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EFFECT OF THICKNESS ON THE RELATIONSHIP BETWEEN SHEAR LIP AND ENERGY IN DYNAMIC TEAR SPECIMENS

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Abstract In two previous papers, a relationship was shown to exist between the fracture energy and shear lip in 16–25 mm thick dynamic tear (DT) tests of quench and tempered carbon and low alloy steels and their weldments over a wide range of temperatures, compositions and locations in the weldments. The relationship between shear lip and energy was found to be independent of specimen thickness for the 16–25 mm thicknesses. In this paper it will be shown that the relationship holds for 7–15 mm thicknesses as well. Data used in these studies have been acquired from samples of 350 WT, A517 Grade F, HY80, HY100 and HLES steels and submerged arc, shielded metal arc, flux cored arc and gas metal arc welds of these steels. Crown copyright © 1998 Published by Elsevier Science Ltd. All rights reserved

Keywords—dynamic tear, shear lip, transition, ductile to brittle transition, shear index.

NOMENCLATURE

s	maximum width of shear lip (the average of two sides is used in the correlations)
S_I	shear index opening mode (2 s/B)
a	crack length
Δ_{ac}	critical crack blunting
b	uncracked ligament
B	thickness of sample (7–25 mm)
W	height of specimen (41 mm)
r_{yc}	critical plastic zone size
K_{Ic}	plane strain fracture toughness
σ_y	yield strength
σ_u	ultimate strength
J_{Ic}	elastic-plastic fracture toughness
DT_E	dynamic tear energy value
σ_{flow}	flow stress, $[(\sigma_y + \sigma_u)/2]$
C_1, C_2, C_3	coefficients of polynomial.

1. INTRODUCTION

VISUAL examination of fracture surfaces subsequent to testing is an important step in determining the temperature sensitivity of structural materials [1]. The morphology of the fracture surface can vary from flat when the resistance to crack propagation is low (as is the case for a transgranular cleavage) to a surface which has developed varying widths of oblique shear lips when the resistance to crack propagation is high (Fig. 1). In many fracture tests such as the Charpy V notched (Cv)[2] and dynamic tear (DT)[3] standard test methods, measurement of percentage shear which is somewhat related to shear lip size (s) is optional, while in the drop weight tear test (DWTT)[4], it is the basic physical measurement required.

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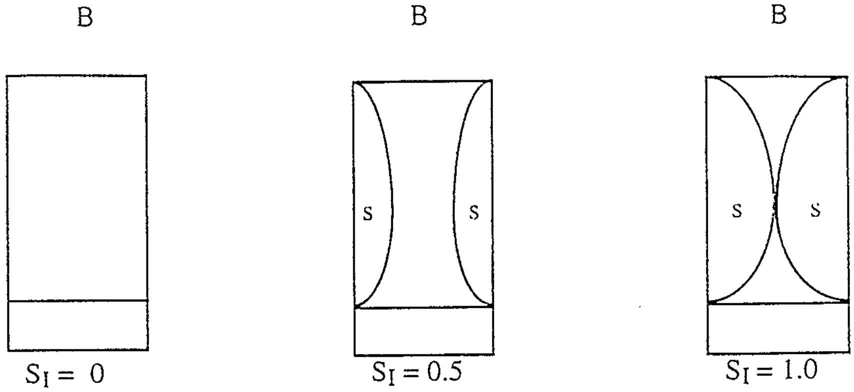

Fig. 1. Typical morphologies for dynamic tear impact samples (shear index is measured at the point of the closest contact between the two shear lips: $S_I = 2s/B$).

In the past, techniques for evaluating the morphology of fractured specimens have been primarily concerned with percentage shear[5]. In the drop weight tear test, this measurement is carried out for the central areas of the sample only. The area close to the notch and the area near the back of the specimen are not utilized in the evaluation. This approach results in a measurement that is well related to toughness because the notch and hinge effects are eliminated. The rules applied to drop weight tear percentage shear measurements cannot be applied to the 16 mm dynamic tear specimen because the specimen is narrower. Accordingly, it was decided in our earlier work[6] to make one measurement on the specimen at the location of closest contact between the two shear lips. This would ensure that the measurement reflected the toughness of the material rather than the flow stress. In practice, the closest distance between the two shear lips was measured, subtracted from the original width and divided by two to obtain an average shear lip estimate (s).

In attempting to use shear index (S_I) to describe the toughness of thicker specimens (25 mm), it was discovered that shear index was thickness dependent[7]. (Shear index is two times the shear lip (s) divided by the original thickness). Accordingly, a shear index equation would be required to describe the relationship for each thickness. However, when the original relationship for 16 mm specimens was written in terms of shear lip (s) it was discovered that the shear lip version of the equation worked equally for both the 16 mm and 25 mm specimens[7].

This paper examines the thickness range from 7 to 15 mm and compares the results to the earlier 16 and 25 mm results[6, 7]. It will be shown that the original equation for shear lip can be used to evaluate toughness of DT specimens independent not only of temperature, steel and weldment type but also independent of thickness from 7 to 25 mm thicknesses. This equation and its use has great ramifications for the cost of quality control testing in fabrication in that DT shear lip transition curves can be used to accept steel and weld procedures without the normal requirement for instrumentation and data processing.

2. BACKGROUND

Much effort has gone into finding relationships between less expensive impact toughness tests (C_v, DWTT, DT) and the more expensive fracture mechanics tests (K_{Ic} and J_{Ic})[8, 9]. Also, work has gone into trying to use the less expensive tests in the development and selection of specific structural materials and weldments. Researchers have identified an inadequacy of Charpy V notch testing when evaluating high-strength structural metals but have found that the DT test has some desirable features for this use[10, 11].

The Welding Institute in England[11] for example, has indicated that the arbitrary values derived from Charpy V notched testing have proved adequate for many of the purposes intended (that is, evaluation of shielded metal arc (SMAW) welded mild steel plate in thicknesses up to 38 mm). However, outside these limits, the test is not sensitive to all the factors which influence brittle susceptibility. The Welding Institute also pointed out that when weld deposits were made by different processes or different conditions within a process, the

Charpy impact test provides no real comparative guide to the brittle fracture risk of the weld metal in low strain rate conditions. Charpy transition curves continue to be obtained, however, in order to provide correlation with more meaningful tests so that the Charpy test may hopefully be used for quality control.

Despite the problems that have been encountered in using Charpy V notched testing for these correlations and subsequent material selections, this common test continues to be studied and used. The attention given to the other qualitative tests (DT and DWTT) has not been as great because their costs are higher and the tests are not used as extensively.

In this paper, the DT and shear lip results given for several steels and their weldments is used to show that the DT test can provide valuable information without the need for the expensive instrumentation required to obtain the energy results. The thickness independence of the correlation between shear lip and DT_{E} makes the test even more attractive. Though not the subject of this paper, it is equally important that the transition curve for the DT test reflects the performance of structures considerably better than C_{v} which often exhibits a non conservative temperature shift of 50–100°C.

3. RELATIONSHIP BETWEEN SHEAR LIP "S" AND FRACTURE ENERGY "DT_{E}"

Analysis of the relationship between shear lip "s", fracture toughness and fracture energy "DT_{E}" for the dynamic tear specimen studied in this paper is extremely complex and covers the whole range of mechanics, elastic through plastic. In previous papers [6, 7], the relationship between fracture toughness and DT energy was discussed in general terms. At low toughness, an elastic analysis would be used to analyze the fracture and determine the relationship, while at very high toughness, a fully plastic analysis would be relevant. As the procedure is not used to measure a specific toughness property, but the energy of total separation, edge and hinge effects exist to complicate any analysis.

To understand this better, and to try to define some of the factors involved in understanding the expected relationship between shear lip and energy, the approximate range for which elastic, elastic–plastic and plastic conditions are relevant will be described:

3.1. *Elastic*

For plane strain elastic conditions to exist in a DT specimen, just after crack advance at least, the plastic zone must be very small compared to the dimensions of the specimen. The agreed upon limit for valid test conditions to exist in ASTM E399 [8] uses the following relationship:

$$a, b, B > 50r_{\mathrm{yc}} = 2.5\left(\frac{K_{\mathrm{Ic}}}{\sigma_{\mathrm{y}}}\right)^2 \tag{1}$$

the corresponding plastic zone is

$$r_{\mathrm{yc}} = \frac{1}{6\pi}\left(\frac{K_{\mathrm{Ic}}}{\sigma_{\mathrm{y}}}\right)^2. \tag{2}$$

If we estimate the shear lips to be of the order of the critical plastic zone size, then the elastic case would hold for shear lips of up to 0.4 mm for the materials that are considered in this paper. This corresponds to an energy of about 50 J. Contributions from hinge and edge effects would be very small and the relationship between shear lip and energy would be linear.

3.2. *Elastic–plastic*

The approximate energy level and shear lip maximums for which elastic–plastic conditions would exist in a DT specimen, just after crack advance, could loosely be estimated from the following conditions set out for valid specimen size requirements from ASTM E813 [9] and a knowledge of critical crack blunting:

$$a, b, B > 50\frac{J_{\mathrm{Ic}}}{\sigma_{\mathrm{flow}}}. \quad (3)$$

We can calculate critical crack blunting for the DT specimen using the maximum J_{Ic} determined from eq. (3) and the following approximate empirical formula:

$$\Delta_{\mathrm{ae}} = \frac{J_{\mathrm{Ic}}}{2\sigma_{\mathrm{flow}}}. \quad (4)$$

Using eq. (4), and our experience with direct stretch zone measurements and blunting line determination we estimated then Δ_{ae} would be no more than 0.125 mm for the materials studied in this paper with the upper end of elastic–plastic conditions prevailing.

We judge that the shear lip size will be related to this critical blunting in the elastic–plastic range but apparently not to the specimen thickness as originally suggested [6]. Our estimate is that the shear lip would be about 50 times the critical crack blunting.

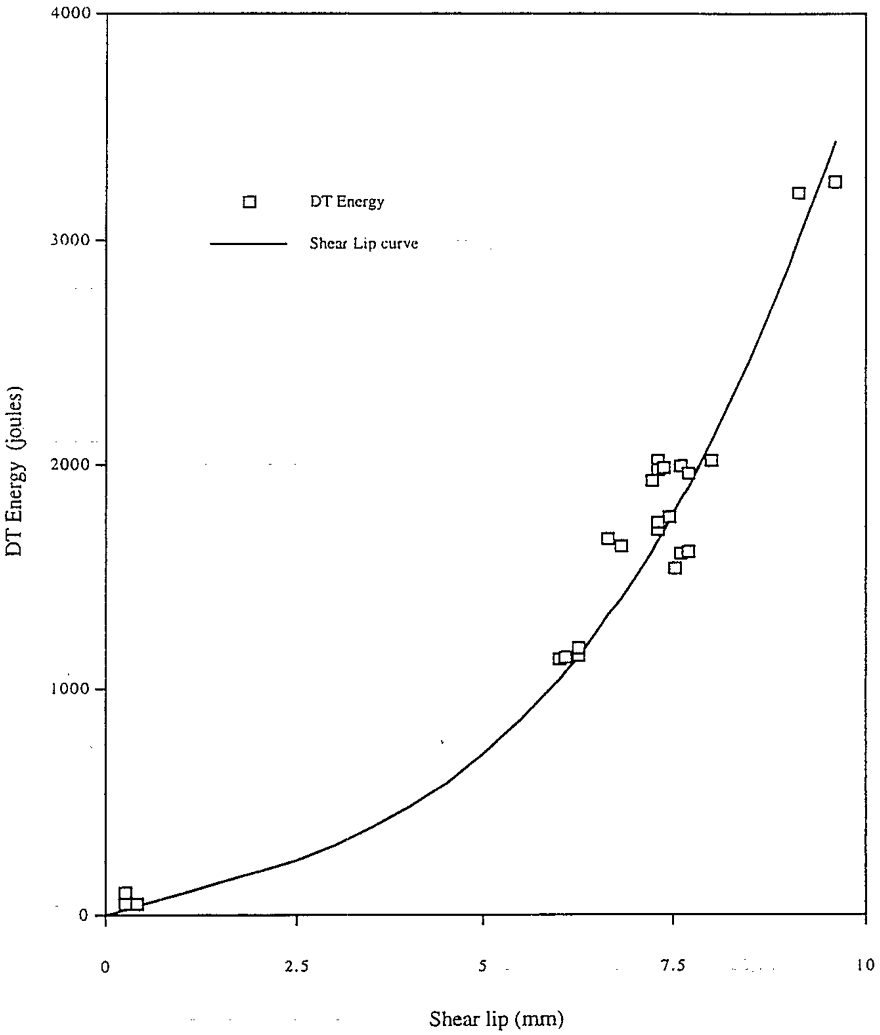

Fig. 2. Graph of shear lip "s" vs DT energy for the thicker steels from the earlier studies plotted with the original shear lip curve.

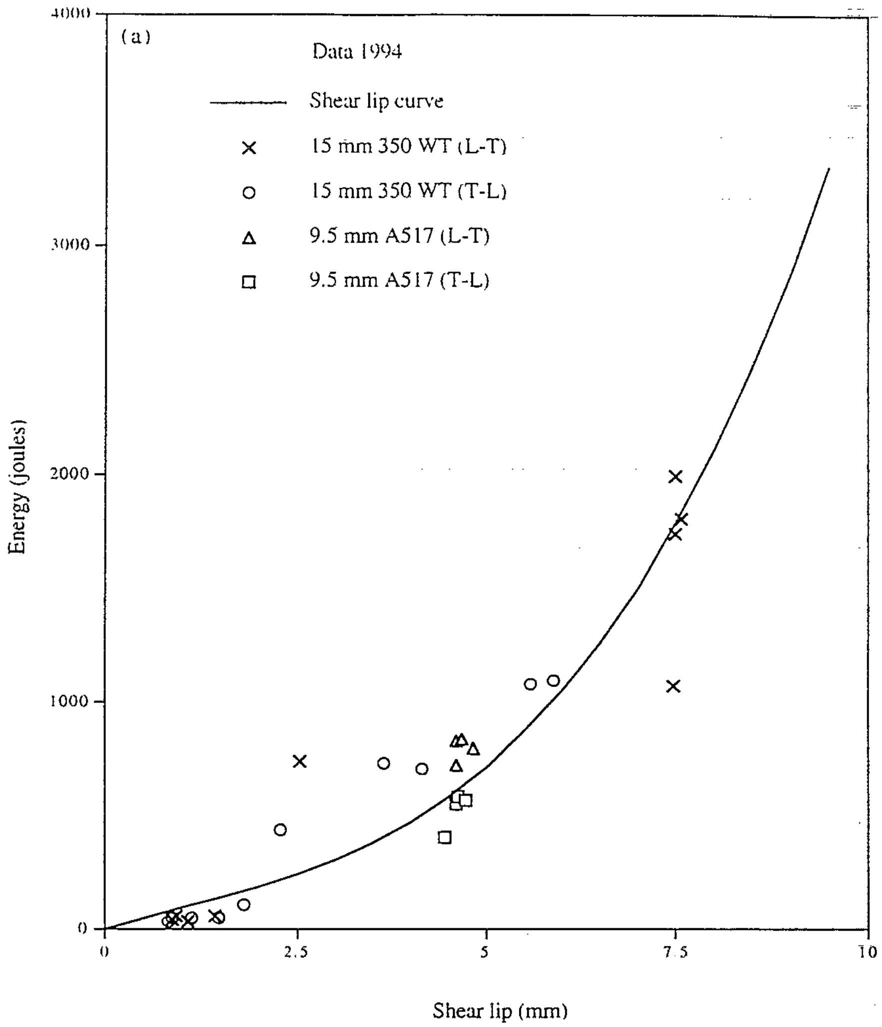

Fig. 3a. (a) Graph of shear lip "s" vs DT energy for steel data collected in 1994 plotted with the original shear lip curve. The specimens were approximately 9.5 and 15 mm thick.

3.3. *Plastic*

When elastic–plastic conditions are exceeded, the mode of failure becomes plastic. This is the case for the 16 mm samples that exhibit fracture energies near 2000 J. In the case of plastic fracture, the flow stress should dominate and energy should be related to it and the specimen size. Hinge effects alter this condition and edge and hinge effects cause plastic dominance at lower toughness values. What this means is that even though elastic–plastic conditions might exist for a short part of the separation, the beginning, end and sides are predominantly plastic and overall dominating. This is the case for shear lips of 7 to 8 mm for the 16 mm specimen. In the thicker specimen (25 mm) upper shelf shear lips are only 1 mm larger and therefore do not touch. In the thin specimens 100% shear is common at upper shelf.

Table 1. Chemical composition of steels

	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
350WT	0.22	0.8–1.5	0.03	0.04	0.15–0.4				
A517 (F)	0.1–0.2	0.6–1.0	0.035	0.04	0.15–0.35	0.7–1.0	0.4–0.65	0.4–0.6	0.15–0.5
HY100	0.12–0.20	0.1–0.4	0.02	0.02	0.15–0.35	2.25–3.5	1–1.8	0.2–0.6	0.25
HY80	0.12–0.18	0.1–0.4	0.025	0.025	0.15–0.35	2.0–3.25	1–1.8	0.2–0.6	0.25
HLES	0.15	0.37				4.29	0.56	0.29	

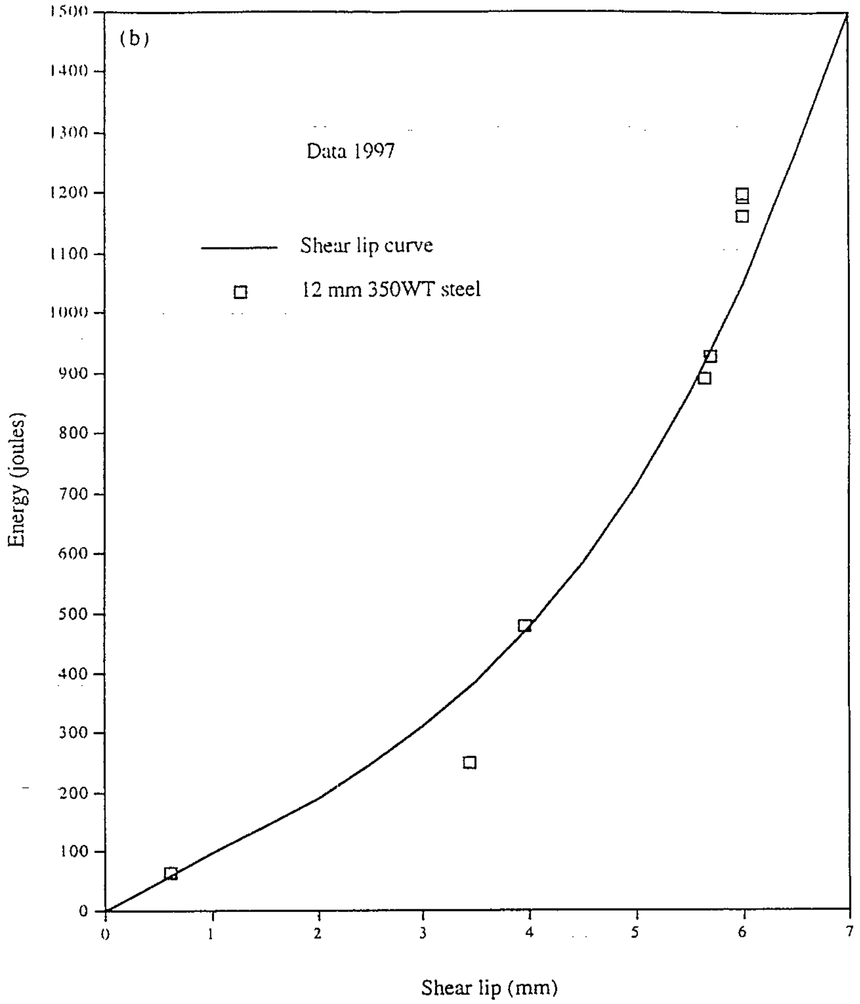

Fig. 3b. (b) Graph of shear lip "s" vs DT energy for steel data collected in 1997 plotted with the original shear lip curve. The specimens were 12 mm thick.

The influence of yielding on the relationship between shear lip and energy is generally nonlinear except at low values of toughness, in the elastic range, where it is linear. It was found for DT specimen thicknesses from 15 to 25 mm [6, 7] for the full range of energies (0–3500 J) and the full range of shear lips (0–9.5 mm) that the following empirical equation determined by curve fitting gave a good fit:

$$DT_E = 105\,s - 12.96\,s^2 + 4.096\,s^3. \tag{5}$$

To show this, and to determine how well this equation fits data for thin specimens, eq. (5) is overlaid on data for steel from the previous papers [6, 7] in Fig. 2 and steels and welds from two sets of recent data on thin samples in Figs 3, 4 and 5 later in this paper. Standard deviation for the energy residuals is used to assess the value of the fit for the new thin data and to compare it to the original thick specimen data fit.

4. MATERIALS

The materials evaluated in this and the previous studies included 350 WT, A517 Grade F, HY80, HY100 and HLES steels (Table 1) and submerged arc (SAW), shielded metal arc (SMAW), flux cored arc (FCAW) and gas metal arc (GMAW) welds of these steels. Welds were prepared in all positions with various joint configurations.

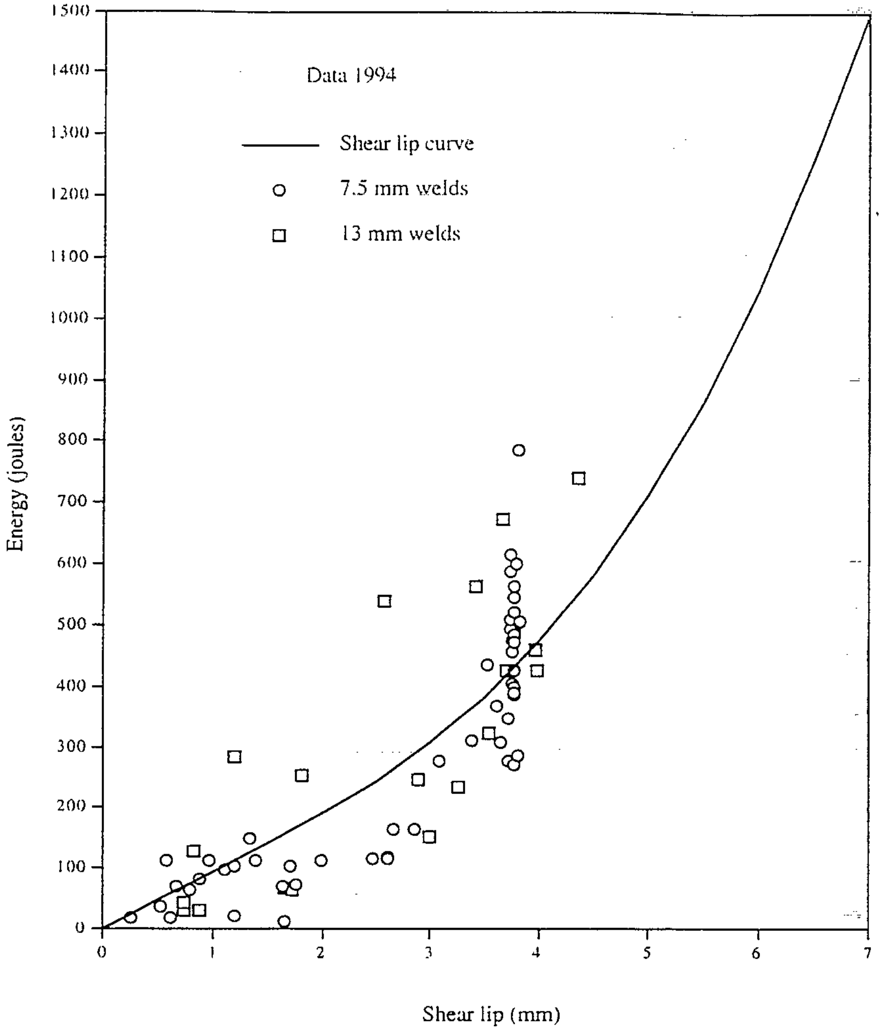

Fig. 4. Graph of shear lip "s" vs DT energy for weld data collected in 1994 plotted with the original shear lip curve. The specimens were 7.5 and 13 mm thick.

Table 2. Weldment conditions

Identification	Steel/Consumable/Steel	Position/condition
1994 series		
WA	350WT E7018 350WT	Weldmetal
WB	350WT E7018 A517	Weldmetal, interpass 100°C, 3.2 kJ/mm
WC	350WT E7018 A517	Weldmetal, interpass 60°C, 1.8 kJ/mm
WD	A517 E11018 M A517	Weldmetal
WH	350WT E7018 350WT	350WT-E7018 HAZ
WG	350WT E7018 A517	350WT-E7018 HAZ
WF	350WT E7018 A517	A517-E7018 HAZ
WE	A517 E11018 M A517	A517-E11018 M HAZ
1997 series		
1	8 mm 350WT	SMAW 3G SV
2	8 mm 350WT	SMAW 1G/4G SV
3	8 mm 350WT	SAW 1G SQ
4	8 mm 350WT	FCAW 1G Ceramic SV
5	8 mm 350WT	FCAW 3G SV
7	12 mm 350WT	SMAW 1G/4G DV
8	12 mm 350WT	SMAW 3G DV
11	12 mm 350WT	SAW 1G SQ
12	12 mm 350WT	FCAW 1G Ceramic SV
13	12 mm 350WT	FCAW 3G SV
16	10 mm A517	SMAW 3G SV
18	10 mm A517	SMAW 1G/4G SV
20	10 mm A517	FCAW 3G SV
21	10 mm A517	SMAW 3G SV

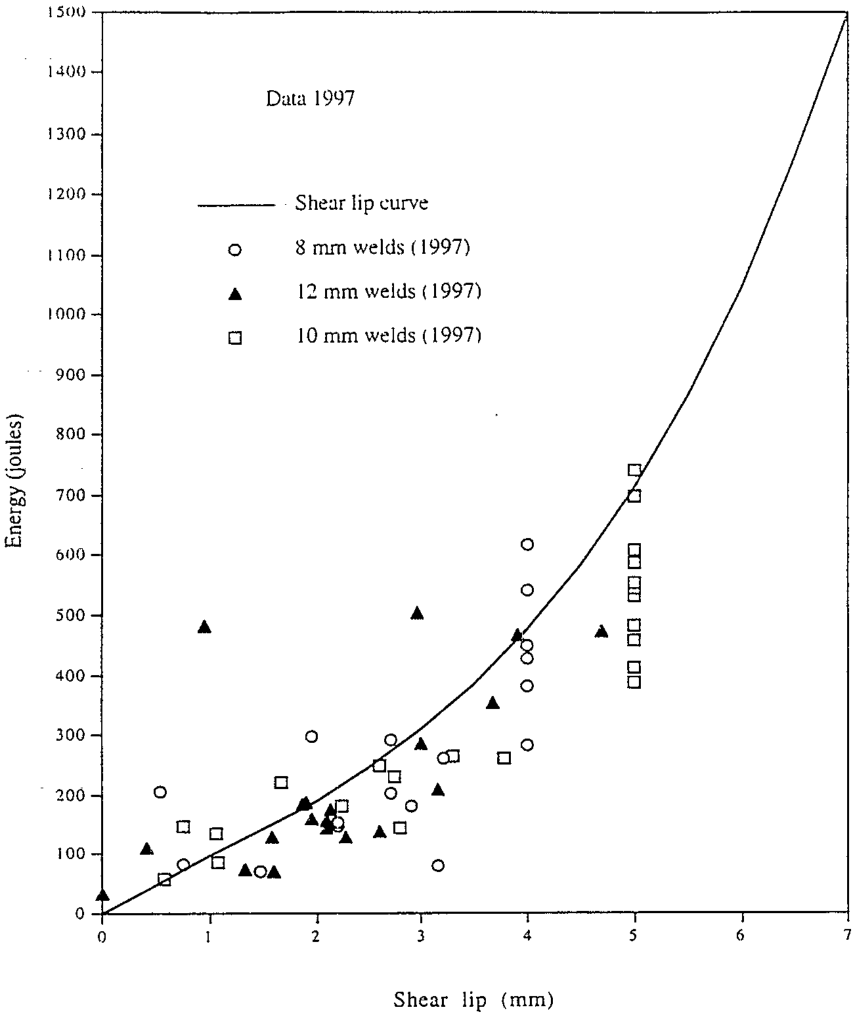

Fig. 5. Graph of shear lip "s" vs DT energy for weld data collected in 1997 plotted with the original shear lip curve. The specimens were 8–12 mm thick.

One set of welds in thin plates was produced in 1994 and a second set in 1997. Details of these weldments are contained in Table 2.

5. PROCEDURE

The dynamic tear specimens were tested in a drop tower loading frame from a height of 1.52 m. The base plate specimens were cut with the notch oriented in the longitudinal direction or the transverse direction, and the weldment specimens were cut with the notch located in either weld metal or in the heat affected zone. Load time data were converted to load–displacement with a velocity–energy balance, and the energy under the load deflection curve was calculated numerically. The shear lip measurements were made with calipers and an optical microscope.

The tests on the steel base plate were conducted at room temperature, 15, 0, −15, −18, −29, −30, −40, −45 and −174°C. The tests on the weldments were conducted at −45, −30, −15, 0 and 15°C.

All energy data were graphed against shear lip in selected figures and the original third order least squares curve fit, eq. (5), was overlaid on each graph. The correlation between shear lip and DT_E for the data was then evaluated by determining the standard deviation of the energy residuals between the curve and the different sets of data.

Table 3. Dynamic tear results for the 16 and 25 mm base plate[6, 7]

Temperature °C		DT_E Joules	Shear lip mm	Thickness mm
HY80 (L–T)	−174	50	0.24	16
	−40	1995	7.6	16
	−29	1960	7.68	16
	−18	1930	7.2	16
	0	2005	7.28	16
HY80 (T–L)	−40	1132	6.0	16
	−29	1140	6.08	16
	0	1151	6.24	16
	0	1182	6.24	16
HY100 (L–T)	−174	99	0.24	16
	−29	2017	7.28	16
	RT	1975	7.28	16
	RT	1981	7.36	16
	RT	2016	8.0	16
HY100 (T–L)	−174	47	0.4	16
	−29	1634	6.8	16
	−29	1611	7.68	16
	−29	1669	6.64	16
	−29	1710	7.28	16
	RT	1607	7.6	16
	RT	1537	7.52	16
	RT	1741	7.28	16
	RT	1763	7.44	16
HLES (T–L)	−40	3257	9.6	25
HLES (L–T)	−40	3208	9.14	25

6. DT RESULTS

Table 3 is a repeat of the base plate data from the previous two papers[6, 7] in which the correlation between DT_E and shear lip was determined. Table 4 contains data collected in 1994 for 7–15 mm thick steels and weldments. Table 5 contains new data collected in 1997 for 8–12 mm thick steel and weldments. Figure 2 is a graph of the original 16–25 mm thick weldments with the original third order least squares curve fit, eq. (5), overlaid.

Figure 3(a) contains the steel data collected in 1994 with eq. (5) drawn through the data and Fig. 3(b) contains steel base plate data collected in 1997. The original curve determined for the thick steels appears to fit the thin steel data well.

Figure 4 contains the weldment data collected in 1994. The original curve appears to fit the data well. Figure 5 contains the weldment data collected in 1997.

7. CORRELATION BETWEEN SHEAR LIP AND DT ENERGY

The shear lip vs energy data from Tables 4 and 5 which is plotted in Fig. 3(a) and (b) (base plate) and Figs 4 and 5 (weldments), along with eq. (5) (the original shear lip curve [6, 7]) displays a very good curve fit for these thin specimens (7–15 mm) with the original curve acquired for the thicker specimens (16–25 mm). The standard deviation of the energy residuals for the fit of the curve with the data for the 16–25 mm steels was 208 J overall. It was 45 J on the low end.

The shear lip vs energy data for the steels tested in 1994 (9.5–15 mm thick) from Table 4 which is plotted in Fig. 3(a) also displays a very good fit. The standard deviation of the energy residuals for the fit is 214 J overall which matches well the earlier fit at 208.

The shear lip vs energy data for the steels tested in 1997 (12 mm thick) from Table 5 which is plotted in Fig. 3(b) displays an excellent fit. The standard deviation of the energy residuals for the fit is 100 J.

The shear lip vs energy data for the weldments tested in 1994 (7.2–13.9 mm thick) from Table 4 which is plotted in Fig. 4 also displays a very good fit. The standard deviation of the energy residuals for the fit is 110 J overall which exceeds the fit for weldment data on thick specimens (320 J for 16 mm and 520 J for 25 mm data) from [6, 7] considerably. This suggests that the equation is excellent for the thin specimens. It is understood that lower energy values

Table 4. 7 15 mm DT results for steel and eldments (1994 tests)

Identification	Thickness mm	Temperature C	DT_1 Joules	Shear lip mm
WF	7.56	−40	112	1.39
	7.54	−40	104	1.18
A517 to 350WT	7.44	−30	347	3.72
E7018	7.51	−30	456	3.75
HAZ in A517	7.56	−15	522	3.78
	7.56	−15	546	3.78
WC1	7.51	−40	279	3.09
	7.49	−30	311	3.39
350WT to A517	7.46	−30	588	3.73
E7018	7.49	−15	493	3.74
Weldmetal	7.54	−15	484	3.77
WE	7.54	−40	37	0.52
	7.54	−40	18	0.6
A517 to A517	7.51	−30	98	1.1
E11018	7.56	−30	69	0.66
HAZ	7.59	−15	82	0.86
	7.56	−15	112	0.95
	7.31	0	307	3.65
	7.26	0	104	1.7
	7.23	15	368	3.61
	7.44	15	279	3.72
WG	7.51	−40	69	1.63
	7.51	−40	20	0.25
350WT to A517	7.56	−30	13	1.65
E7018	7.51	−30	23	1.18
HAZ in 350WT	7.51	−15	65	0.78
	7.51	−15	112	0.57
	7.06	0	437	3.53
	7.51	0	475	3.75
	7.46	15	615	3.73
	7.59	15	599	3.79
A517(L-T)	9.67	−40	800	4.83
	9.37	−40	836	4.68
	9.22	−30	724	4.61
	9.22	−30	829	4.61
A517(T-L)	9.29	−40	589	4.64
	9.22	−40	408	4.45
	9.22	−30	550	4.61
	9.49	−30	572	4.74
WB	7.56	−40	149	1.32
	7.56	−40	473	3.78
350WT to A517	7.51	−30	404	3.75
E7018	7.54	−30	386	3.77
Weldmetal	7.54	−15	400	3.77
3.2 kJ/mm	7.56	−15	427	3.78
	7.64	0	507	3.82
	7.54	0	565	3.77
	7.62	15	787	3.81
	7.49	15	508	3.74
WD1	7.56	−40	120	2.6
	7.56	−40	75	1.75
A517 to A517	7.56	−30	117	2.6
E11018	7.56	−30	117	2.47
Weldmetal	7.54	−15	112	1.98
	7.51	−15	164	2.85
	7.54	0	272	3.77
	7.56	0	165	2.66
	7.62	15	286	3.81
	7.56	15	391	3.78
WA	13.84	−40	246	2.89
	13.86	−40	234	3.25
350WT to 350WT	13.86	−30	322	3.55
E7018	13.84	−30	63	1.72
Weldmetal	13.84	−15	427	3.7
	13.91	−15	428	3.98
	13.86	0	489	3.77
	13.74	0	459	3.96
	13.84	15	673	3.67
	13.86	15	740	4.35

350WT(L-T)	14.96	−40	37	1.05
	14.93	−40	1072	7.46
	15.01	−30	62	0.92
	15.34	−30	43	0.86
	14.96	−15	1743	7.48
	15.34	−15	54	1.42
	15.13	0	1802	7.56
	14.93	0	741	2.53
	14.96	15	1987	7.48
350WT(T-L)	14.88	−40	36	0.8
	14.88	−40	50	1.11
	14.9	−30	51	1.46
	14.88	−30	46	0.87
	14.88	−15	103	1.8
	14.96	−15	439	2.27
	14.85	0	705	4.16
	14.85	0	734	3.64
	14.88	15	1083	5.58
	14.9	15	1097	5.9
WH	12.54	−40	128	0.82
	12.54	−40	32	0.87
350WT to 350WT	12.57	−30	31	0.72
E7018	12.57	−30	254	1.8
HAZ	12.52	−15	44	0.72
	12.52	−15	284	1.18
	12.49	0	154	3.0
	12.47	0	66	1.65
	12.64	15	564	3.41
	12.57	15	538	2.56

tend to produce better results and this explains part of the improvement but certainly not all of it. The fit for the thick steels at the low end (standard deviation of the energy residuals at 45 J) may be a better bench mark for comparison.

The shear lip vs energy data for the weldments tested in 1997 (8–12 mm thick) from Table 5 which is plotted in Fig. 5 also displays a very good fit. The standard deviation of the energy residuals for the fit is 127 J overall which also exceeds the fit for weldment data on thick specimens (320 J for 16 mm and 520 J for 25 mm data) from [6, 7], considerably. This confirms that the equation is excellent for the thin specimens.

Table 6 contains a statistical summary of our evaluation of the various data sets against the equation that we originally acquired by curve fitting to the thicker steel data set [6, 7]. To test each data set, the standard deviation of the energy residuals was calculated and to allow a fair comparison of each result, the standard deviation was divided by the nominal maximum of the energy range for that data set. As can be seen in Table 6, the steels at all thicknesses fit the curve at about 7–10%. The welds at all thicknesses fit the curve at 14–18%. These consistent results for both steel samples and welds support our observation that the curve fit developed for energy vs shear lip is independent of thickness from 7 to 25 mm thickness.

Further, considering that all these weld samples were tested at temperatures ranging from −45– + 15°C, that they were taken from weld metal and heat affected zones, that the samples were welded in three positions, that several wires and gases were employed, and that four welding processes were involved, these fits are very good. The standard deviations of the residuals are of the same order of magnitude as those found in studies determining the ability to simply measure percentage shear [5].

8. DISCUSSION

The data and graphs for steel and weldments in this study show a correlation between shear lip and fracture energy in 7–25 mm thick DT specimens. The use of shear lip as opposed to shear index in our earliest work [6] evolved because of the now confirmed independence of shear lip vs energy relationship with specimen thickness.

In our previous work, it was determined that the correlations only faltered in the presence of significant defects such as gross slag or porosity. Also, it was noted in the earliest study [6] in the case of poorly pressed notches, that even though an excessive energy over that with a properly pressed notch occurred, that there was no discrepancy in the shear lip or shear index

Table 5. 8–12 mm DT results for steel and weldments (1997 tests)

Identification	Thickness mm	Temperature °C	DT_1 Joules	Shear lip mm
350WT Steel	12	−30	63	0.6
L-T	12	−15	1159	6
	12	−15	1189	6
	12	0	1194	6
350WT Steel	12	−30	927	5.7
T-L	12	−30	249	3.45
	12	−15	477	3.96
	12	0	890	5.64
1	8	−30	71	1.46
		−15	178	3.16
		0	426	4
		15	540	4
		21	617	4
2	8	−30	296	1.95
		−15	180	2.9
		0	447	4
		15	427	4
3	8	−15	147	2.2
		0	81	0.76
		15	205	0.54
4	8	−15	153	2.2
		0	261	3.2
		15	281	4
5	8	−30		2.2
		−15	291	2.7
		0	201	2.7
		15	381	4
7	12	−30	160	1.96
		−15	157	2.1
		0	504	2.95
		15	471	4.7
8	12	−30	174	2.13
		−15	127	1.57
		0	284	3
		15	466	3.9
11	12	−30	33	0
		−15	111	0.41
		0	482	0.95
		15	183	1.87
12	12	−30	72	1.32
		−15	70	1.6
		0	127	2.28
		15	137	2.6
13	12	−30	187	1.9
		−15	144	2.1
		0	209	3.15
		15	351	3.68
16	10	−45	85	1.08
		−30	259	3.78
		−15	248	2.6
		0	179	2.24
		15	482	5
18	10	−45	134	1.06
		−30	607	5
		−15	456	5
		0	530	5
		15	586	5
20	10	−30	148	0.76
		−15	698	5
		15	740	5
21	10	−45	144	2.8
		−30	230	2.75
		−15	264	3.3
		0	385	5
		15	411	5
16end	10	−45	59	0.57
		−30	221	1.67
		0	544	5
		15	551	5

Table 6. Statistical summary: standard deviation of energy residuals for the various data sets with the shear lip vs DT_E curve ($DT_E = 105\,s - 12.96\,s^2 + 4.096\,s^3$)

Data set	Thickness	Steel or weld	Standar deviation of residuals	Standard deviation of residuals divided by max of range ‡ (%)
Standard†	16–25 mm	Steels	208 J	7%
1994 set	9.5–15 mm	Steels	214 J	10%
1997 set	12 mm	Steels	100 J	8%
1994 set	7.2–13.9 mm	Welds	110 J	14%
1997 set	8–12 mm	Welds	127 J	18%
Welds for thick specimens[6, 7]	16 mm	Welds	320 J	16%
Welds for thick specimens[6, 7]	25 mm	Welds	520 J	17%

†Data used to generate the original equation: ($DT_E = 105\,s - 12.96\,s^2 + 4.096\,s^3$).

‡Maximum of range taken as 800 J for 94 weld set, 700 J for 97 weld set, 1200 J for 97 steels, 2000 J for 94 steels, 2000 J for 16 mm welds and steels and 3000 J for 25 mm welds and steels.

values. This contributes significantly to the reliability of the shear lip data and transition curves obtained and also indicates that a lot of the scatter in the relationship between shear lip and energy is due to factors which only affect the energy component.

For a small percentage of specimens (less than 1%) it is difficult to interpret shear lip size. Typically, this occurs when a significant number of defects are present and when local brittle zones interfere with symmetrical shear lip production. It has been found that, to make a measurement in these difficult cases, one should either measure "s" at "half W" or reject the data point altogether. For two specimens tested, measuring "s" at "half W" proved inadequate. Both of these cases occurred in the testing of weldments in ultraservice steels (HY 80 in one case and A517 grade F in the other case). In each case, local brittle zones occurred in parts of the heat affected zone. In the HY 80 case, the initial notch was in the heat affected zone and nearby base metal. The energy was as expected[12], but the shear lips (really the shear lip on one side) was not. It is felt that this narrower shear lip occurred because a brittle fracture surface with dimensions W by less than 0.1 B occurred in the coarse grained heat affected zone near the specimen edge. This localized brittle fracture would have interfered with the development of the full symmetrical shear lip. In the A517 grade F case, the initial notch was in the center of the weld. Prior to the crack reaching half W, ductile shear lips expected to give a shear index of one were observed. At a point just before half W, brittle fracture initiated on an unusually flat plane of the heat affected zone. Here again, brittle fracture on a fortuitously placed local brittle zone interfered with the development of shear lips. These are unusual but clearly recognizable sets of circumstances, which will occasionally invalidate and require discarding of the test results.

We gave accepted equations as guides to understand the relationship between shear lip and energy in this paper. We then used these equations to estimate shear lip sizes in elastic, elastic–plastic and fully plastic situations. Development of more rigorous equations from basic fracture mechanics could be the focus of considerable effort for theoretical fracture analysts.

9. CONCLUSIONS

1. Correlations exist between shear lip (s) and energy (DT_E) in dynamic tear specimens from carbon and low alloy steels and their weldments. The correlation ($DT_E = 105\,s - 12.96\,s^2 + 4.096\,s^3$) was found to fit well for a large spectrum of steels and welds.
2. The standard deviation of the energy residuals divided by the nominal maximum of the energy range for each data set for the steels at all thicknesses was about 7–10% and the welds at all thicknesses about 14–18%. This implies a thickness independence for the correlation from 7–25 mm thickness.

10. RECOMMENDATION

The results of this paper and our previous two papers[6, 7] support a recommendation that shear lip measured impact tests on DT specimens provides a reasonable alternative to energy measured impact test results. This will allow determination of structurally relevant transition curves using large specimens without the complexity and expense associated with the determination of fracture energy.

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