Effect of Notch Acuity on the Fracture Toughness of Three Low Alloy High Yield Strength Steels

In addition to comparing notch toughness at three strength levels, study suggests a low cost test specimen for metallurgical research

BY G. JOLLEY, I. M. KILPATRICK AND R. MAIN

ABSTRACT. A comparison has been made between the crack opening displacement (COD) values of fatigue pre-cracked and machine notched specimens of three naval alloy steels of increasing yield strength. It has been shown that the effects of notch acuity, within the limits stated, are slight, in the three materials investigated, when compared with published data on lower strength steels. It has been demonstrated that the COD for fibrous fracture is most affected by change in notch acuity in the steel of lowest yield strength while fracture transition is most affected by notch acuity change in the highest yield steel.

Introduction

Material selection, defect significance and design criteria problems where toughness is a dominant consideration have been facilitated in recent years by the development and application of fracture mechanics techniques which attempt to characterize a material by the consideration of the stress/strain relationships occurring at the tip of a crack or crack-like defect.

When fracture is preceded by appreciable amounts of crack tip plastic yielding the fracture toughness of the material may be assessed in terms of the extent of crack tip deformation occurring prior to the onset of fracture. This is the situation obtaining with the majority of lower strength (say less than about 180 ksi) structural and pressure vessel steels when used at their operating thicknesses and temperatures. The relevant parameter in this instance is termed the crack opening displacement, COD or δ (Ref. 1). Crack tip yielding due to the applied loading causes separation of the crack faces without extension until such time as the critical COD is achieved, which depends upon test temperature, material thickness, defect acuity and microstructure whence fracture occurs.

The COD approach has been extensively investigated and developed in recent years (Ref. 2). However, it has the disadvantage of requiring a fatigue pre-cracked specimen if design data is required on which to base working stresses and inspection requirements (i.e., critical defect sizes). The production of an initial fatigue crack is an expensive and time consuming process especially where full plate thickness specimens must be used, and in an extensive research program fatigue pre-cracking may well become a major consideration. If a research program is concerned more with an investigation of metallurgical variables than the acquisition of absolute design data then the necessity for fatigue precracking becomes questionable and it may be justifiable to use simple notched specimens in such cases in view of the saving in time and expense. Nevertheless it would still be desirable to have some indication of the extent of the effect of increased notch acuity on the notch toughness of a particular steel, especially the degree to which the fracture transition might be raised.

The present work was therefore designed to provide a comparison between COD values obtained from fatigue cracked (FC) and machined slit notched (SN) specimens in three low alloy Ni-Cr-Mo-(V) Naval constructional steels.

Comparisons of this nature have been made on other types of steel by various workers. Frederick and Salkin (Ref. 3) compared COD values of fatigue pre-cracked and machine notched Charpy sized specimens in a C-Mn steel. Their results showed virtually identical values of upper-shelf COD (stable ductile tearing), for the two notch configurations. However, the fatigue pre-cracked specimens showed a transition approximately 40 C higher than that revealed by the slit notched specimens. Similar work was carried out by Elliot and May (Ref. 4) on a mild steel. They found similar differences in COD transitions between machine notched and fatigue pre-cracked Charpy sized specimens although in this case 'off load' COD's were measured. These workers also carried out a comparison of the two notch acuities in 2¼ in. square specimens (i.e., full plate thickness) taking 'on load' COD measurements and in this case the difference between the two transition curves was less marked. Birkbeck and Wraith (Ref. 5) carried out COD tests on plain and side grooved Charpy sized specimens and demonstrated that fatigue precracking resulted in a

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Table 1 — Chemical Composition														
Steel	C	Mn	Si	S	P	Ni	Cr	Mo	V	Al	Cu	Sn	As	Sb	N
Q1(N)	0.16	0.32	0.27	0.007	0.007	2.46	1.41	0.35	<0.01	0.027	0.08	0.006	0.010	0.002	0.010
Q2(N)	0.11	0.28	0.25	0.013	0.009	3.12	1.24	0.38	0.06	0.020	0.15	0.012	0.020	0.0038	0.009
HY130	0.12	0.76	0.25	0.008	0.008	4.81	0.51	0.51	0.06	0.022	0.05	<0.001	0.005	<0.001	0.010

lowering of the COD for fibrous fractures but did not affect the COD in the cleavage mode. Unfortunately these workers did not carry out full COD transitions on their specimens.

Experimental Procedure

The three steels examined in the present work were the Ni-Cr-Mo-(V) low carbon Naval constructional steels Q1(N), Q2(N) and HY130. The first two of these are U.K. steels while the third is a U.S. steel. Chemical compositions of the steels are given in Table 1 while Table 2 gives the mechanical properties. Table 3 gives some indication of the cleanness of the steels. The inclusion counts were performed on representative samples using the NCRE inclusion count technique (Ref. 6) and a Quantimet image analyzing computer which allowed greater coverage and flexibility. In both cases the counts were obtained by examination of the longitudinal/short transverse plane. In addition to this the mean interparticle spacing was determined in the plane normal to the notch tip axis.

The steels were tested in the 'as-received' condition, i.e., quenched and tempered. Heat treatment details are given in Table 4 while the respective microstructures which were essentially tempered martensite can be seen in Fig. 1.

COD Testing Facility

The basis of the COD test equipment was a 50kN/250kN "Mand" servo-hydraulic test system and in the present series of tests position control was used throughout with a constant cross-head speed of 1 mm/min.

The specimens were tested in three point bending in the fixture illustrated in Fig. 2. As shown, the anvil was anchored to the base of an insulated box for testing at temperatures below ambient. The front wall of the box had been removed for the photograph to allow a clear view of the apparatus. The temperature of the specimens was maintained constant to ±2 C using either solid CO_2/isopentane for temperatures to −80 C or liquid nitrogen for temperatures between −80 C and −196 C. A Chromel-Alumel thermocouple, spot welded close to the notch on the top surface of the specimen was used to indicate the temperature of the specimen during testing.

Table 2 — Mechanical Properties						
Steel	Orientation	0.2% YS, N/mm²(tsi)	UTS, N/mm²(tsi)	0.2% YS/UTS, %	El., %	R. of A., %
Q1(N)	L	670 (43.4)	774 (50.1)	86.6	22	72
Q2(N)	L	781 (50.6)	839 (54.3)	93.1	20	72
HY130	L	937 (60.7)	984 (63.7)	95.2	19	69

Crack opening displacement was measured by means of a double cantilever beam gage (Ref. 7) mounted on saddle type knife edges. These were located on the specimen using the arrangement illustrated in Fig. 3.

The specimens were Charpy sized, i.e., 10 × 10 × 55 mm and were cut from plate mid-thickness positions parallel to the longitudinal direction. In the machined notched specimens slit notches were machined of approximately 0.15 mm width and a total depth of 3 mm. The notch in the fatigue pre-cracked specimens comprised a slit notch (0.15 mm wide) of approximately 1.25 mm deep which was subsequently extended by fatigue to a total crack length of 3 mm. The fatigue cracking was carried out on an Amsler Vibrophore in accordance with CODA recommendations (Ref. 8). COD testing procedures were also in accordance with these recommendations.

Results

The results of the COD tests are illustrated in Figs. 4-8. At higher temperatures the COD values were calculated using the displacement at maximum load while at lower temperatures where failure was by fast fracture prior to attainment of maximum load the COD was calculated from the displacement at the onset of unstable fracture. Only the former values are included on the curves thus distinguishing the temperatures at which stable fracture occurred. A study of Figs. 4, 5 and 6 reveals that, for each steel, the upper-shelf COD values for the SN specimens tends to be higher than those for the fatigue cracked specimens, although the difference decreases with increase in yield strength. Other workers have observed this effect in mild steel (Ref. 5).

Figures 7 and 8 compare the three steels on the basis of similar notch acuity. These show a decrease in the upper-shelf COD value with increase in yield strength. It is interesting to note that for both the SN and FC specimens the steels Q1(N) and Q2(N) exhibited virtually identical transitions while HY130 shows a flatter type of curve with a consequent increase in transition.

Fig. 1 — Typical microstructures of three steels in the as-received condition: (a) Q1(N), X3384; (b) Q2(N), X5268; (c) HY130, X3384. (all reduced 33%)

Figure 9 gives Charpy V-notch impact values on the three steels. It will be seen that the impact results exhibit a similar pattern for the three steels as the COD results displayed in Figs. 7 and 8.

The fracture surfaces of the broken COD specimens were essentially sim-

Table 3 — QTM Inclusion Counts

Steel	Oxide, no. inclusions/mm²			Sulfide, no. inclusions/mm²			Total, no. inclusions/mm²			Avg. area, %	Mean particle spacing,	NCRE count
	>3μ	>10μ	>20μ	>3μ	>10μ	>20μ	>3μ	>10μ	>20μ			
Q1(N)	9.72	0.87	0.093	0.75	0.19	0.057	10.47	1.06	0.15	0.044	107	0.23
Q2(N)	12.96	1.66	0.224	19.90	1.71	0.190	32.86	3.37	0.414	0.048	108	0.49
HY130	21.46	1.90	0.425	8.87	1.64	0.692	30.33	3.54	1.117	0.050	123	0.80

Table 4 — Heat Treatment and Plate Sizes

Steel	Heat treatment	Original plate dimensions, in.
Q1(N)	930 C — water quench, 640 C — 1½ h, air cool	174×72×1½
Q2(N)	930 C — water quench, 845 C — water quench, 660 C — 1½ h, air cool	294×84×1
HY130	Quenched and tempered — details not known	336 × 96 × 1½

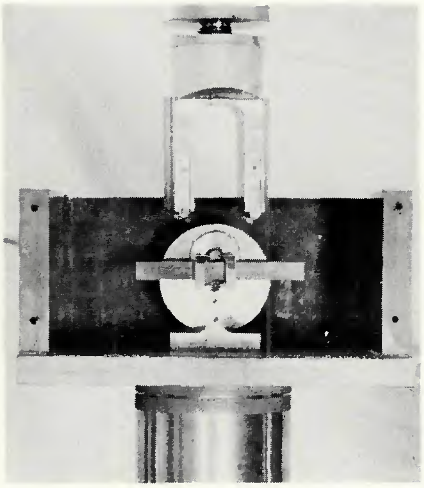

Fig. 2 — Three point bend rig

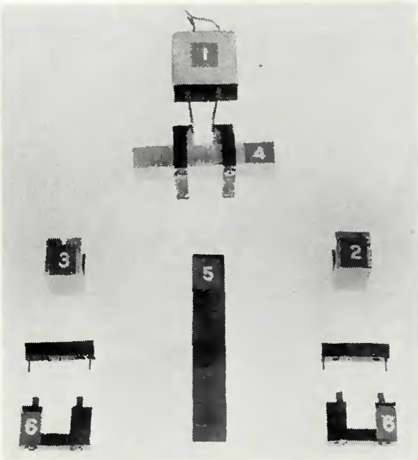

Fig. 3 — Knife edge location arrangement: (1) clip gage, (2) saddle spacer for slit notched specimens, (3) saddle spacer for V-notched specimens, (4) specimen 10 × 10×55 mm, (5) 0.005 in. shim for aligning specimen notch with spacer notch, (6) saddle type knife edges with locating dowels

ilar to those of the Charpy specimens for the same material. The higher temperature fractures were ductile in character exhibiting extensive shear lips indicative of conditions tending towards a plane stress fracture mode. With decrease in test temperature the shear lip dimensions diminished until at around -196 C flat fractures were generally observed indicating the expected trend towards a plane strain fracture mode. The low temperature flat fractures were more crystalline and exhibited chevron markings typical of brittle failure.

Scanning electron microscope observations were carried out on both the Charpy and the COD specimens. In both cases it was found that the flat areas of the fracture surfaces were mainly of the quasi-cleavage type (Ref. 9) mixed with areas of fibrous fracture. It was generally observed that the amount of fibrous fracture (microvoid coalescence) decreased with temperature. Figures 10 and 11 show scanning electron micrographs of fracture surfaces of Charpy V-notch specimens from HY130 which were typical of the effects of decreasing temperature on Charpy and COD specimens in the three steels.

Figure 10 shows the fracture surface of a Charpy V-notched specimen in HY130 steel broken at -70 C where the predominant fracture mode was microvoid coalescence mixed with some areas of cleavage.

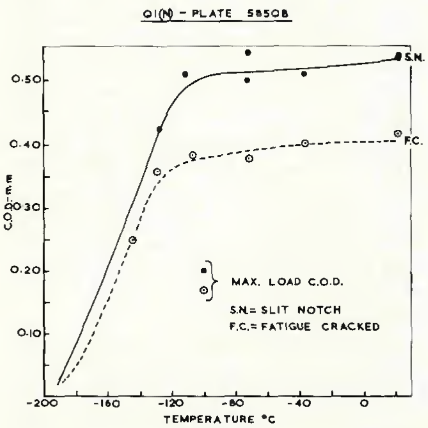

Fig. 4 — Comparison of slit notched and fatigue cracked COD values for Q1(N) steel

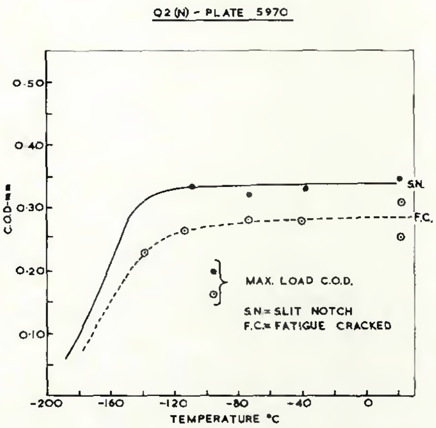

Fig. 5 — Comparison of slit notched and fatigue cracked COD values for Q2(N) steel

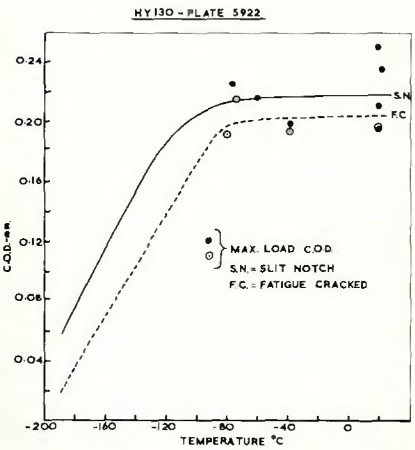

Fig. 6 — Comparison of slit notched and fatigue cracked COD values for HY130 steel

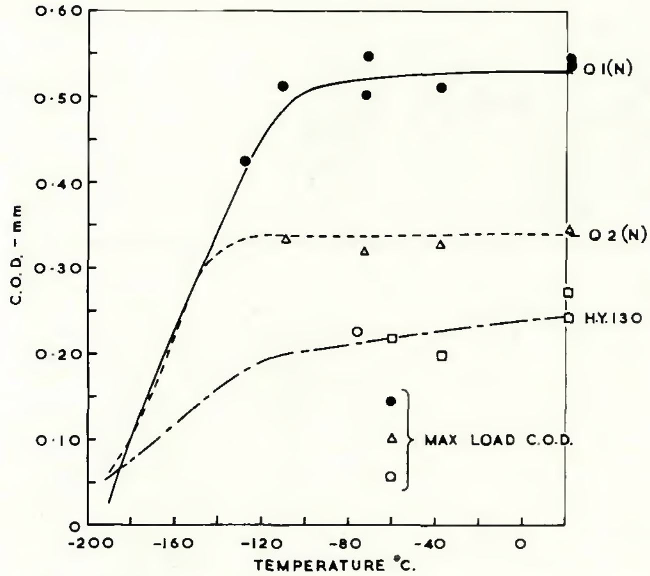

Fig. 7 — Comparison of slit notched COD values for Q1(N), Q2(N) and HY130 steels

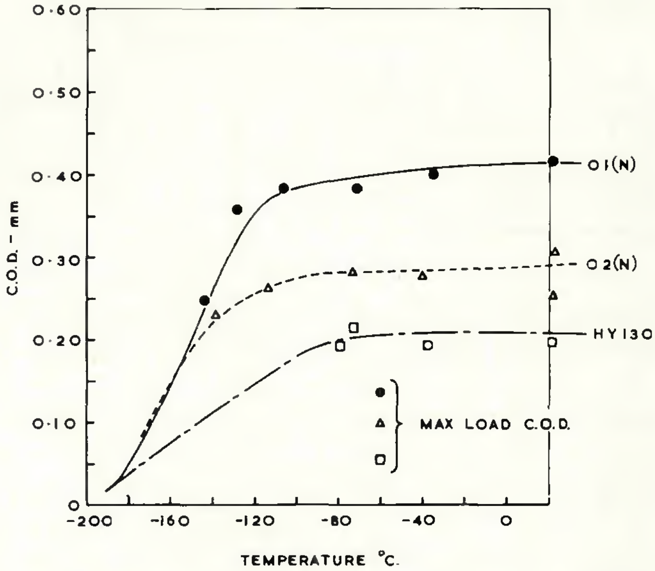

Fig. 8 — Comparison of fatigued cracked COD values for Q1(N), Q2(N) and HY130 steels

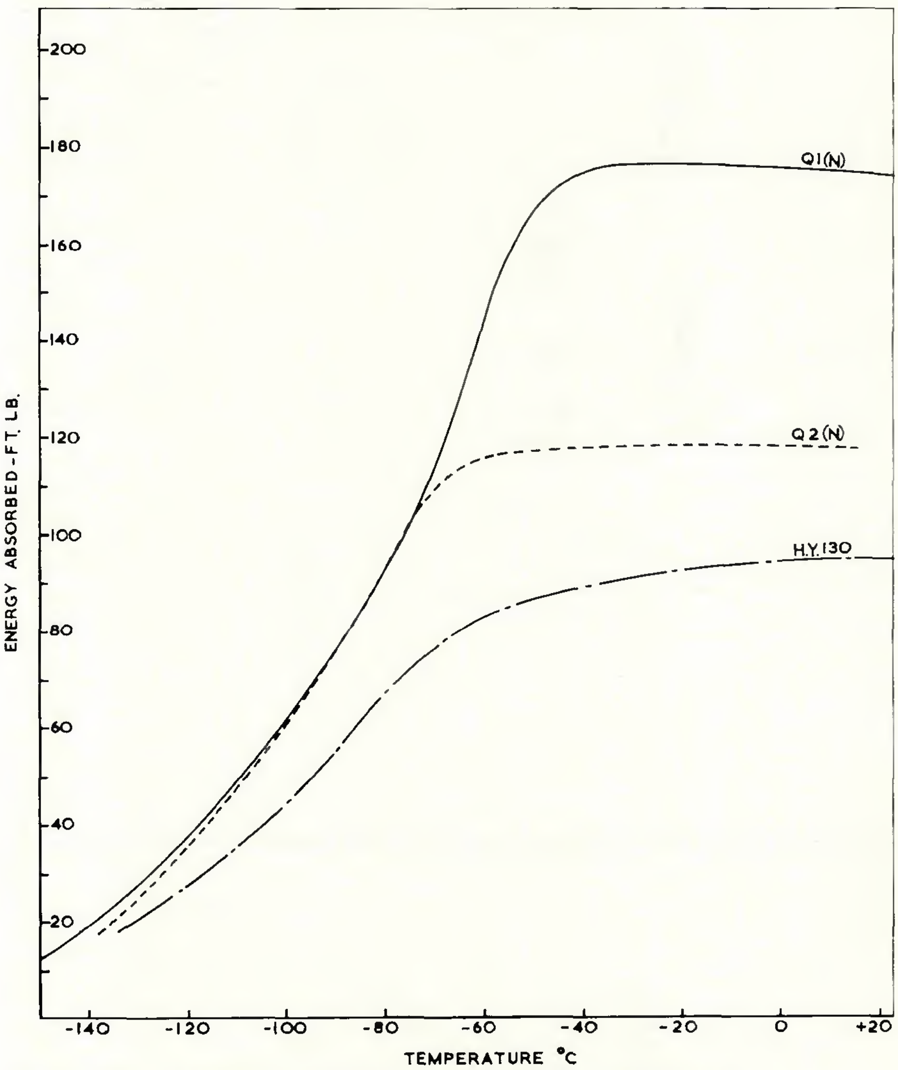

Fig. 9 — Impact transition characteristics of Q1(N), Q2(N) and HY130 steels

Figure 11 shows the same steel broken in Charpy impact at −170 C when the major feature was quasi-cleavage but some microvoid coalescence can be observed indicative of appreciable amounts of plastic deformation occurring even at this low temperature.

Discussion

The COD results illustrated above demonstrate that, in this work, the effect of notch acuity on COD transition temperatures was greater in the higher yield strength steel than in the other two steels. The difference between fatigue cracked (FC) and slit notched (SN) COD transition temperatures being about 25 C in HY130 while a difference of about 10 C was noted in the other two steels.

The effect of notch acuity on the upper-shelf CODs on the other hand was most marked in the lowest yield strength steel, Q1(N), where the ratio of crack opening displacement in the slit notched specimens to that in the fatigue cracked specimens (δ SN/δ FC) is about 1.3 which falls to just over 1 in the FC specimens. The effects of notch acuity on fibrous fracture and brittle failure are summarized in Fig. 12.

The three steels described in this paper have been developed to be resistant to brittle fracture while at the same time possessing high strength and ductility. This has been achieved by careful control of alloy content and heat treatment to produce a low carbon tempered martensite. Great emphasis has been placed on achieving a high degree of cleanness so that premature ductile failure is not initiated at inclusions and to ensure freedom from lamellar tearing when the steel is welded. There is a lack of published data on the effects of notch acuity on the fracture transitions of such materials.

However, perhaps a clue to the effect which might be anticipated can be gleaned from the work of Elliot and May (Ref. 4) who showed that the COD transition difference in 2¼ in. mild steel specimens was much less between FC and SN specimens than was observed with Charpy sized specimens. As the ratio of plastic zone size at the crack tip to plate thickness decreases, the amount of through thickness stress relaxation decreases so that the effect of elastic constraint in a larger specimen will increase the tendency to plane strain fracture. Under such conditions these workers showed that the fracture transition became less influenced by notch acuity.

In the present work the ratio of plastic zone size to thickness has been decreased by using high yield strength materials rather than increasing the specimen size. The relative insensitivity of these materials may now appear to be a logical development of Elliot and May's work; however the greater sensitivity of the strongest steel, HY130, is somewhat surprising in view of the foregoing argument and more work is in progress at NCRE to clarify this problem.

Fig. 10 — Scanning electron micrograph from Charpy V-notch specimen broken at -70 C, HY130 (reduced 51%)

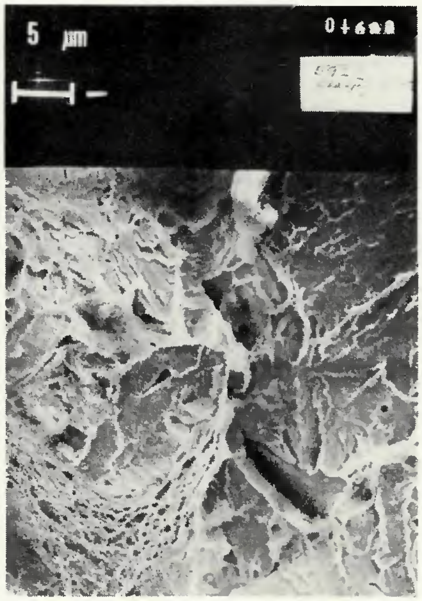

Fig. 11 — Scanning electron micrograph from Charpy V-notch specimen broken at -170 C, HY130 (reduced 51%)

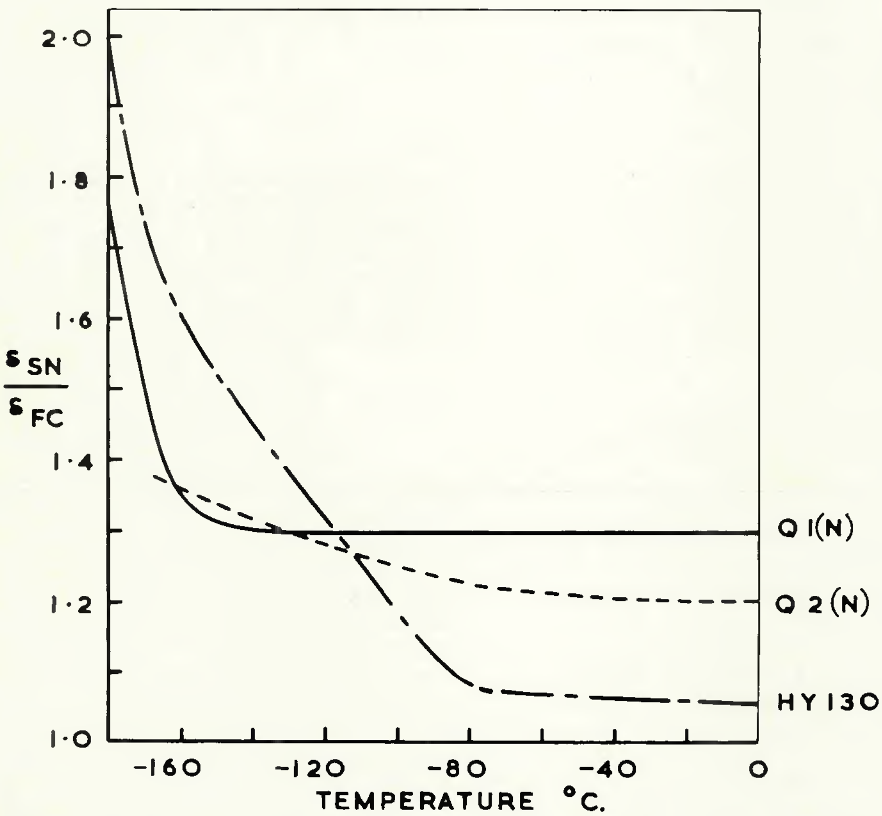

Fig. 12 — Variation of δ_{SN}/δ_{FC} ratio with temperature, where δ_{SN}= COD in slit notched specimens and δ_{FC} = COD in fatigue cracked specimens

Work by Smith and Knott (Ref. 10) has shown that notch acuity effects on fibrous fracture initiation in free machining mild steel are related to the mean interinclusion spacing in the plane at right angles to the root of the notch. In a steel with a mean inter-particle spacing of 0.042 mm these workers showed that the COD for fibrous fracture initiation in a fatigue pre-cracked specimen was less than was measured for 0.15 mm slit notched specimens. They explained this result with the suggestion that fibrous fracture occurred when the strain at the notch root exceeded a critical proportion of the mean interparticle spacing or effective gage length of the inclusions. They concluded that for notches of width greater than the gage length of the inclusions the COD for fibrous fracture initiation, δ_1 , was related to the notch width but for notches of width less than this value δ_i could be related to the gage length of the inclusions.

In the present work the analysis of Smith and Knott would not be expected to be rigorous since no allowance for slow crack growth prior to attainment of maximum load on the COD/load curve was made. However the effect of notch acuity does show that the COD for fibrous fracture is lowered when using fatigue cracked specimens and that in these three steels the effect is most marked in the cleanest and lowest yield strength steel, Q1(N). It can be seen from Table 3 that the inter-inclusion spacing of all the steels is less than 0.15 mm so that the type of notch acuity influence predicted by Smith and Knott would be expected to prevail which agrees with the experimental findings. However it would be imprudent to attempt to explain the greater notch acuity sensitivity of Q1(N) using these arguments bearing in mind the relatively small difference involved and the fact that the interparticle spacing is of the same order as the 0.15 mm notch.

A further interesting point is the similarity of the Charpy results with the COD figures which suggests that the Charpy test provides realistic data as to the order of fracture toughness of different steels of this type although the test is obviously unable to produce quantitative design data.

It must be emphasized that the major conclusion from these tests is the relative insensitivity of these high strength steels to changes in notch acuity when compared with lower yield strength steels which is encouraging as a preliminary stage in the development of a testing procedure to obviate fatigue precracking. It would be anticipated from the foregoing arguments that increasing the specimen dimensions would further diminish these effects. Work is continuing at NCRE (Ref. 11) on the effects of specimen dimension and geometry changes on the effects reported in this paper so that a more complete appraisal of the possibility of replacing FC specimens by SN specimens, in future research work involved with the effects of metallurgical variables, can be made.

Conclusions

1. The COD for fibrous fracture in the three steels investigated is slightly lower in fatigue pre-cracked specimens than in slit notched specimens, the effect being most manifest in the lowest yield strength steel, Q1(N).

2. The COD transition temperatures in all three steels are slightly lower for fatigue cracked than slit notched specimens. The effect is most manifest in the highest yield point steel, HY130.

3. The trends demonstrated by COD work were also shown by Charpy V-notch impact tests.

4. The results in this paper indicate that it might well be possible, in these steels, to carry out research programs on the effects of metallurgical variables using the less expensive slit notched specimens, rather than fatigue pre-cracked specimens.

Acknowledgements

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STRUCTURAL WELDING CODE

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Published in September, 1972, the Structural Welding Code, AWS D1.1-72, combines into a single document, completely updates, and replaces the Code for Welding in Building Construction, AWS D1.0-69, and Specifications for Welded Highway and Railway Bridges, AWS D2.0-69. Also, for the first time anywhere, requirements are presented for the design and fabrication of welded tubular structures.

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