Fracture 1977, Volume 3, ICF4, Waterloo, Canada, June 19 - 24, 1977

MEASUREMENT OF STRETCH ZONE WIDTH AND δ_i IN A LOW ALLOY NAVAL STEEL

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INTRODUCTION

The development of the low alloy high yield strength naval steels has taken place with great emphasis on the need for cleanliness and toughness. These steels sustain extensive plastic deformation before the onset of stable fracture at service temperatures and unstable fast fracture is not considered to be a problem in the thicknesses used in practice. From a design or material selection point of view the linear elastic fracture mechanics approach is therefore inapplicable and a greater interest has been shown in general yielding fracture mechanics parameters in particular the C.O.D. (crack opening displacement) concept. Safe defect size predictions for service components may be made on the basis of critical C.O.D. at the onset of fast fracture, (δ_c), measured on laboratory specimens [1]. The correlation is only accurate, however if fracture occurs before extensive plasticity [2]. Until recently when unstable fracture does not occur in the test, the critical C.O.D. has been taken to be the maximum load point on the load/C.O.D. curve (i.e. δ_{max}). This value has been shown to vary with specimen size and has proved difficult to use in the prediction of acceptable defect sizes in actual components.

Harrison and Fearnehough [3] have shown that the C.O.D. at which ductile crack initiation occurs, δ_i, is lower but gives a much more constant value of C.O.D. than δ_{max} over a range of specimen sizes. Work is taking place at several research establishments to quantify this parameter and establish its potential use in design. This paper describes the results to date of an ongoing project at Salford University to investigate the effects of metallurgical variables on δ_i in Q1(N) a low alloy high yield strength steel. The particular metallurgical variables investigated were testing temperature and orientation of the test specimens to the rolling direction of the plate.

EXPERIMENTAL

The material used was a 25mm thick Q1(N) steel the chemical composition of which is given in Table 1. The steel was in the 'as received condition' i.e. water quenched at 1203 K and tempered at 913 K for 1 1/2 hours. The microstructure of the material is shown in Figure 1.

The fracture toughness specimens used in the investigation were 10mm x 20mm x 100mm the dimensions conforming with recommended procedure [4]. The specimens were machine notched initially by milling and then by a rubber bonded slitting wheel to a depth of 7.7mm. The cracks were then extended to 10mm by fatigue pre-cracking. The test pieces were loaded in

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3 point bending over a load span of 80mm at a loading rate of the order of 50MPa $m^{1/2}s^{-1}$ (cross head velocity of 8 x 10^{-5} ms^{-1}). Double cantilever beam clip gauges were used to measure the crack face displacement. The positive location of the clip gauge over the crack openings was achieved by the use of saddle type knife edges, clamped to the test piece by means of grub screws.

A number of techniques have been developed to detect the onset of slow crack growth during a fracture toughness test including potential drop (p.d.) techniques [5], acoustic emission [6] and ultrasonics [7]. In the present investigation a potential drop technique was used. The method monitors the potential change around the crack tip against the crack opening displacement at the tip. This is done by connecting a constant current supply (in this case capable of producing 50A) to the ends of the specimen and measuring the potential change around the crack tip as it opens and grows. Copper probes spot welded at either side of the crack measure this change while the C.O.D. is obtained by attaching a clip gauge above the crack. Both these readings can be monitored on an autographic XY plotter and a curve of the type shown in Figure 2 is obtained where δ_i is the value of C.O.D. at the point of gradient change on the graph. The curve in Figure 2 is idealised and in the present work it was often very difficult to detect the change in slope possibly because of the relatively small specimens used. To overcome this problem the potential change at the crack tip was plotted as a function of the applied load rather than C.O.D. Also by using an XYY plotter it was possible to monitor C.O.D. versus load simultaneously (load being the common abscissa). The potential change versus load curve shows a gradient change at a load Y between loads of X and Z (see Figure 3a), the two portions of the curve XY and YZ being linear. These three loads can be related to C.O.D. by referring to the C.O.D. versus load curve obtained simultaneously (Figure 3b). It will be shown later that XY represents the growth of the stretch zone and the point Y represents δ_i.

RESULTS

Fracture Mode

In general, a reasonably tough material after a C.O.D. test will have a fracture surface containing a region of fibrous crack growth at the base of the fatigue crack followed by a brittle cleavage fracture if the specimen has been broken open in liquid nitrogen. In a ductile material such as Q1(N) there is a stretch zone between the fatigue crack base and the beginning of the fibrous crack (Figure 4). This is due to conditions in the volume of material immediately ahead of the crack tip (i.e. the plastic zone) being such as to promote a 45° shear type mechanism of crack extension. As the C.O.D. test progesses the microcrack extension within the stretch zone is followed by macroscopic fibrous crack growth (microvoid coalescence) which continues until plastic collapse. The presence of stretch zones on the fracture surface of fracture toughness specimens has been the topic of several recent investigations [8 - 13] and correlation between fracture toughness parameters and the width of the zone have been suggested in all these investigations. It is now well established that the stretch zone is a result of blunting of the crack tip [14, 15]; strain and localised yielding at the crack tip enabling the stretch zone to form by alternating shear along slip bands originating from the tip.

Attempts to relate stretch zone width (S.Z.W.) to fracture toughness parameters have not yet produced a completely unified approach. Spitzig [17], proposed that S.Z.W. was equal to the critical crack tip opening displacement which was disputed by Gerberich and Hemmings [11], who concluded that the region was controlled by the fatigue pre-crack operation. Bates et al [10], have shown for both steels and aluminum alloys that the S.Z.W. can be correlated with the ratio of stress intensity to yield stress ($K_1/\sigma y$) giving the relationship

$$S.Z.W. = 10^{-3}\left\{\frac{K_1}{\sigma y}\right\}^{1.6} \qquad (1)$$

This was substantiated by Brothers et al [12] who showed additionally that the S.Z.W. could be numerically correlated with C.O.D. However the scatter in all the data is considerable, [12], and there are differences of opinion on many points, the most common being the definition of S.Z.W. and the angle of inclination of the zone to the fatigue crack plane, [18, 19]. Since the width of the zone varies along its length past workers have assumed a mean value between the maximum and minimum width.

Figure 5 shows the stretch zone length plotted against C.O.D. for the material used in the investigation. This figure was compiled from specimens loaded to increasing C.O.D. values and broken in liquid N_2. The length of the stretch zone was measured using a scanning electron microscope. It can be seen from Figure 5 that stretch zone formation does not commence upon initial loading. No stretch zone was evident on the fracture surface until a C.O.D. of .09mm was reached. Between C.O.D.s of .09mm and .17mm the length of the stretch zone increased from zero to .12mm. At C.O.D.s greater than .17mm fibrous crack growth was observed along the crack front, the amount of which increased with C.O.D.

Previous attempts to measure the angle of inclination of the stretch zone to the fatigue crack plane have involved stereo viewing of crack profile replicas, [14], which can be tedious. In these present investigations two further techniques have been used. The first employed the tilt stage of a scanning electron microscope. The fracture surface was placed on the stage in a horizontal position and any particular point on the stretch zone was chosen and tilted until its maximum length was realised. The angle through which it had been tilted was then the angle of inclination. The stretch zone formed in Q1(N) is very large and this technique might not be so successful in less ductile materials. Furthermore location of the corresponding point on the mating fracture surface can be difficult. The second method adopted was to trace the crack profile using a Talysurf which produced a trace similar to that shown in Figure 6. Where the stretch zone deviated from the crack plane is very clear enabling its angle of inclination to be measured very easily but it was impossible to identify the demarkation between the stretch zone and the initiation of fibrous fracture. The Talysurf instrument leaves a scratch along the crack profile which can be viewed using a scanning electron microscope where the stretch zone width can be measured and the information transferred to the Talysurf trace. Using the above techniques the angle of the stretch zone in Q1(N) was found to lie within the range 21 - 23°.

C.O.D. Results

Since the potential drop equipment used for this work had not been used on any previous investigations it was decided to calibrate the technique with the more laborious procedure of measuring fibrous crack growth on specimens tested to various values of C.O.D., the specimens being then broken in liquid nitrogen, and producing plots of fibrous crack growth versus C.O.D. [20]. Every specimen tested was also simultaneously tested by the p.d. method. Figure 7 shows the results obtained in this way for specimens tested at room temperature and at 193 K. Up to point A on the curve only a stretch zone was evident on the fracture surface and so the increase in crack length is solely due to the formation of the stretch zone. After point A fibrous crack growth is evident on the fracture surface along with the stretch zone. It can be seen from Figure 7 that the δ_i value of 0.17mm is the same for both testing temperatures. This value was also obtained by the potential drop technique when the point Y (Figure 3) gave a consistent value of 0.17mm in all specimens tested. The vertical line B in Figure 7 relates to point Z on the p.d. curves (Figure 3) and from scanning electron microscopy this point is the point at which the whole of the crack front moves by fibrous crack growth only. At levels beneath this figure there were still some regions of the crack front which were advancing solely by stretching. Both the points Y and Z on the p.d. curves gave consistent values of 0.17 and 0.31 respectively.

The effect of orientation to the plate rolling direction was examined on specimens machined 0°, 22½°, 45°, 77½° and 90° to the rolling direction. Table 2 gives the details of inclusion counts on sample specimens at each orientation which were obtained on a scanning X-ray image analyser. Figure 8 shows the room temperature values obtained for the specimens machined at 0° and 90° to the rolling direction which shows that δ_i is only slightly lowered by a change in specimen orientation in the rolling direction plane. Figure 9 shows details for all the orientations tested and also gives δ_{max} and charpy upper shelf figures. Further details of the charpy tests are given in Figure 10. The differences in δ_i although small were consistently obtained by both methods used and the differences in fracture characteristics are further emphasised by the charpy and δ_{max} results.

DISCUSSION

The work reported in this paper deals with the development of techniques with which to study and determine the stretch zone width and δ_i values in Q1(N) as well as the effects of metallurgical variables on these values. It is felt that the combination of the scanning electron microscope and the Talysurf instruments described earlier offers a very good technique for studying the width and angle of inclination of stretch zones and will be used in the further work which is to be carried out. This technique as was previously mentioned, should be beneficial in other plastic materials.

Some problems were found with the p.d. equipment using the standard technique of plotting C.O.D. versus potential change at the crack tip, possibly because the samples were small compared with other published work but the revised technique described earlier does give consistent results which were much easier to interpret on the specimen tested.

The C.O.D. tests showed that stretch zone width and δ_i were unaffected by changes in temperature from 293K to 193K. Since the matrix flow stress of Q1(N) will undoubtedly increase with lower temperatures one might expect some difference in the strain to failure at inclusion/matrix interfaces. This change is obviously too small to be detected by the testing technique adopted.

The effect of rolling direction on δ_i was also rather small. As was mentioned earlier the plate material has been developed to have high cleanliness and therefore high ductility. The plate had also been cross-rolled to further remove orientation effects. The results in Table 2 show that the inclusion area etc. was not significantly affected by the change in orientation although the 90° sample did seem to possess an increased inclusion area. It can be seen that the testing technique consistently showed that this orientation had a lower value of δ_i than the other orientations which is substantiated by the δ_{max} and impact data. This was very reassuring and the technique can be used with confidence in future investigations. It is difficult to comment constructively on the higher values obtained for the 22½° orientation which were nevertheless consistently obtained. Further work will perhaps bring clarification on this point.

Further work is in progress using the techniques described in this paper, to further investigate the effects of metallurgical and geometric variables on δ_i in this material.

ACKNOWLEDGEMENTS

The authors would like to thank the Procurement Executive Ministry of Defence for the provision of a contract to carry out this work and in particular Mr. I. M. Kilpatrick of the Naval Construction Research Establishment for helpful discussions.

The opinions expressed in this paper are solely those of the authors and do not necessarily reflect current M.O.D. research policy.

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Table 1 Chemical Composition of Materials Used

Element	C	Si	Mn	S	P	Ni	Cr	Mo	Cu	V	Al
% Composition	0.17	0.31	0.31	0.005	0.010	2.80	1.47	0.39	0.09	<0.01	0.061

Table 2 Inclusion Counts on Material Used

Angle of specimen to rolling direction	No. of inclusions/mm^2			Average area %
	>3μ	>8μ	>15μ	
0°	9.3	1.1	0.13	0.0216
22½°	9.2	0.9	-	0.0218
45°	8.0	0.8	-	0.0223
77½°	9.5	0.9	0.1	0.0223
90°	8.7	1.1	0.1	0.0245

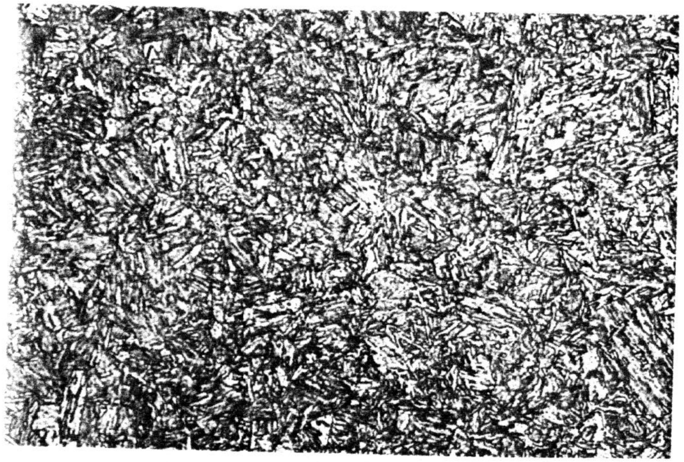

Figure 1 Microstructure of as received material x160.

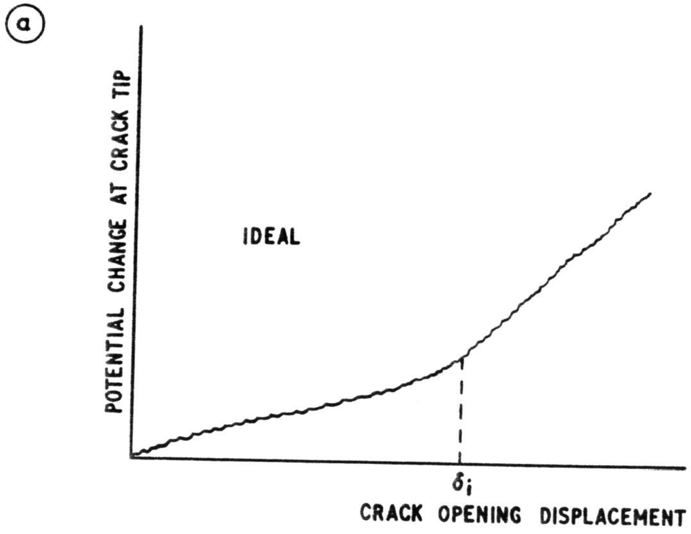

Figure 2 Ideal plot obtained by potential drop technique.

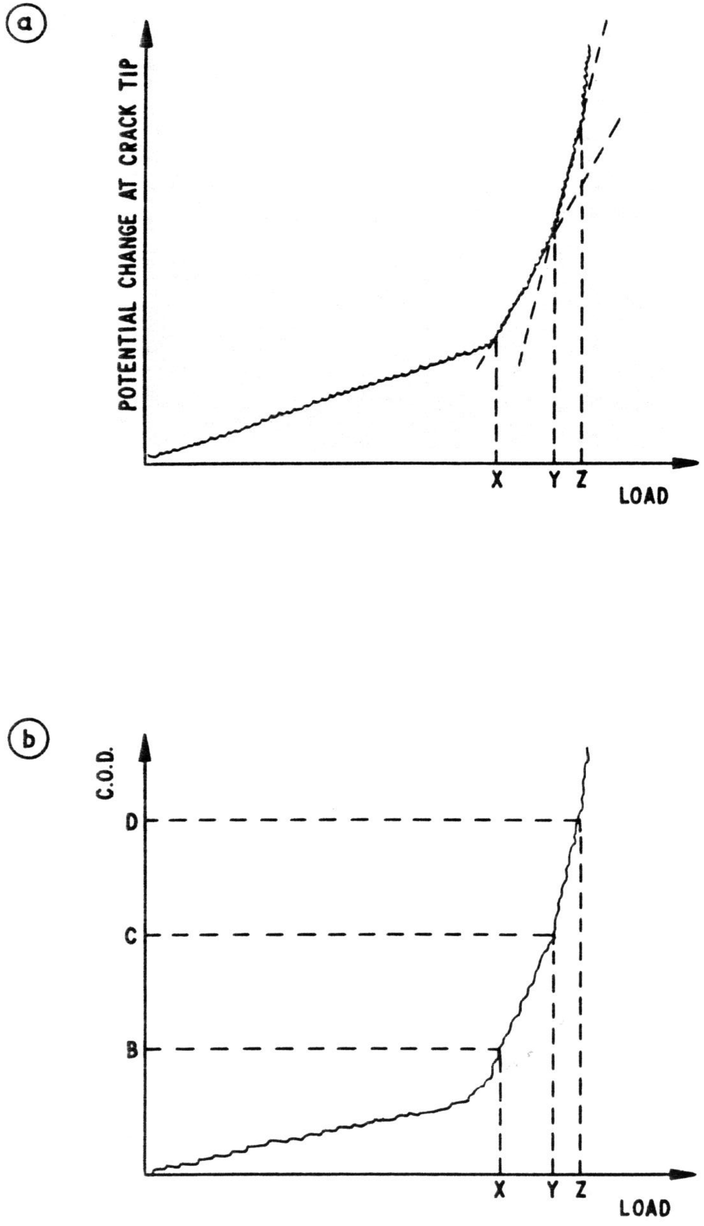

Figure 3 XY plots obtained using modified potential drop technique.

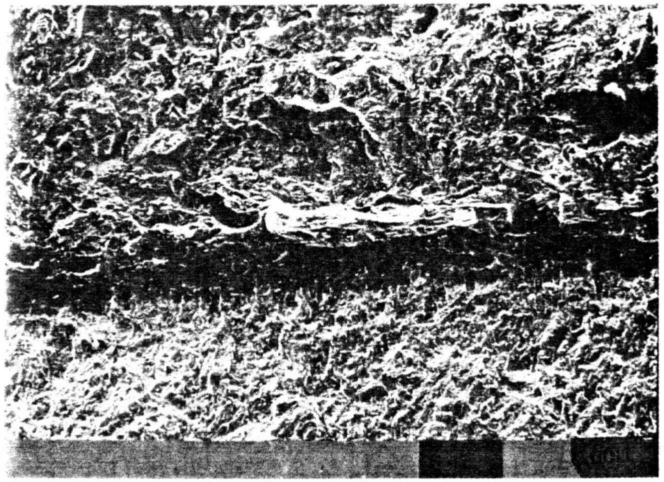

Figure 4 Presence of stretch zone on fractured specimen

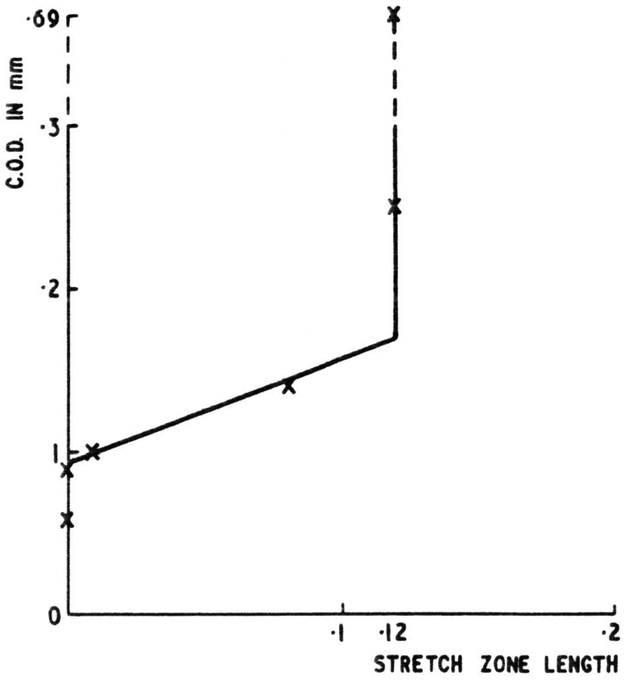

Figure 5 C.O.D. vs stretch zone length.

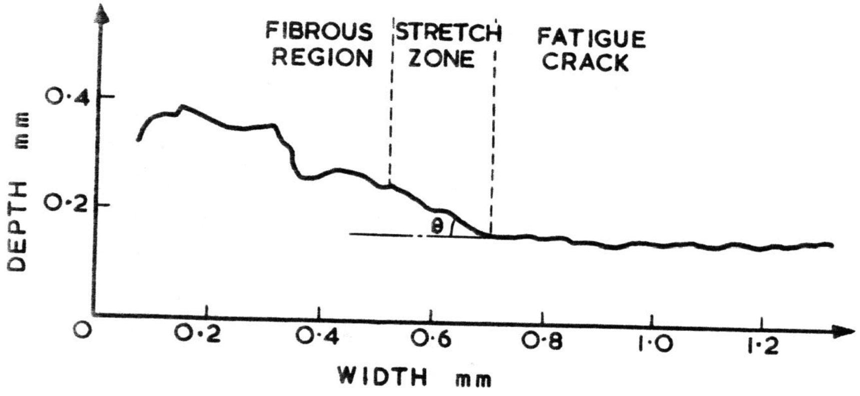

Figure 6 Talysurf trace across fracture initiation region on a broken specimen.

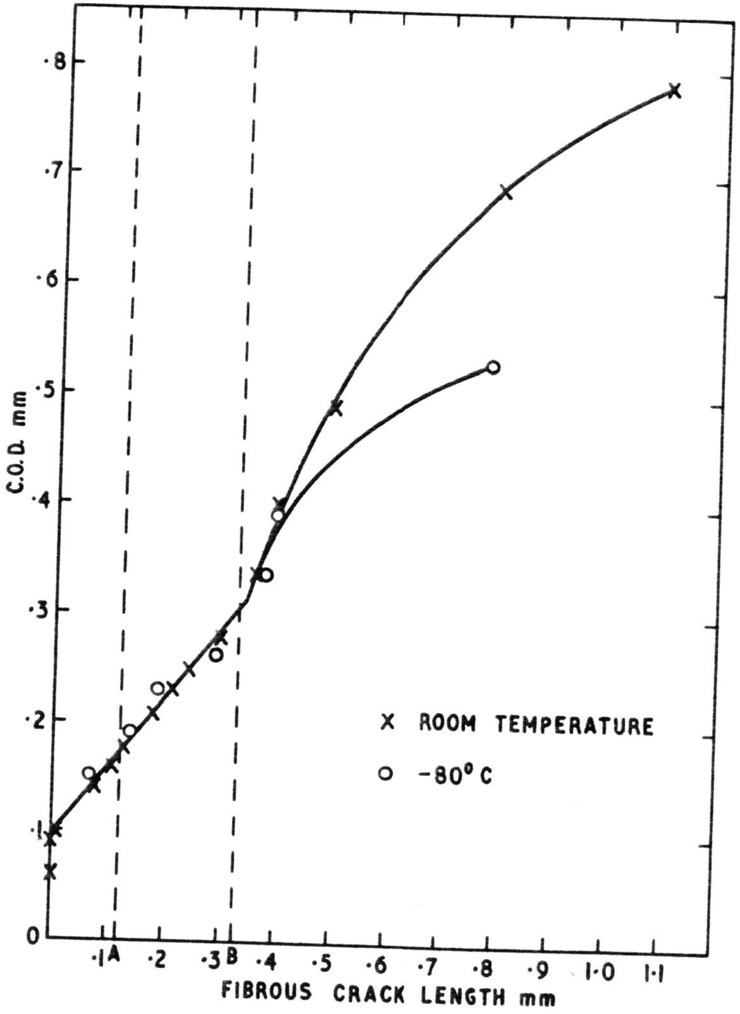

Figure 7 Effect of temperature on C.O.D. vs. fibrous crack growth

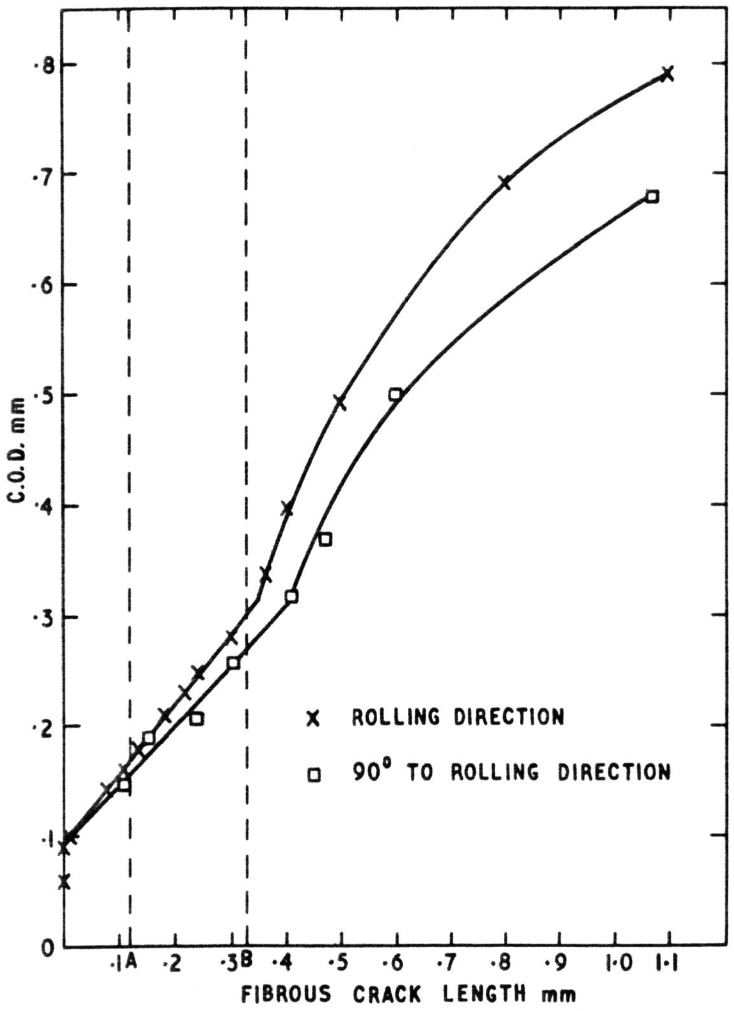

Figure 8 Effect of orientation to the rolling direction on C.O.D. vs. fibrous crack growth.

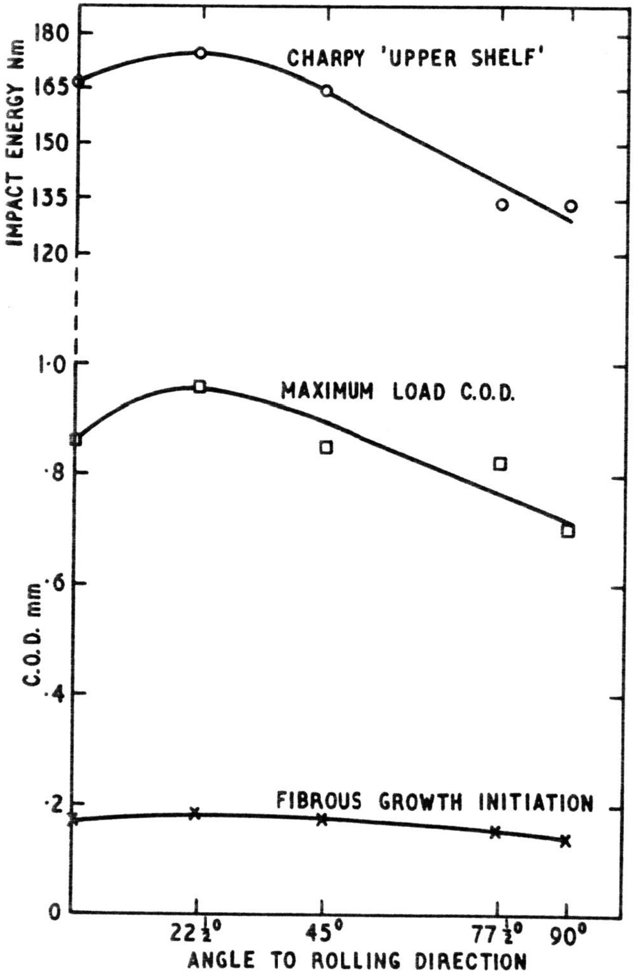

Figure 9 Effect of orientation to the rolling direction on fracture characteristics.

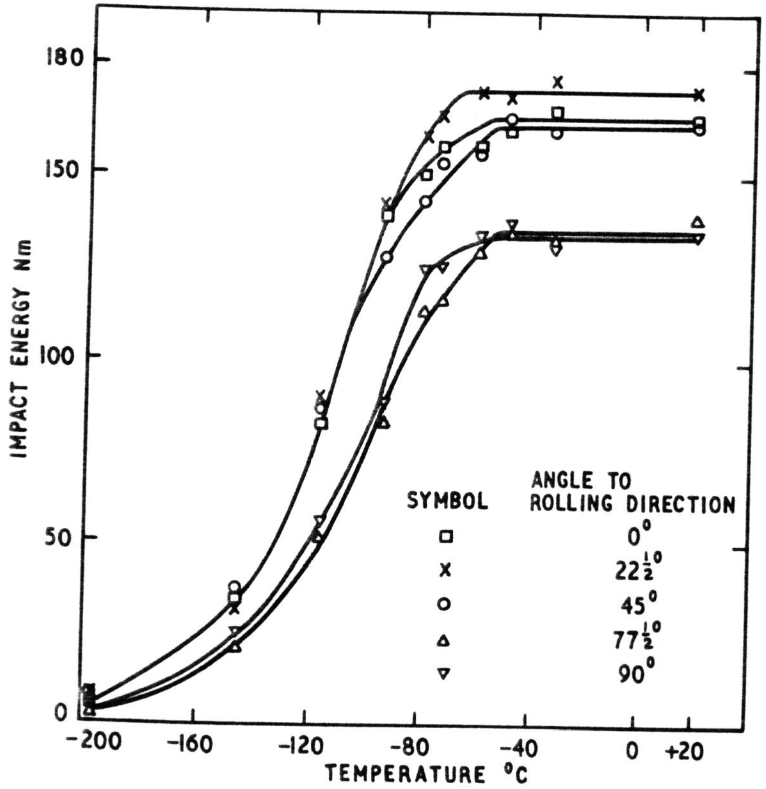

Figure 10 Effect of orientation to the rolling direction on charpy impact values