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Effects of Notch Acuity and Side Grooving on Fracture Toughness

Charpy-sized specimens with modified notches appear to yield improved data for fracture toughness assessment

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Part I — Impact Loading

ABSTRACT. Impact tests were conducted on plain and side grooved Charpy-sized specimens of a vanadium grain refined mild steel (Hyplus 29) containing either Charpy V or 0.15 mm slit notches and with a constant notched cross section of 80 mm^2. Side grooving to a depth of 1 mm produced full width cracks along the notch root at the point of fracture initiation. With shallower side grooves cracks were initiated first at the center of the specimen, while deeper side grooves caused cracks to be initiated first at the edges, thus indicating that the stress concentration at the ends of the notch became more severe as the side groove depth increased.

The increase in notch acuity from Charpy V to a 0.15 mm slit had no significant influence on either the ductile fracture performance or the fracture appearance transition temperature (FATT) but raised the temperature at which low energy fractures occurred by about 27 C and narrowed the transition temperature range. It also slightly reduced the scatter of the results.

Side grooving considerably reduced energy absorption and lateral expansion (LE) at high temperatures, and raised the FATT by between 22 C and 38 C. It substantially reduced the scatter of the results but broadened the transition temperature range primarily by raising the temperature at which the drop in energy absorption from the upper shelf value occurs. The specimen design which produced the maximum rise in the FATT (38 C) showed 100% crystallinity at the nil ductility transition (NDT) temperature determined by the Pellini drop weight test (DWT).

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Introduction

A wide variety of fracture toughness tests has been developed with the basic aim of measuring the capacity of a material to resist brittle fracture. These tests can be divided into those which measure the resistance to crack initiation, e.g. the COD test, those which measure the resistance to crack propagation, e.g. the Robertson test, and those which do not clearly distinguish between initiation and propagation, e.g. the Charpy V-notch test.

Small specimen tests like the Charpy test are important in the assessment of fracture toughness for several reasons, among which is their low cost and simplicity of manufacture and testing. However, quantitative design data cannot be derived from small specimens of less than full plate thickness, primarily due to the lack of mechanical restraint at the notch or crack tip which produces plane strain conditions in the bulk of a thick specimen. Moreover, most small scale tests use relatively blunt notches rather than fatigue cracked notches; this also reduces the restraint at the base of the notch. Even in those tests which use fatigue cracks, such as the COD test, the uncertain effect of cracking on the remaining cross sectional area available for fracture as well as the lack of restraint places some doubt on the test accuracy; so that it can be argued that the expense of using "natural" fatigue cracks in small specimens is not justified. The problem then becomes how to use small specimens for more accurate assessment of fracture toughness, especially in welded fabrications where a wide variety of metallurgical structure and toughness behavior is found.

An improvement is needed which

LIST OF SYMBOLS

COD	—	crack opening displacement
DT	—	dynamic tear
DWT	—	drop weight test
FATT	—	fracture appearance transition temperature
LE	—	lateral expansion
NAT	—	nil-arrest temperature
NDT	—	nil-ductility temperature

will give small specimen test results which can be correlated more readily with large scale test results, thus making quality control assurance at once more reliable, more accurate, and less costly. Specimen design is one variable which has not been fully explored. Attention to notch acuity and artificial restraint techniques (e.g. side grooving) can be used to encourage fracture conditions in small specimens that approach more closely those experienced in full thickness specimens.

There are many examples in the literature of the influence of notch acuity on fracture toughness in small specimens. Most of these papers deal with COD under slow strain rate conditions (Refs. 1-5) and only a few deal with impact loading (Refs. 5-8). Of the latter only two (Refs. 7 and 8) deal with the influence on energy absorption and in both cases V-notches are compared with fatigue cracks. The effect of increasing notch acuity on transition temperature varies from marginal (Refs. 2, 4, and 6) to an increase of 70 C (Ref. 1) and the changes are often difficult to quantify accurately because of the large amount of scatter in the experimental results.

The two papers which examined the influence of fatigue cracks on energy absorption under impact loading (Refs. 7 and 8) showed a much smaller rise in transition temperature in the brittle region than in the ductile region although one might expect the reverse since in the ductile region crack tip blunting may be expected to reduce the effectiveness of sharp cracks. In neither case was the notched cross section after fatigue cracking clearly specified. Fatigue crack shape and depth can easily reduce the cross section to less than that intended which would reduce impact energy levels particularly in the ductile region.

In larger specimens, fatigue cracks are necessary for fundamental K_{Ic} fracture toughness testing, and also for crack initiation tests used to establish fundamental design data in full thickness specimens, but their use for crack propagation and quality control purposes is not necessary. Pellini (Ref. 9) describes clearly how the Dynamic Tear (DT) test was developed through several stages to its present form using a pressed knife edge notch which gives equivalent results to a fatigue crack or a brittle weld crack starter. The precedent thus exists for avoiding the cost and complication of fatigue cracking in quality control specimens while maintaining a sufficient notch acuity to simulate natural cracks.

The second factor to consider in specimen design, artificial restraint, has not received as much attention as notch acuity. Side grooving is a recommended practice in some large specimen tests, but very little has been done to test its effectiveness on smaller specimens used in quality control work. In COD testing the lack of restraint in small specimens is causing some concern, since cracks in fact open at the specimen center before they extend to the edges, and the present tests define the critical COD only when a full width crack has been obtained, i.e. when maximum loading occurs. In impact testing lack of restraint in small specimens causes shear lips to form at much lower temperatures than those occurring with larger specimens, with consequent higher energy absorption and apparent fracture toughness.

In a previous examination of cracking in the Charpy test (Ref. 10), a low energy blow technique, originally developed by Hartbower (Ref. 11), was used to show that cracks initiate at the center of the notch root long before they extend to the sides of the specimen. This indicates that the state of stress near the specimen edges is much less severe than it is at the specimen center and results in the formation of a curved crack front. This has been substantiated by other workers (Refs. 5, 12, and 13). Birkbeck and Wraith (Refs. 5 and 12) have shown that a straight crack front can be produced by introducing side grooves into the specimen which increase the stress concentration at the specimen edges to levels comparable to the specimen center. For this purpose the depth of the side grooves is critical since the shape of the crack front changes from convex to straight to concave with increasing depth of side grooves. Birkbeck and Wraith (Ref. 12) used various depths of side grooving in standard 10 × 10 mm specimens which reduced the fracture area as groove depth increased and would probably, therefore, influence the level of fracture toughness. However, the influence of side grooving on energy absorption in the impact test has, to the authors' knowledge, not been examined before.

The major developments in fracture toughness testing have correctly been concentrated in the recent past on fundamental aspects of fracture in full thickness specimens to establish design criteria for large structures. However, after this movement away from the inadequate small test specimens of the past toward fundamentally accurate large scale tests, there has been little feedback to help redesign the small specimen tests which are required for quality control. Experience with the large scale tests has shown that, for a given material composition, notch acuity and mechanical restraint are the two most important variables, and that fatigue cracks are necessary despite their cost to accurately assess fracture behavior in fundamental tests. However, during impact loading in the DT test no difference is observed between sharp artificial notches and fatigue cracks, and for quality control work fatigue cracks may not be necessary. The existence of differing design philosophies emphasizing the importance of resistance to crack initiation or crack propagation also involves tests at both high and low strain rates for quality control purposes.

This first part of a two part paper examines the influence of notch acuity and side grooving on fracture toughness behavior in small specimens using impact loading with an overall view of developing an attractive quality control test. Part II will describe a similar program using slow bend tests.

Materials

The material used throughout was 38 mm thick Hyplus 29 steel plate with the composition: 0.17 C, 0.29 Si, 1.54 Mn, 0.014 P, 0.020 S, 0.014 Al, 0.016 N, 0.10 V, rem. Fe.

Experimental Procedure

Specimen Preparation

All specimens tested in this program were machined from the mid-thickness of the plate and notched perpendicular to the plate surface. The specimen depth (10 mm), notch depth (2 mm), and notched cross section (80 mm^2) were kept constant while the notch acuity and depth of side grooving were varied. Side grooves were machined using the Charpy broaching tool. Although slit side grooves were tried initially, their effectiveness was limited by the physical support obtained when the slit closed during specimen deformation and they were consequently discarded. Slit notches* on the top surface of the specimens were machined using a 0.15 mm thick SiC wheel revolving at 20,000 rpm.

Preliminary Tests on Side Grooved Specimens

Specimens containing Charpy V-notches and side grooves of 0, 0.5, 1.0, 1.5 and 2.0 mm depth were given a series of low energy blows of approximately 13.6 J (10 ft lb) capacity in an impact testing machine at room temperature using the technique de-

** Throughout this paper the term 'notch' refers to the main notch on the tension surface of the specimen while the term 'side groove' refers to the notches machined down both sides of the specimen in the same plane as the main notch.*

scribed in an earlier report (Ref. 10). The root of the notch was examined under a binocular microscope after each blow in order to observe the manner in which cracking first occurred at the notch root. After full width cracks were developed the specimens were fractured at −196 C in order to observe the shape of the crack front. Full blow impact tests were also carried out at room temperature on the five specimen types.

Main Test Program

As a result of the preliminary tests the six specimen types described in Table 1 were selected for the main program. They were impact tested in a Losenhausen machine using a full blow of 294 J. A minimum of five tests was conducted at 20 C intervals from 20 C down to −140 C, and additionally either three or five tests were conducted at 60 C in order to determine the transitional behavior and indicate the degree of scatter. Energy absorption, lateral expansion (LE), and fracture appearance were recorded for each test. The LE recorded for the side grooved specimens was measured from the surface of the side grooves; this explains the smaller values observed in these specimens since some expansion would be accommodated within the side groove.

Pellini DWT tests were conducted on full thickness specimens measuring 355 × 89 × 38 mm in accordance with the ASTM procedure (Ref. 14) in order to establish the NDT temperature.

Results

Preliminary Tests

Table 2 summarizes the observations made during the low energy blow tests, Fig. 1(b) shows the appearance of the initiating cracks as observed on the notch surface after the second low energy blow, and Fig. 1(a) shows the shape of the crack front after a full energy blow at −196 C following the fifth low energy blow, i.e. after full width cracking had been established at room temperature. Table 3 gives the results of the full blow tests. Figure 1 and Table 2 clearly show that center crack initiation precedes full width cracking in the plain and 0.5 mm side grooved specimens while edge crack initiation precedes full width cracking in the 1.5 mm and 2 mm side grooved specimens. The 1 mm side grooved specimens show uniform full width cracking at the point of crack initiation. Figure 1(b) also demonstrates the effectiveness of side grooving in reducing through-thickness deformation.

As a result of these tests it was decided to use the plain and the 1 mm and 2 mm side grooved specimens for the main program. The plain specimens provide a datum from which the influence of side grooving could be assessed. The 1 mm side grooved specimens were chosen because they produced uniform cracking along the notch root, while the 2 mm side grooved specimens were included because they had the most influence on energy absorption at room temperature.

Main Test Program

The variation in energy absorption, LE, and fracture appearance with temperature for the six specimen types is shown in Figs. 2-4. Although the steel displayed a remarkably high degree of scatter, especially in the transition region (with energy absorption values varying between 50 and 165 J at −40 C for the plain 0.15 mm slit notch specimens), the curves shown passed very closely through the mean values at each temperature and experimental points have been omitted for sake of clarity.

The influence of notch acuity and side grooving on test performance can be quantified in two ways: firstly, by measuring shifts in transition temperature and secondly by measuring changes in toughness parameters at specific temperatures. Both methods are used here and we shall deal first with the influence of notch acuity and then with the influence of side grooving.

Influence of Notch Acuity on Transition Temperature—Figures 2 and 3 show that increasing the notch acuity from a Charpy V-notch to a 0.15 mm slit has little influence on energy absorption or LE for ductile fracture, but at low temperatures, when the frac-

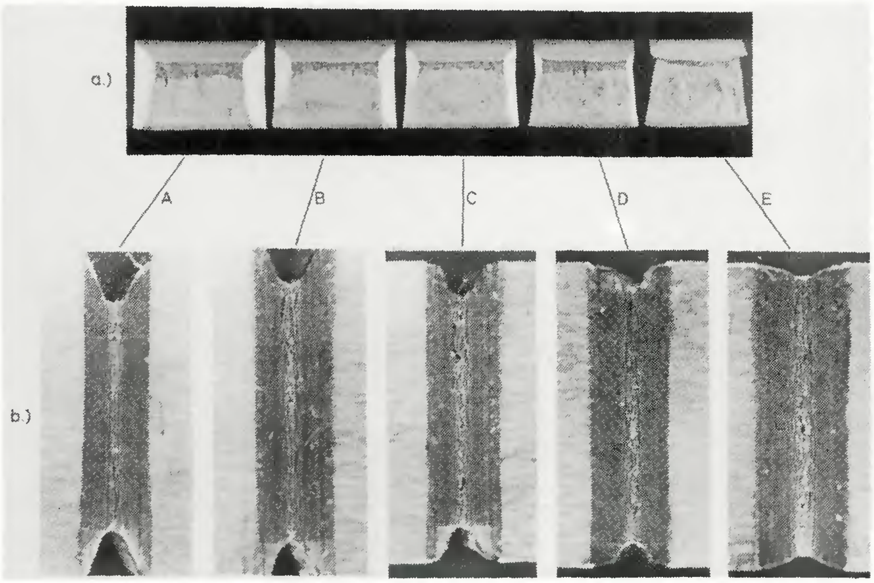

Fig. 1 — Influence of side grooving on (a) the shape of the crack front, and (b) the formation of cracks at the surface of the notch root. All specimens contain V-notches with side groove depths of A=2.0 mm, B=1.5 mm, C=1.0 mm, D=0.5 mm, and E nil

Table 1 — Specimen Types

No.	Notch type	Side groove depth, mm	Spec. width, mm
1	Charpy V	Nil	10
2	0.15 mm slit	Nil	10
3	Charpy V	1.0	12
4	0.15 mm slit	1.0	12
5	Charpy V	2.0	14
6	0.15 mm slit	2.0	14

Table 2 — Low Energy Blow Test Results

Side groove depth, mm	Comment
Nil	Center crack formed after the second blow but did not extend to the sides until after the fifth blow.
0.5	Center crack formed after the second blow and extended to the sides after the fourth blow.
1.0	Uniform crack formed along the entire notch root after the second blow.
1.5	Cracks formed at both edges after the second blow and extended over the entire notch root after the third blow.
2.0	Cracks formed at both edges after the second blow and extended over the entire notch root after the third blow.

ture is predominantly by cleavage, increasing notch acuity lowers energy absorption and LE and raises the transition temperature. In contrast the FATT, Fig. 4, is not significantly affected. However it should be pointed out that the fracture appearance curves are more difficult to define accurately because of the subjective nature of assessment and because crystallinity values are only significantly different from 0% and 100% at three of the test temperatures.

Table 4 indicates the increasing significance of notch acuity at low temperatures. The increases in transition temperature in the ductile, mid-transition, and brittle regions were fairly consistent among the different specimen types with the exception of the LE transition in the 2 mm side grooved specimens where the changes were less marked. This was due to the fact that these specimens developed relatively small LEs even at the highest test temperatures because a large proportion of the expansion was accommodated within the side grooves. This is reflected in the plots of energy absorption against LE shown in Fig. 5. Neglecting this set, the average increases in transition temperature were +5 C, +8 C and +27 C for the ductile, mid-transition, and brittle regions respectively. On the basis of transition temperature, therefore, notch acuity is shown to be significant only in the brittle region

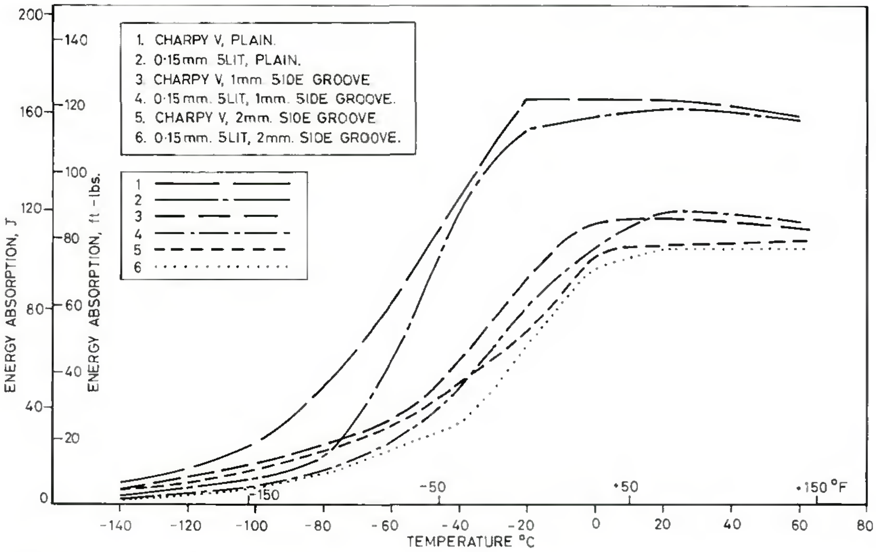

Fig. 2 — Variation in total energy absorption with temperature

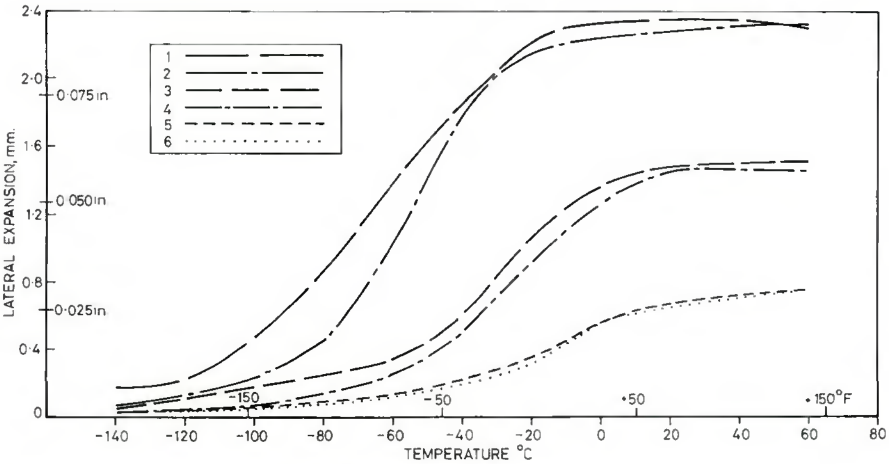

Fig. 3 — Variation in total lateral expansion with temperature

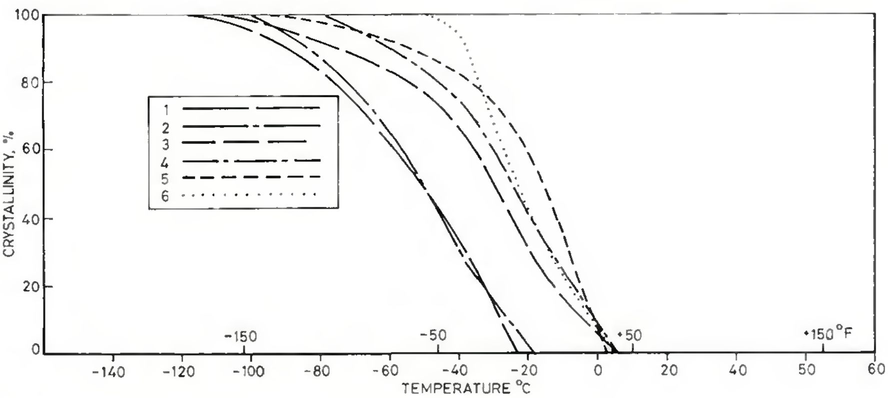

Fig. 4 — Variation in fracture appearance with temperature

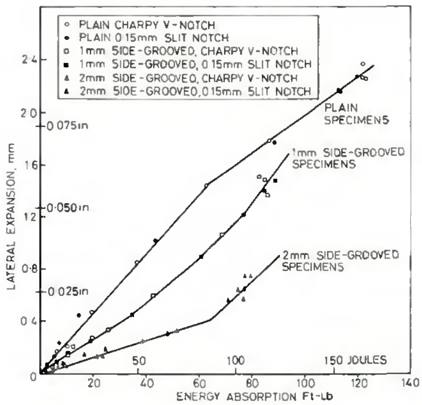

Fig. 5 — Relationship between energy absorption and lateral expansion

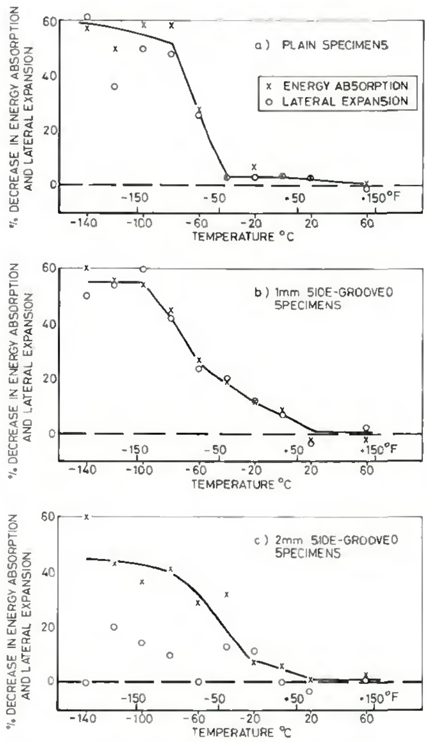

Fig. 6 — Influence of change in notch acuity from Charpy V to 0.15 mm slit on energy absorption and lateral expansion

Table 3 — Room Temperature Impact

Side groove depth, mm	Energy absorption J, (ft lb)
None	165 (122)
0.5	137 (101)
1.0	115 (85)
1.5	108 (80)
2.0	102 (75)

Table 4 — Influence of Notch Acuity on Energy Absorption and Lateral Expansion Transition Temperatures

Side groove depth, mm	Toughness parameter	Increases in transition temperature, C — Ductile region	Mid-transition region	Brittle region
0	Energy absorption	+2 (136J)	+8 (81J)	+30 (20J)
0	Lateral expansion	+1 (2.0 mm)	+12 (1.15 mm)	+19 (0.3 mm)
1	Energy absorption	+10 (95J)	+7 (54J)	+34 (14J)
1	Lateral expansion	+8 (1.2 mm)	+5 (0.8 mm)	+29 (0.2 mm)
2	Energy absorption	+3 (95J)	+10 (54J)	+24 (14J)
2	Lateral expansion	0 (0.6 mm)	+2 (0.35 mm)	+14 (0.1 mm)
Avg.		+4	+8	+25

Table 5 — Influence of Side Grooving on FATT

Notch type	Side groove depth, mm	Increases in FATT — 20% Crystallinity	50% Crystallinity	80% Crystallinity
Charpy V	1	+19	+21	+21
0.15 mm slit	1	+26	+26	+25
Average	1	+22.5	+23.5	+23
Charpy V	2	+27	+36	+39
0.15 mm slit	2	+25	+28	+37
Average	2	+26	+32	+38

and this applies to both the plain and the side grooved specimens. One consequence of this is that the transition temperature range is reduced by approximately 20 C by increasing notch acuity.

Influence of Notch Acuity on Toughness Parameters — The second method of quantifying the influence of notch acuity is to plot the decrease in toughness parameters brought about by changing the notch from a Charpy V to a 0.15 mm slit against temperature. The results are shown in Fig. 6. It should be noted that the values plotted at the lowest temperatures are more prone to scatter because of the small values measured at these temperatures. This was taken into account when drawing the curves. When drawing the curve for the 2 mm side grooved specimens the LE values were neglected since they obviously do not show the same degree of reliability as the energy absorption values for reasons described above.

There is close agreement between the energy absorption and LE values for the plain and the 1 mm side grooved specimens which would be expected from the near linear relationship between these two parameters shown in Fig. 5. In the plain specimens notch acuity first becomes significant below −40 C, increases to a maximum at −80 C, and remains substantially constant below this temperature. In contrast, notch acuity first becomes significant below 20 C in the side grooved specimens, increases to a maximum at −80 to −100 C, and remains fairly constant below this temperature. With all specimen types the full effectiveness of notch acuity at low temperatures was to reduce the toughness parameters by about 50%.

Influence of Side Grooving on Transition Temperature — Figures 2 and 3 show that side grooving reduces energy absorption and LE considerably especially at high temperatures, but its effectiveness decreases with decreasing temperature. Moreover the temperature at which the values fall from the upper shelf is affected by side grooving, being −20 C for the plain specimens and 0 C for the side grooved specimens. However its influence on transition temperature is difficult to define because the different shapes of transition curves make comparison on a fixed energy absorption and LE basis difficult. However the fracture appearance curves show a distinct upward shift in transition temperature brought about by side grooving as shown in Table 5.

Similar changes in FATT are shown by the two notch types. One mm side grooves produced a constant shift in FATT over the 20-80% crystallinity range of 23 C. Two mm side grooves produced greater increases in FATT, the average value being 32 C although the changes were somewhat higher in the brittle region (38 C) than in the ductile region (26 C).

In order to compare the energy absorption and LE transitions for the plain and side grooved specimens it was considered more appropriate to convert the data to values expressed in terms of the percentage of the upper shelf values since this would give the curves a similar shape. The results are replotted in this form in Figs. 7 and 8. This confirms that side grooving causes a drop from upper shelf values at a higher temperature than in the plain specimens and that at low temperatures, below about −100 C, the influence of side grooving is relatively small. In the range between the upper and lower shelf side grooving raises the transition temperature appreciably. Specific changes are shown in Table 6.

These results show greater increases in transition temperature based on LE compared to energy absorption. This inconsistency may well arise from the different energy absorption-LE relationships shown for

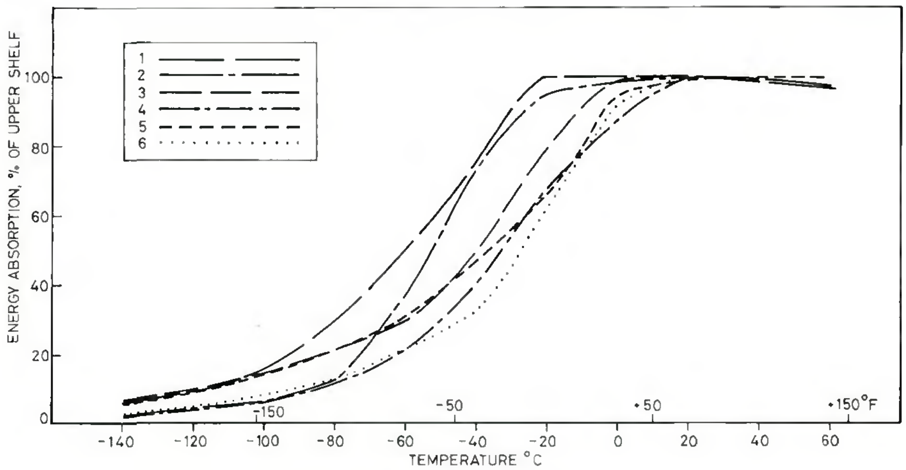

Fig. 7 — Variation in % energy absorption with temperature

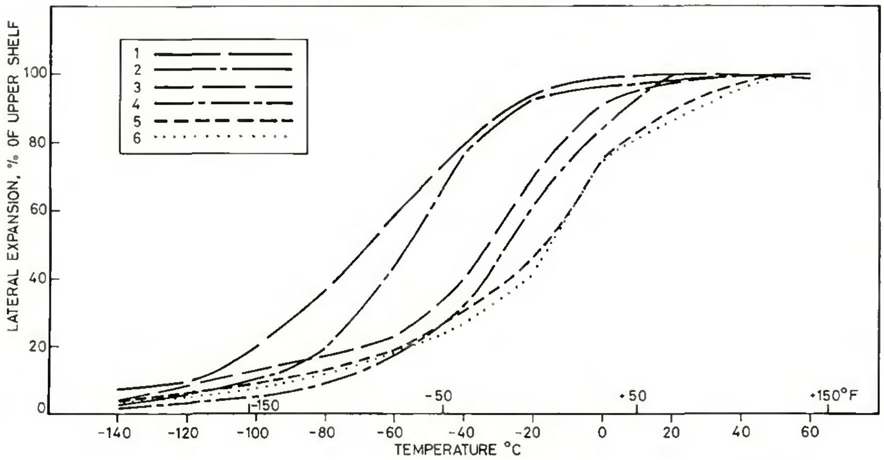

Fig. 8 — Variation in % lateral expansion with temperature

Table 6 — Influence of Side Grooving on Energy Absorption and LE Transition Temperatures

Notch type	Side groove depth, mm	Energy absorption, % 10	50	90	LE, % 10	50	90
Charpy V	1	− 4	+20	+19	+ 6	+34	+25
0.15 mm slit	1	0	+21	+31	+19	+30	+31
Average	1	− 2	+20.5	+25	+12.5	+32	+28
Charpy V	2	+ 2	+24	+27	+25	+49	+56
0.15 mm slit	2	−11	+24	+26	+16	+42	+50
Average	2	− 4.5	+24	+26.5	+20.5	+45.5	+53

Changes in Transition Temperature, C

each side groove type in Fig. 5. Since the LE in a side grooved specimen will be somewhat different to that in a plain specimen it is considered that more emphasis should be placed on the energy absorption results. Nevertheless a consistent pattern is shown by each group, viz. much greater changes in transition temperature in the mid-transition and ductile regions than in the low temperature region. Furthermore the 2 mm side grooved specimens produce greater changes than the 1 mm side grooved specimens. The increases in transition temperature in the mid-transition and ductile regions compare favorably with the changes in FATT described earlier.

Influence of Side Grooving on Toughness Parameters — The influence of side grooving on toughness parameters is shown in Fig. 9 where the values plotted represent the decrease in energy absorption on changing from plain to side grooved specimens. LE values are not included since these are not comparable on specimens of different side groove configurations. There is reasonably good agreement between the Charpy V and 0.15 mm slit-notch results. With both side groove depths the decrease in energy absorption is relatively constant outside the temperature range 0 C to −100 C, being of the order of 30%. Within this temperature range the effectiveness of the side grooving is much more pronounced, the maximum effect occurring at approximately the middle of this range where decreases of 50-60% were recorded. This temperature interval over which side grooving was most effective corresponds roughly to the temperature interval over which mixed fractures were observed which can be seen from Fig. 4.

Scatter of Results — As mentioned previously the steel used in this investigation displayed a remarkably high degree of scatter within the transition temperature although in the upper and lower shelf regions the scatter was much less pronounced. The effect was particularly apparent in the plain specimens. Because of this it was necessary to carry out several tests at each temperature in order to evaluate the influence of notch acuity and side grooving with any degree of confidence.

Tables 7 and 8 summarize the scatter observed with each specimen type over the temperature interval of maximum scatter and include scatter ranges, mean values, and standard deviations. It is readily apparent that the scatter ranges and the standard deviations show a consistent and marked decrease on moving from the plain to the side grooved specimens. However this may simply be a reflection of the greater energy absorption and LE capacity of the plain specimens. To check whether this was so,

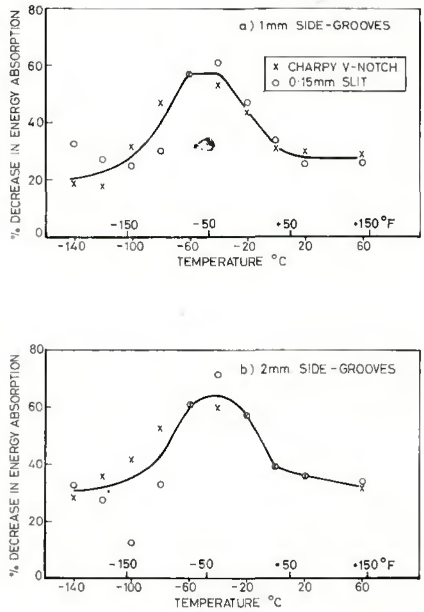

Fig. 9 — Influence of side grooving on energy absorption

scatter factors defined as Standard Deviation × 100/Mean Value were calculated and are included in the tables.

A comparison of energy absorption and LE as alternative methods of assessing fracture toughness shows little difference in scatter factors overall. However when the plain and side grooved specimens are examined separately significant differences are revealed. For the plain specimens a change from energy absorption to LE reduces the scatter factor by 23% while in the side grooved specimens the scatter factor increases by 14%.

The most significant effect on scatter is shown by side grooving which reduces the average scatter factor based on energy absorption by over 40%. The average decrease in the scatter range is even more pronounced at over 60% but this is affected by the lower energy absorption capacity of the side grooved specimens. In terms of LE the average decrease in scatter factor is only 16%.

Increasing the notch acuity from a Charpy V-notch to a 0.15 mm slit reduced the scatter factors by an average of 14% which is small in comparison with reductions due to side grooving. The present results show that the minimizing of scatter in notch impact tests can best be achieved by side grooving. A decrease of about 60% in scatter factor was observed on changing from energy absorption in standard Charpy V-notch specimens to energy absorption in 0.15 mm slit notch specimens containing 1 mm side grooves. The corresponding increase in scatter range was about 75%.

Table 7 — Details of Maximum Scatter In Energy Absorption

Notch type	Side groove, mm	Temp., C	No. tests	Energy absorption, ft lb Max.	Min.	Range	Mean	S.D.[a]	S.F.[b]
Charpy V	0	−40	11	127	47	80	87.0	23.8	27.4
	0	−60	6	87	33	54	63.0	20.6	32.7
	0	−80	6	62	22	40	37.3	13.4	36.3
Average	0					58.0	62.4	19.3	32.1
0.15 mm slit	0	−40	11	122	37	85	88.5	20.7	23.3
	0	−60	6	66	22	44	44.0	16.0	36.1
	0	−80	6	22	9	13	15.2	4.2	28.2
Average	0					47.3	49.2	13.6	29.2
Charpy V	1	−20	6	91	52	39	69.3	15.2	22.0
	1	−40	5	46	38	8	43.0	3.1	7.2
	1	−60	5	41	16	25	26.4	9.1	34.5
Average	1					24.0	46.2	9.1	21.2
0.15 mm slit	1	−20	5	70	46	24	61.2	9.8	16.0
	1	−40	5	40	29	11	35.2	4.4	12.4
	1	−60	5	22	16	6	19.0	2.0	10.5
Average	1					13.7	38.5	5.4	13.0
Charpy V	2	−20	5	63	43	20	51.6	6.4	12.5
	2	−40	5	43	31	12	38.6	4.5	11.7
	2	−60	5	29	13	16	24.0	6.0	25.1
Average	2					16.0	38.1	5.6	16.4
0.15 mm slit	2	−20	5	54	41	13	48.0	4.6	9.5
	2	−40	5	36	13	23	25.0	7.7	30.9
	2	−60	5	20	12	8	17.2	2.8	16.2
Average	2					14.7	30.1	5.0	18.9

(a) Standard Deviation. (b) Scatter Factor

Table 8 — Details of Maximum Scatter in Lateral Expansion

Notch type	Side groove, mm	Temp., C	No. tests	Lateral expansion, mm Max.	Min.	Range	Mean	S.D.[a]	S.F.[b]
Charpy V	0	−40	11	2.34	1.17	1.17	1.79	0.34	19.1
	0	−60	6	2.08	0.82	1.26	1.45	0.46	31.5
	0	−80	6	1.37	0.60	0.77	0.86	0.25	29.8
Average	0					1.07	1.37	0.35	26.8
0.15 mm slit	0	−40	11	2.28	0.94	1.34	1.78	0.32	18.0
	0	−60	6	1.44	0.66	0.78	1.03	0.27	26.2
	0	−80	6	0.55	0.34	0.21	0.45	0.07	16.4
Average	0					0.78	1.09	0.22	20.2
Charpy V	1	−20	6	1.48	0.71	0.77	1.07	0.29	27.5
	1	−40	5	0.67	0.49	0.18	0.60	0.06	10.3
	1	−60	5	0.52	0.19	0.33	0.34	0.11	33.1
Average	1					0.43	0.67	0.15	23.6
0.15 mm slit	1	−20	5	1.44	0.85	0.59	1.13	0.21	18.7
	1	−40	5	0.68	0.45	0.23	0.59	0.10	17.8
	1	−60	5	0.33	0.14	0.19	0.24	0.06	25.1
Average	1					0.34	0.65	0.12	20.5
Charpy V	2	−20	5	0.39	0.28	0.11	0.33	0.04	11.3
	2	−40	5	0.30	0.20	0.10	0.26	0.04	17.2
	2	−60	5	0.18	0.08	0.10	0.14	0.04	25.8
Average	2					0.10	0.24	0.04	18.1
0.15 mm slit	2	−20	5	0.33	0.27	0.06	0.31	0.02	6.6
	2	−40	5	0.24	0.12	0.12	0.19	0.05	24.5
	2	−60	5	0.20	0.11	0.09	0.16	0.03	20.5
Average	2					0.09	0.22	0.03	17.2

(a) Standard Deviation. (b) Scatter Factor

Pellini Drop Weight Tests — The NDT temperature was indexed using the standard Pellini test, and was found to be −40 C.

Discussion

The preliminary tests which aimed at establishing the manner of crack initiation at the notch root were confined to the V-notch specimens since the binocular microscope could not be focussed on the root of the slit notches. Birkbeck and Wraith (Ref. 5) have shown, however, that the shape of the crack front is independent of notch acuity in a comparison of V-notches and fatigue cracked specimens, so it seems reasonable to assume that the same would apply to the slit notches.

The side groove depth necessary to produce a plane crack front was found to be 1 mm which contrasts with 0.5 mm determined by Birkbeck and Wraith (Ref. 12). However, their side grooves were cut into standard 10 × 10 mm specimens thus reducing the notched cross section. In earlier work, (Ref. 5), these workers used 1 mm side grooves on 10 × 12 mm specimens to achieve a plane crack front although the side groove geometry was somewhat different.

The relative insensitivity to notch acuity of the Charpy upper shelf energy contradicts results of other workers on different steels (Refs. 4,5,7,8). However two of these references (4 and 5) are too critical COD for ductile crack initiation under slow strain rate conditions while in reference 7 the upper shelf energy was not clearly established. Zeno and Low (Ref. 8) observed a drop of 15 to 20 ft lb in the upper shelf energy of two mild steels but these results may have been influenced by the fact that the fatigue notches were extended from standard 2 mm deep V-notches and would thus reduce the notched cross section.

Additionally it has been shown that fatigue precracking of Charpy sized specimens produces a curved crack front (Ref. 12) and therefore the fatigue notch depths quoted by Zeno and Low (0.33 mm), whether measured from the specimen edge or the specimen center, would not be constant along the width of the specimen. In support of the present results is the work of Frederick and Salkin (Ref. 3) who showed that notch acuity did not influence the upper shelf COD of a C-Mn steel tested in a slow bend. The lack of any influence of notch acuity on ductile fracture can be explained by the high degree of plasticity developed at the crack tip causing crack tip blunting.

The onset of brittle fracture, on the other hand, would be expected to be influenced by notch acuity through its effect on stress concentration and plastic zone size. This would result in brittle fracture occurring at higher temperatures with increases in notch acuity. This was observed in the present work, the specific changes falling within the range quoted by other workers (Refs. 1-4, 7, 8). Moreover this increase of about 27 C in the transition temperature for brittle fracture was displayed by both the plain and the side grooved specimens. One consequence of this was that the temperature interval between high energy and low energy fractures was reduced by increasing notch acuity, especially with the plain specimens. This obviously implies that the ductile-brittle transition is more clearly defined with the sharper notch.

Another interesting feature of the present tests was the absence of any influence of notch acuity on the FATT. Radon and Turner (Ref. 6) also found that fatigue cracking had little influence on the FATT although in their case fatigue cracking was combined with side grooving to a depth of 0.5 mm. In the present tests, however, side grooving raised this transition temperature substantially; this will be discussed later. These observations suggest that increasing notch acuity mainly influences the conditions for crack initiation at low temperatures but that once the fracture gets started the material ahead of the crack tip is subjected to a fast moving natural crack irrespective of the initial notch acuity and this explains the similarity in FATT.

The observation that cracks initiate first at the center of plain specimens and become full width cracks only at a much later stage casts doubt on the suitability of COD at maximum load as an adequate description of the conditions for ductile crack initiation. This point has been discussed by Birkbeck and Wraith (Ref. 12). This is due to the fact that the COD at maximum load has been shown to coincide with the formation of full width cracks (Refs. 5 and 13). Therefore, it is apparent that cracks have initiated well before this stage.

Additionally it has been shown (Ref. 5) that the COD for full width cracks in side grooved specimens is substantially the same as that for center crack initiation in plain specimens. The results shown in Table 2 are in accord with this where it was shown that center crack initiation in plain specimens and full width cracking in side grooved specimens both occurred after the second low energy blow. Moreover this effect would be expected to persist, although to a decreasing extent, as the temperature falls and the fracture changes from ductile to brittle. At very low temperatures when plane strain fracture occurs in both plain and side grooved specimens, the two specimen types would be expected to show the same behavior. This agrees with the present results, Figs. 2 and 3, where the influence of side grooving was shown to be most marked in the upper shelf and mid-transition regions and to be less effective in the lower shelf region.

However, at the lowest temperature (−140 C) the side grooved specimens still exhibited lower energy absorption than the plain specimens, indicating that in the latter at least plane strain conditions were not attained. The decrease in energy absorption and LE shown in Figs. 2 and 3 is undoubtedly influenced by the suppression of shear lips and on this basis would mainly affect crack propagation.

The % energy absorption and % LE plots shown in Figs. 7 and 8, however, demonstrate clearly that side grooving raises the transition temperature except at very low temperatures; this is substantiated by the FATT curves shown in Fig. 4. This effect of side grooving on the FATT would be expected because of the increased stress concentration at the notch root near the edges of the specimen permitting the formation of a running fracture at a higher temperature than in the plain specimens. Furthermore the running fracture would be less inhibited by the edges of the specimen since the stress concentration effect of the side grooves will persist down the full depth of the specimen.

The NDT at −40 C correlates well with only one parameter, the FATT. The specimen design using the slit notch and 2 mm side grooves shows virtually 100% crystallinity at −40 C but the other side grooved specimens averaged about 80% crystallinity while the two plain sided specimens were quite ductile with only about 30% crystallinity at this temperature, Fig. 4. Of the specimen types investigated the 2 mm side grooved slit notch specimen appears to give the best assessment of fast fracture properties with results similar to the Pellini DWT test, although the effects of steel chemistry and mechanical properties on this correlation must be assessed before any general validity is assumed.

Significance of the Results

The present tests have clearly shown that side grooving can create a constant stress concentration along the notch root of Charpy-sized specimens thus promoting a plane crack front. Under constant cross sectional area conditions, fracture parameters (e.g. energy absorption, % crystallinity) show effects similar to those to be expected from increasing specimen thickness, since the increase in width of the highly stressed central region of the specimen is a function of the increase in thickness. A further improvement in fracture toughness assessment is accomplished by increasing notch acuity (increasing stress concentration at the notch root) from a V-notch to a slit notch i.e. reducing the root radius from 0.25 mm to 0.15 mm. Fatigue cracks would offer a further improvement in notch acuity but with the twin disadvantages of high cost and uncertain cross sectional area.

Side grooved specimens also offer an advantage in reducing the scatter normally associated with toughness tests and should be particularly valuable in assessing such metallurgical structures as weld metals and heat-affected zones although work on other materials will be necessary to confirm this.

Conclusions

Impact tests on plain and side grooved specimens of Hyplus 29 steel containing Charpy V and 0.15 mm slit notches have yielded the following information:

1. An increase in notch acuity does not affect the conditions for ductile fracture or the FATT in either plain or side grooved specimens.
2. An increase in notch acuity raises the temperature at which low energy absorption and LE failures occur by approximately 27 C in both plain and side grooved specimens. In the lower shelf region the toughness parameters are reduced by about 50%.
3. Side grooving to a depth of 1 mm promotes the formation of a plain crack front during bending of 80 mm^2 notched cross section specimens. In contrast shallower side grooves cause center crack initiation to occur first while deeper side grooves cause cracking to occur first at the edges of the specimen.
4. Side grooving considerably reduces the energy absorption and LE for ductile fracture but the effect decreases with decreasing temperature. The percentage decrease in toughness parameters is fairly constant at about 30% outside the temperature range 0 to −100 C. Towards the middle of this range the decrease is more pronounced at about 50 to 60%.
5. Side grooving to a depth of 1 mm raises the FATT by about 23 C, while 2 mm side grooves raise this temperature by about 32 C. Similar changes in energy absorption and LE transition temperatures occur when the results are plotted as percentages of the upper shelf value.
6. Scatter factors within the transition temperature range, defined as Standard Deviation/Mean Value are reduced 14% by increasing notch acuity and 43% by side grooving. The equivalent reduction in scatter range (maximum value minus minimum value) due to side grooving is over 60%. Scatter in the plain specimens is 23% less when LE is used instead of energy absorption but in the side grooved specimens energy absorption gives 14% less scatter than LE. The combined effect of increasing notch acuity and side grooving to a depth of 1 mm reduces the scatter factors of standard Charpy V-notch specimens by about 60% with a corresponding reduction in the scatter range of about 75%.

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(Part II — Slow Bend Tests — To Follow in July)