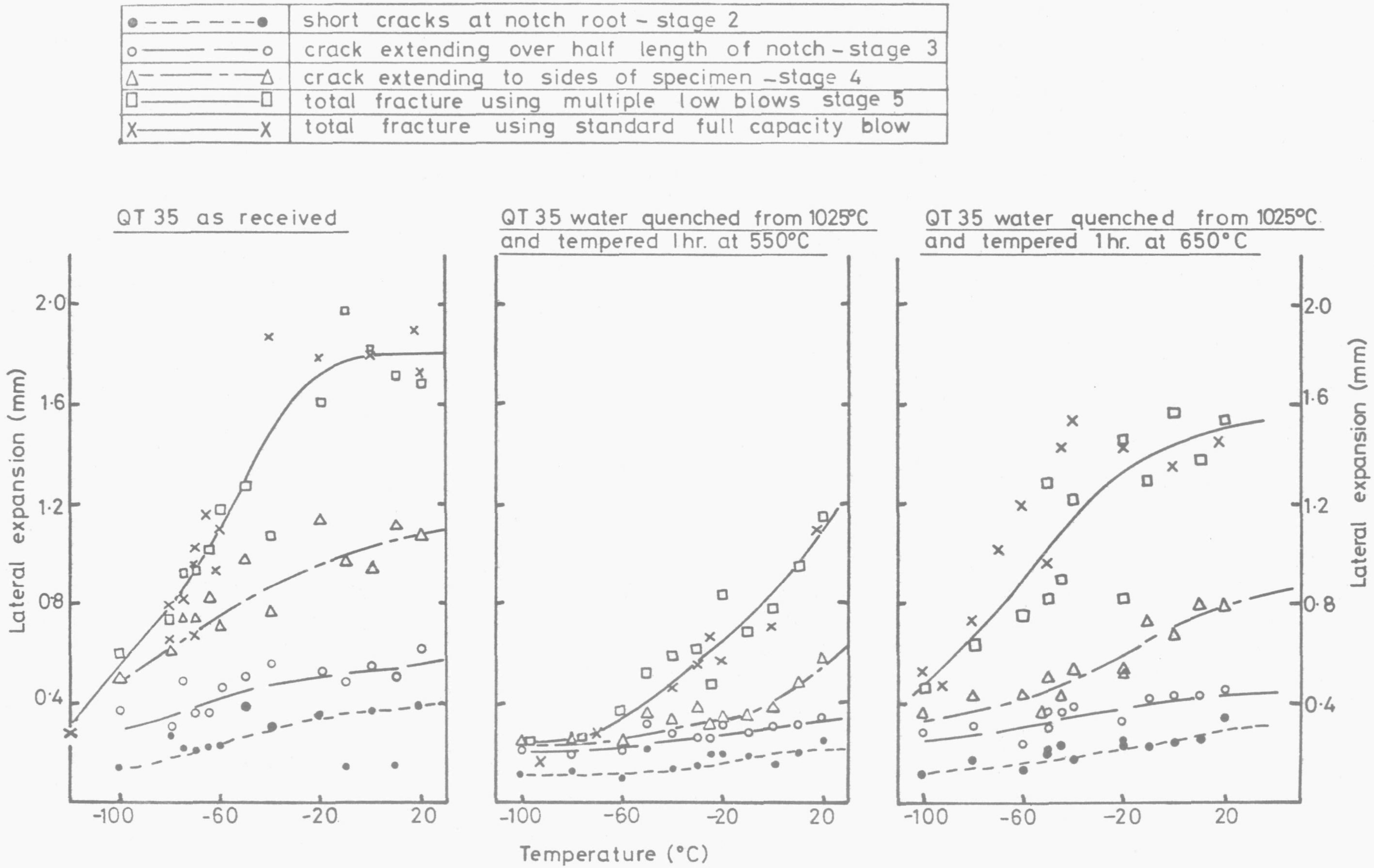


FIG. 4. LATERAL EXPANSION TRANSITION CURVES FOR VARIOUS STAGES OF CRACKING AND TOTAL FRACTURE

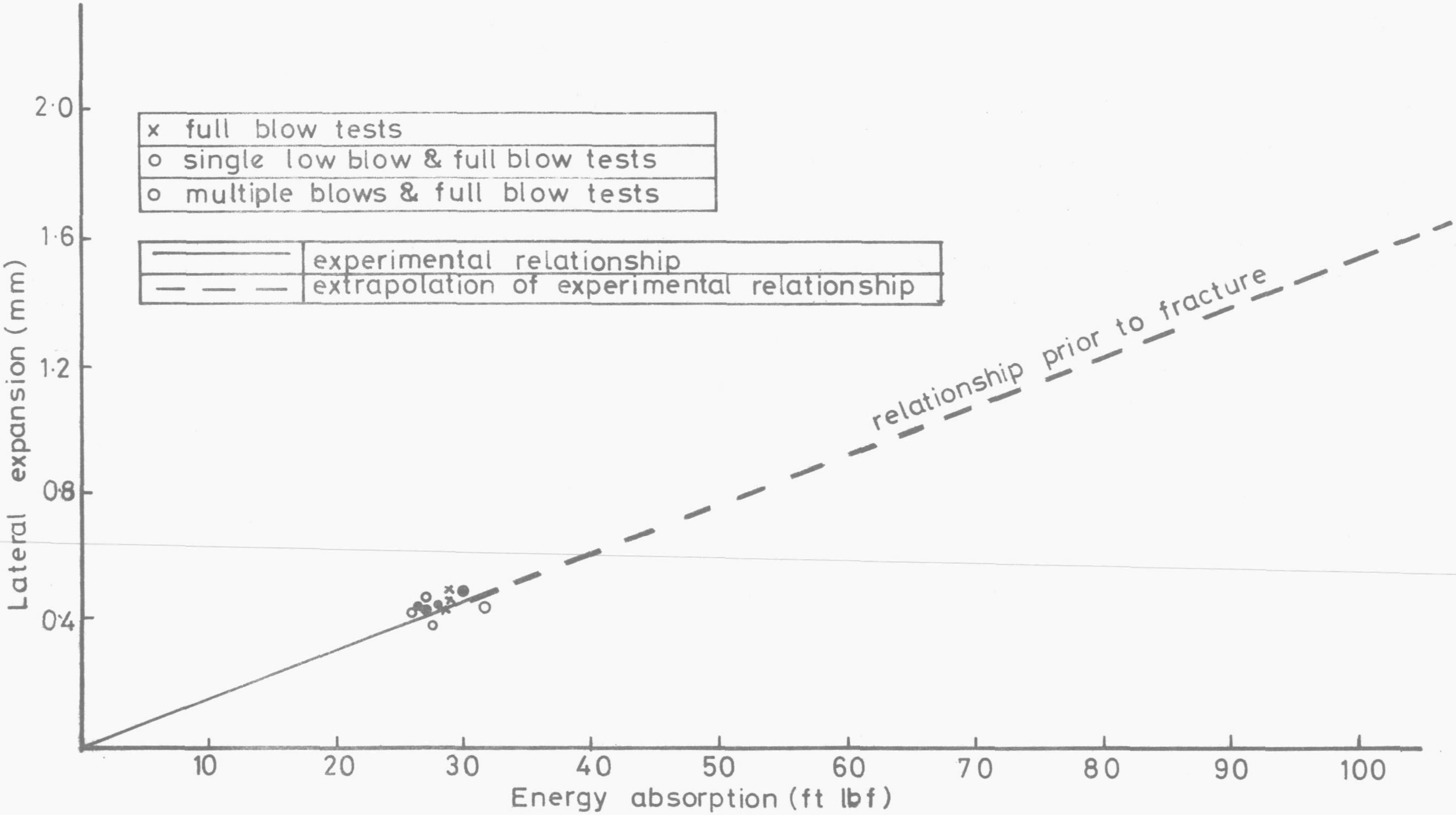


FIG. 5. LATERAL EXPANSION – ENERGY VALUES AT FRACTURE FOR QT35 WATER QUENCHED FROM 1025°C

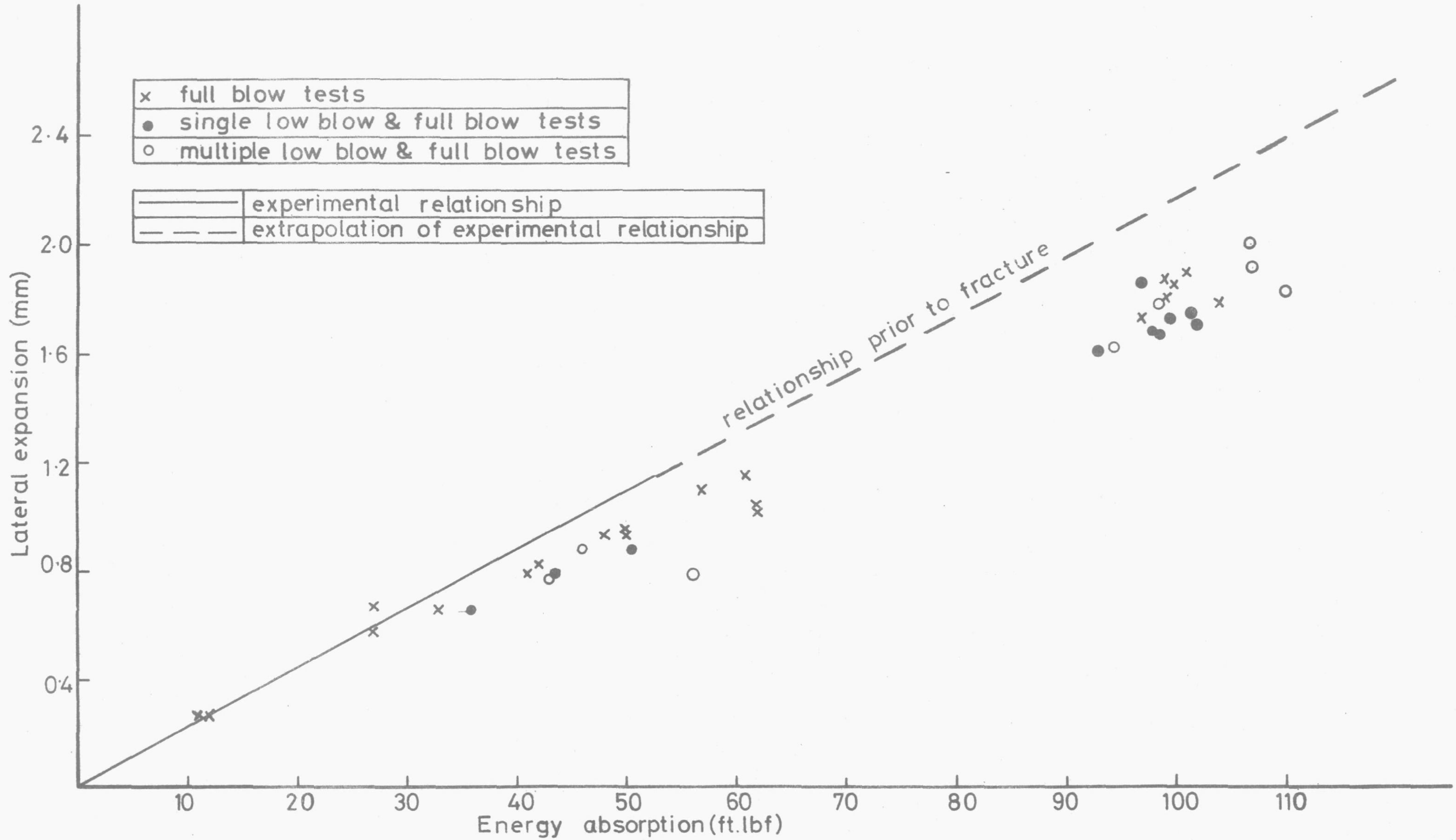


FIG. 6. LATERAL EXPANSION OF ENERGY VALUES AT FRACTURE FOR QT35 PARENT MATERIAL