NOMENCLATURE

s	maximum width of shear lip (the average of two sides is used)
a	crack length
Δa_c	critical crack blunting
b	uncracked ligament
B	thickness of sample
W	sample width (specimen dimension parallel to notch)
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
Cv_E	Charpy energy value
σ_{flow}	flow stress, $(\sigma_y + \sigma_u)/2$
T - L	specimen orientation transverse (T), notch longitudinal (L)
L - T	specimen orientation longitudinal (L), notch transverse (T)
EDM	electrostatic discharge machining

Introduction

Prediction of ductile behaviour in welded structures requires a knowledge of the structural transition behaviour for the steel and weldments, the minimum service temperatures for the environments surrounding the structure, and the temperature of the steel and weldments themselves taking into consideration any heating and insulation. From this information it can be determined if the structure will exhibit ductile behaviour under all service conditions. Material selection, quality control, weld consumable approval, weld procedure qualification and design are all guided by this information.

Design of structures against fracture therefore requires, at the simplest level, that the minimum service temperature coincide with the upper shelf of the structural ductile to brittle transition curve for the steel and weldments. Material specifications in shipping standards often have no requirement for notch toughness (ie grade A steels) and when they do specify toughness (grades B, C, D, etc.) the specimen (Charpy) is of insufficient size and notch acuity to guarantee that the small scale test transition curve (Charpy transition curve) will reflect the structural transition behaviour and that the structure will be ductile at the lowest service temperatures.

Many commercial ships are built to grade A with no requirement for toughness. It has been estimated that up to 90% of shipping falls into this category. There have been approximately 1000 commercial shipping losses since World War II and many of these losses could have been prevented if notch tough steel had been used. The losses are usually associated with significant events such as collisions, groundings and heavy seas. Poor maintenance and corrosion are often cited as contributing factors. Naval vessels have also been involved in collisions, groundings and severe weather but there have been almost no naval vessel losses in this period. While some of this is attributable to the difference in design, large open tankers, vs small compartment construction etc., all those parts of the ship, exposed to an environment that places the structure on the lower shelf of the plate or weld transition curve, will be subject to brittle fracture.

Historical data on ship fractures and losses is shown in Figures 1a and 1b. The bulk of the data in Figure 1a comes from the final report of the board of investigation into the design and methods of construction of welded steel merchant vessels (i.e. Liberty ships) [1]. For comparison data on the World Concord, the Kurdistan and BS4360 43A (a Lloyd's A steel) are included.

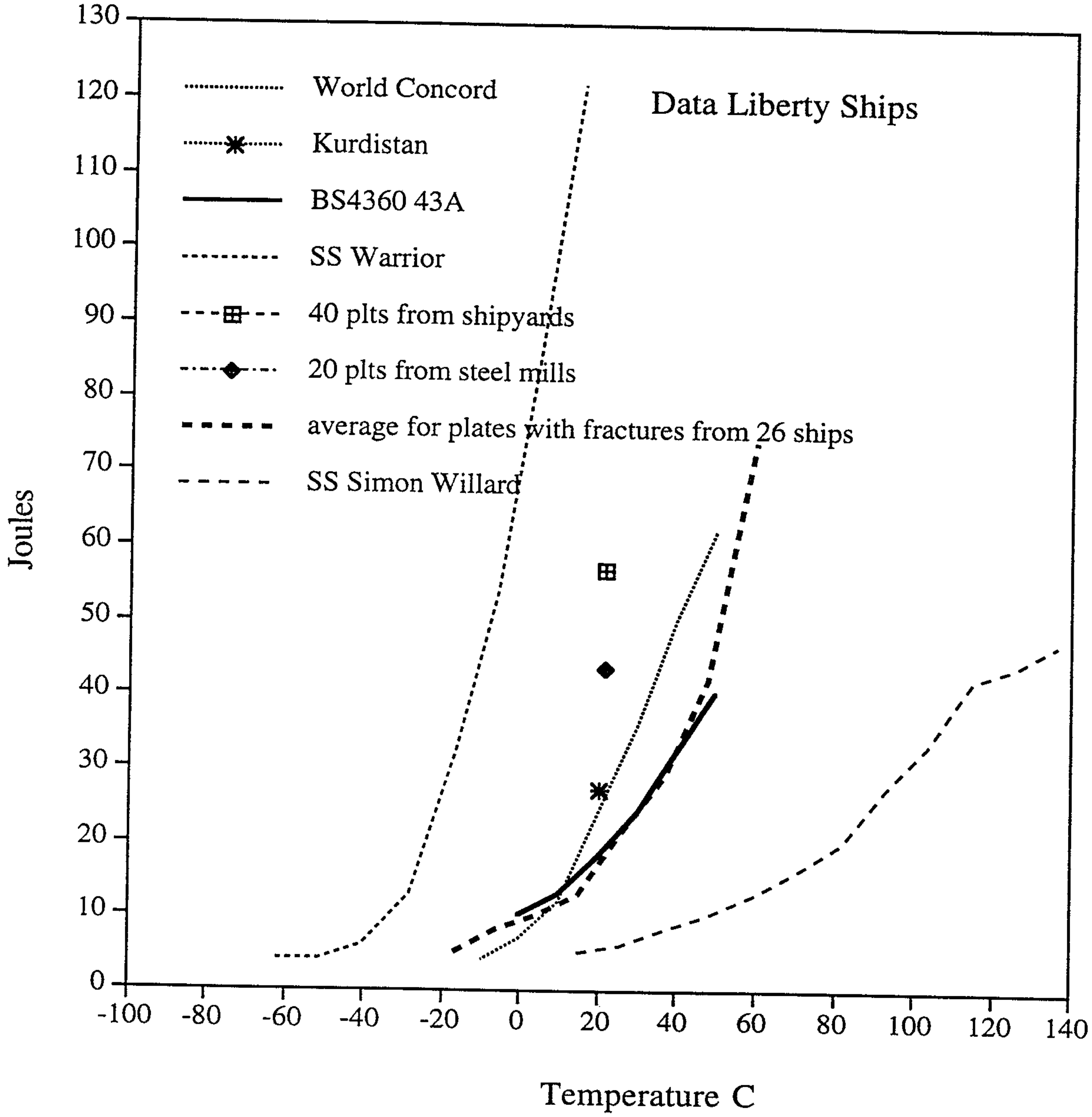

Figure 1a: Charpy transition curve data for Liberty ships[1], BS 4360 43A (a Lloyd's grade A steel) and two recent ships losses.

To compare this data to steels used to construct Canadian Naval vessels, and to other commercial grades of ship steel (B, C, D and E), Figure 1b is included. The area on these two graphs between the transition curve for SS Warrior and SS Simon Willard encompasses most losses. This area also encompasses standards for grades B, C and D. For interest, data for the piece of steel retrieved from the Titanic is also shown. While the requirement for the Canadian Navy (Naval in Figure 1b) and the 350WT steel transition behaviour lie outside the zone of losses, that does not guarantee that our ships are not subject to brittle fracture given the worst conditions. The balance of this report quantifies the risk for our ships.

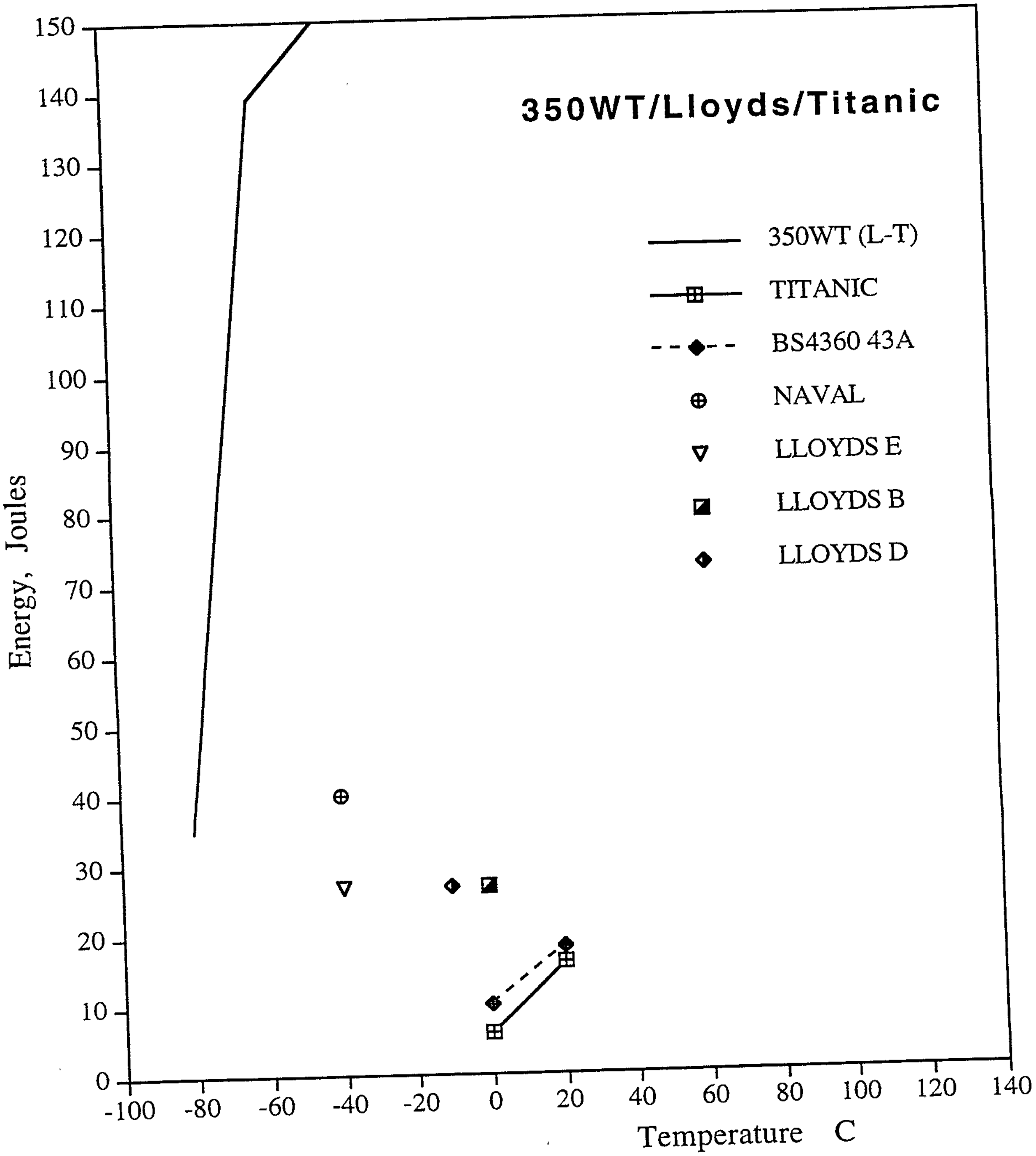

Figure 1b: Charpy transition data for steels used to construct Canadian Naval vessels, and commercial grade standards for grades B, C, D and E steels.

While naval vessel design and material control is better than commercial, it is not perfect. In smaller naval vessels some countries use commercial practice. For frigates and destroyers a minimum Charpy value, Cv_E, is specified for a test temperature typically -40°C. Nevertheless, the latter have suffered small brittle fractures which stop as they enter areas of higher temperature. The brittle fractures occur because the Charpy requirement does not guarantee ductile behaviour. The Charpy specimen does not behave like the structure. The specimen is too small.

The Welding Institute in England[2] has indicated in the past that the arbitrary values derived from Charpy V notched testing have proved adequate for many of the purposes intended (that is, evaluation of SMAW welded mild steel plate in thicknesses up to 38 mm). However, outside these limits, they concluded that the test is not sensitive to all the factors which influence brittle susceptibility. The Institute also pointed out that when weld deposits were made by different processes or different conditions within a process, the Charpy impact test, Cv, provided 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. These limitations were defined to limit errors resulting from use of the Charpy.

In this paper, we go further to not only identify the limitations of (i) often having no impact requirement, and (ii) of using the Charpy as the vehicle for material selection and evaluation but to (iii) suggest that a switch to a structurally comparable impact specimen (Dynamic Tear, DT[3], being the most appropriate of the common specimens) be made.

In this paper; the general use of transition curves in material design for ships will be reviewed; specific design requirements for commercial shipping and naval vessels will be highlighted; the relationship between Cv and DT will be given for 350WT and A517; the effect of altering Cv with an EDM notch will be presented; the relationship between shear lip width and energy in DT specimens will be presented; comparison of shear lip width results for several steels and their weldments will be given (to show that the DT test can provide valuable information without the need for the expensive instrumentation required to obtain the energy results); and finally the thickness independence of the correlation between shear lip and DT_E will be shown (this makes the test even more attractive).

Design

In design of commercial ships there is often no requirement to use notch tough steel. It has been estimated that 90% of ships fall into this category. The implications for fracture are considerable. Steel taken from ships which have fractured and sunk is generally of the same notch toughness as the steel used to fabricate most of these vessels [4]. Even steel from the Titanic exhibits transition behaviour in the range of these steels [5,6]. From a materials perspective the conclusion here is simple, if there is no requirement for impact toughness, brittle fracture will accompany most losses which result from collision, grounding or extreme seas.

For naval vessels, a minimum Cv at a design service temperature has been used to specify steel and weldments for some 50 years. In our case, ships built since 1960 were built to a requirement of 40 ft lbs @ -40°C. Metric conversion seems to be responsible for a more recent change to 28 ft lbs (40 joules) @ - 40°C. Fabrication and repair are rigorously controlled to this requirement as well. Weld consumables are approved and quality control for plate are driven by this simple requirement.

In more recent years, naval architects have been asking materials people to provide methods to predict probability of fracture in fatigue cracked ships and also damaged ships. While it has been tempting to launch into a dissertation on ductile fracture, elastic-plastic fracture mechanics, plastic collapse etc., it was quickly recognized that service temperatures exist where the structure will be brittle. Accordingly instead of fracture control the focus becomes temperature control:

a. there is a temperature where the ship will be subject to brittle fracture

b. if cracks appear, move to warmer water and heat affected areas to 15°C.

c. when areas have known fracture problems, move thermal insulation to outside

d. when fracture analysis is required, temperatures where linear elastic fracture will apply are identified and basic equations provided.

The first step in the process is clearly an upgrade to material requirements so that ships will always behave in a ductile manner. Then ductile fracture prediction and prevention can be considered in detail.

Finally, material specifications in shipping standards (in addition to often no requirement for notch toughness) rely on test specimens of insufficient size and notch acuity to guarantee that the structure will be ductile at the lowest service temperatures. This problem is contributory to the brittle issue and must be simultaneously resolved. Minimum standards must be adopted and specimen size and notch acuity requirements chosen to consistently predict ductile behaviour. In Figure 1c, the problem of specimen size is presented. The designer needs a materials approach that will guarantee good structural performance. The Charpy does not predict the structural performance and must be corrected for. The corrections are different for different types of steel, and are affected by thickness. On the other hand a larger specimen like a DT would be expected to predict the structural performance directly without empirical temperature corrections. The testing cost may be greater but the education and engineering analysis costs would be less. From our perspective the issue is the simplest, cheapest way to predict structural performance (ie DT transition curves), new requirements for all shipping (ie minimum transition temperatures for steel and weldments), and temperature control in the interim.

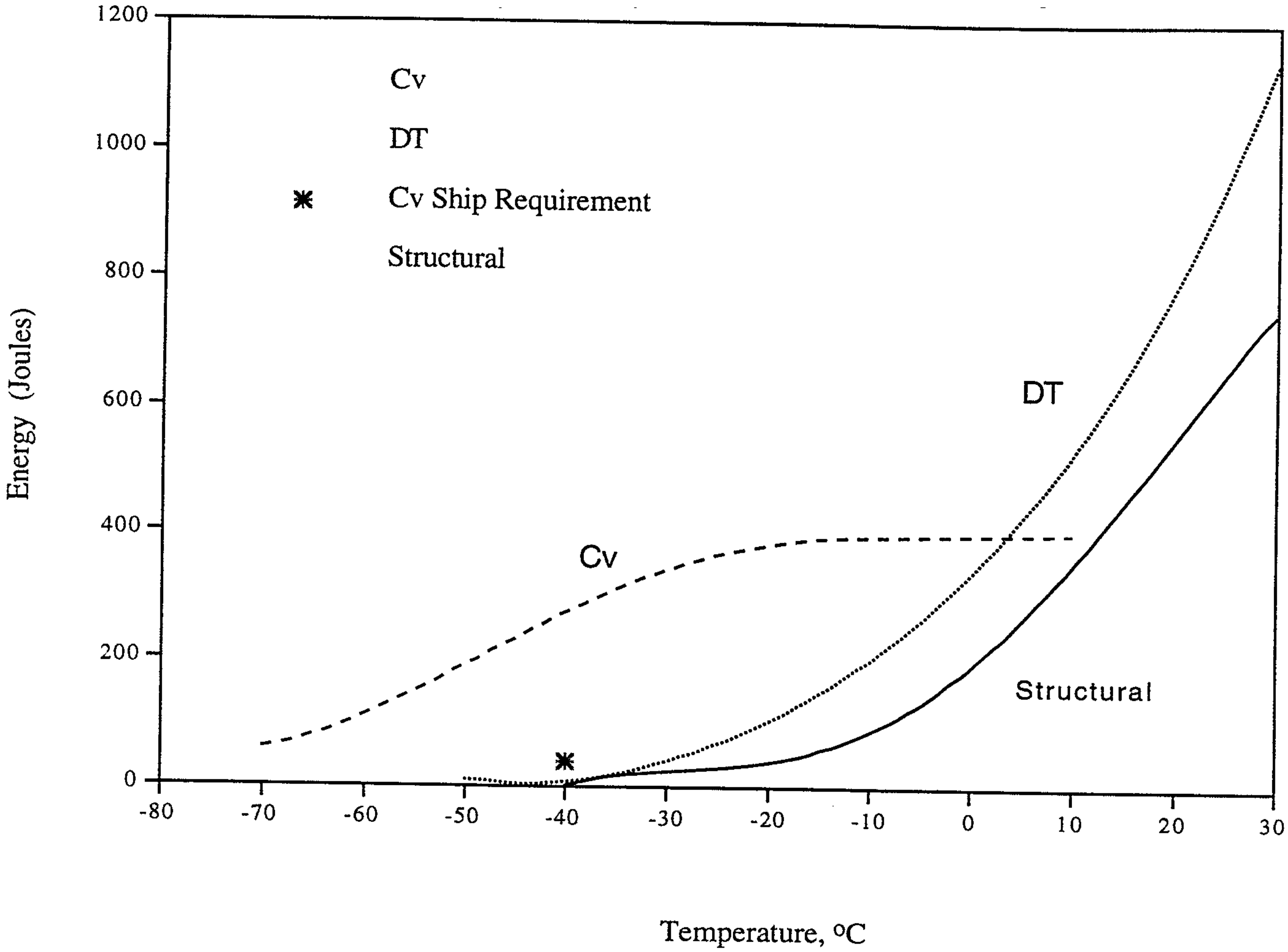

Figure 1c: Schematic of Basic Material Design to Guarantee Ductile Behaviour. (In this schematic, the requirement seems reasonable; the material (Cv) seems much better than the requirement; but the structure is unacceptable: this is typical)

Materials

The materials mentioned in this paper include 25 mm HY80 and HY100 steel plate, 15 mm 350WT steel plate (CSA G40.21-350WT), 9.3 mm ASTM A517 Grade F steel plate and various GMAW weldments of HY80 and HY100 [7,8,9]. The chemical composition for the steels and welding consumables are given in Tables 1 and 2.

Table 1: Chemical Composition of Plates and Welding Wires.

	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
350WT	.22	.8-1.5	.03	.04	.15-.4				
A517 (F)	.1-.2	.6-1.0	.035	.04	.15-.35	.7-1.0	.4-.65	.4-.6	.15-.5
HY100	.12-.20	.1-.4	.02	.02	.15-.35	2.25-3.5	1-1.8	.2-.6	.25
HY80	.12-.18	.1-.4	.025	.025	.15-.35	2.0-3.25	1-1.8	.2-.6	.25
100S1	.08	1.25-1.8	.01	.01	.2-.5	1.4-2.1	.3	.25-.55	.25
120S1	.1	1.4-1.8	.01	.01	.25-.6	2.0-2.8	.6	.3-.65	.25

Table 2: Composition of Welding Gases

gas	Ar	CO_2	He	O_2
95/5	95	5		
T.I.M.E. 1	65	8	26.5	0.5

The steel plates are typical of those used to fabricate naval vessels.

The welding processes mentioned are all GMAW. TIME welding [7] was conducted with either a standard GMAW L-Tec 650 welding machine or a Fronius Transarc pulsed welding machine. The 95% Ar 5% CO_2 gas was used with the Fronius machine only. The TIME process is a gas metal arc welding process which employs a special gas and a specially designed nozzle. The process produces welds that are very clean with reduced sulfur and phosphorous levels and enhanced weldment toughness. The transfer characteristic is effective in the short arc mode as well as the globular and spray modes. Weldments mentioned in this work were all produced in the spray arc mode. The Fronius is a synergic pulsed system which uses variable speed wire feed to compensate for rate of metal transfer requirements.

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. An instrumented tup was connected to a signal conditioner and from there to a digital oscilloscope to capture the load-time data. The 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.

Charpy specimens for the base steels were cut from the DT specimens after testing. The tests were conducted from room temperature to liquid nitrogen temperature.

Ductile to Brittle Transition Behaviour

Transition behaviour for Charpy size specimens is sometimes 50 to 100°C below that for larger DT specimens. Figure 2a shows the Charpy and DT behaviour for 350 WT steel. Figure 2b includes transition data for EDM notched Charpys and Figure 2c shows results for the L-T orientation alone. The basic shift between Charpy and DT transition is some 60°C, while the EDM notch transition is 20°C above the standard Charpy and only 40°C below the DT.

Transition behaviour for A517 is less clear possibly because of the thinner (B) plate. Figure 3a shows the lower bound Charpy and DT behaviour for the A517 steel. Figure 3b includes transition data for EDM notched Charpys and Figure 3c shows results for the T-L orientation alone. The basic shift between Charpy and DT transition for the T-L orientation is some 40°C, while the EDM notch transition is 20°C above the standard Charpy and may be 20°C below the DT. In the L-T orientation the lower bound data is less clear mainly because so few of the specimens tested exhibited brittle behaviour. Many more tests would be necessary to clarify the relationship.

Confusion related to the A517 data supports use of the larger specimen. Simply modifying the notch of the Charpy will not make it reflect the structural behaviour. With the A517 steel, thickness and crack size effects may have competed significantly with reducing temperature. The basic behaviour is that as specimens decrease in thickness apparent toughness increases as plane strain gives way to plane stress and apparent toughness drops off as notches and ligaments decrease in size. Accordingly, without fully explaining the A517 behaviour, the DT specimen is probably the simplest existing specimen whose transition behaviour would approximate that of a structure.

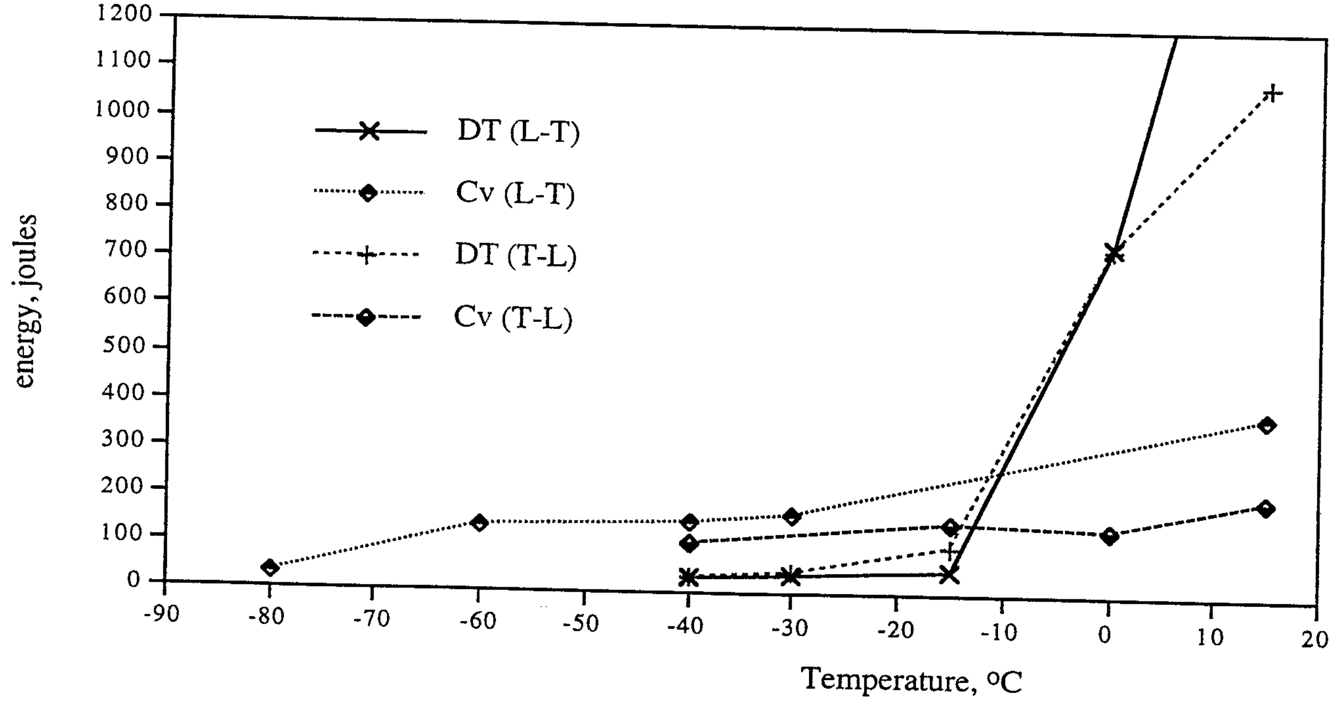

Figure 2a: Lower Bound Cv and DT Transition Curves for 350 WT.

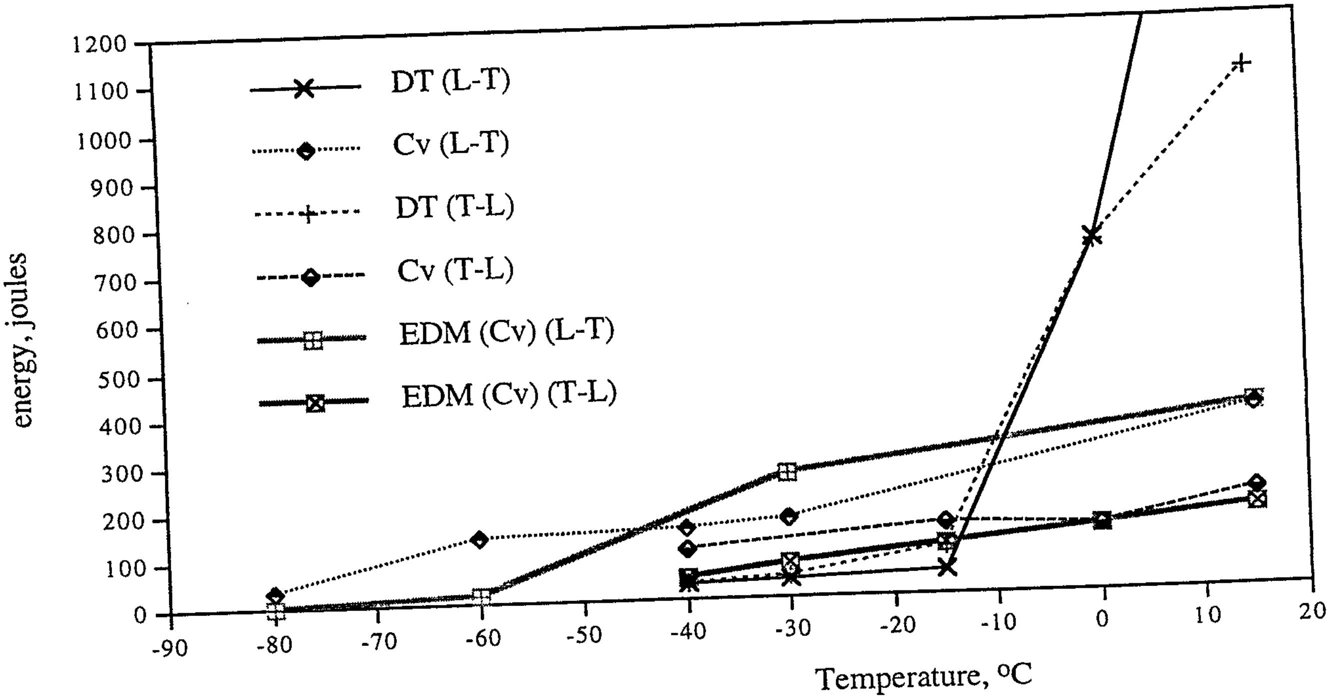

Figure 2b: Lower Bound Cv, EDM (Cv) and DT Transition Curves for 350 WT.

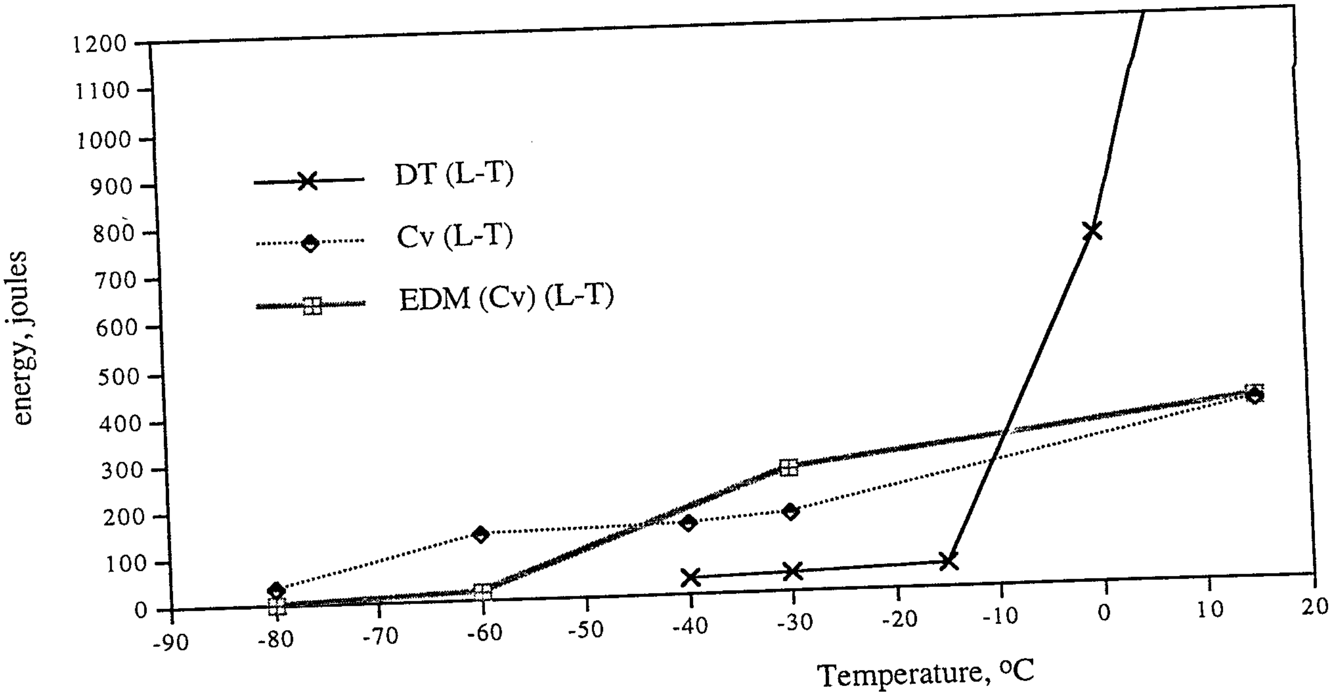

Figure 2c: Lower Bound Cv, EDM (Cv) and DT Transition Curves for 350 WT (L-T).

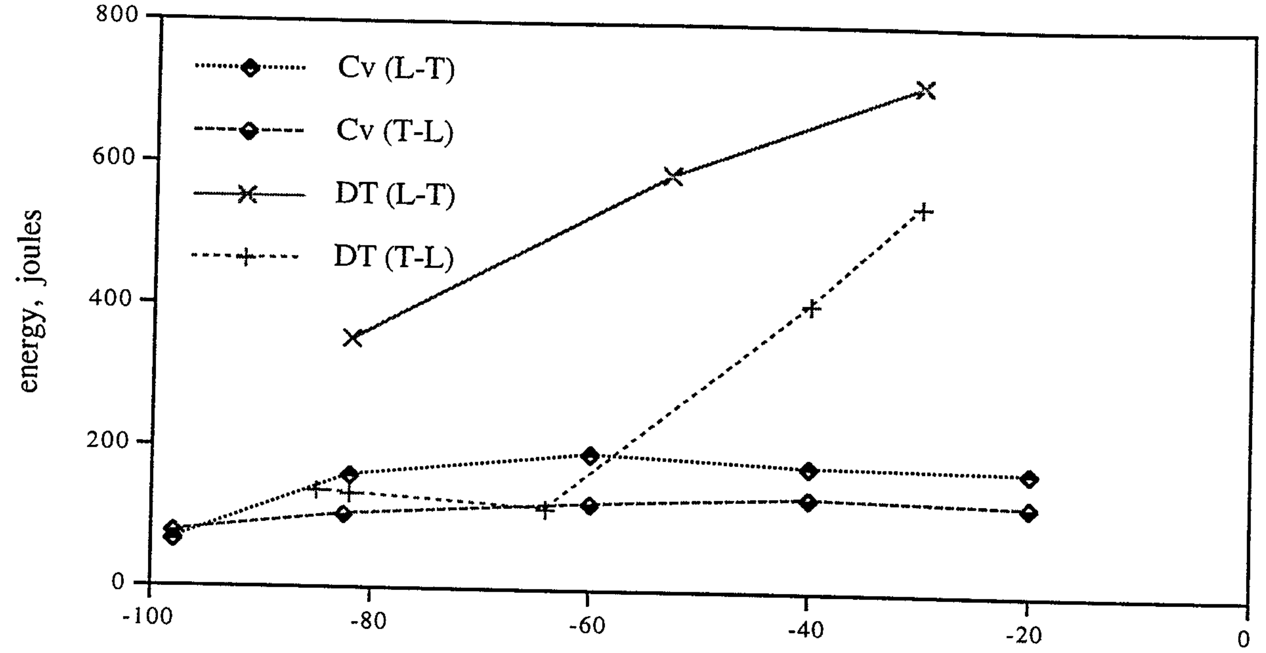

Figure 3a: Lower Bound Cv and DT Transition Curves for A517.

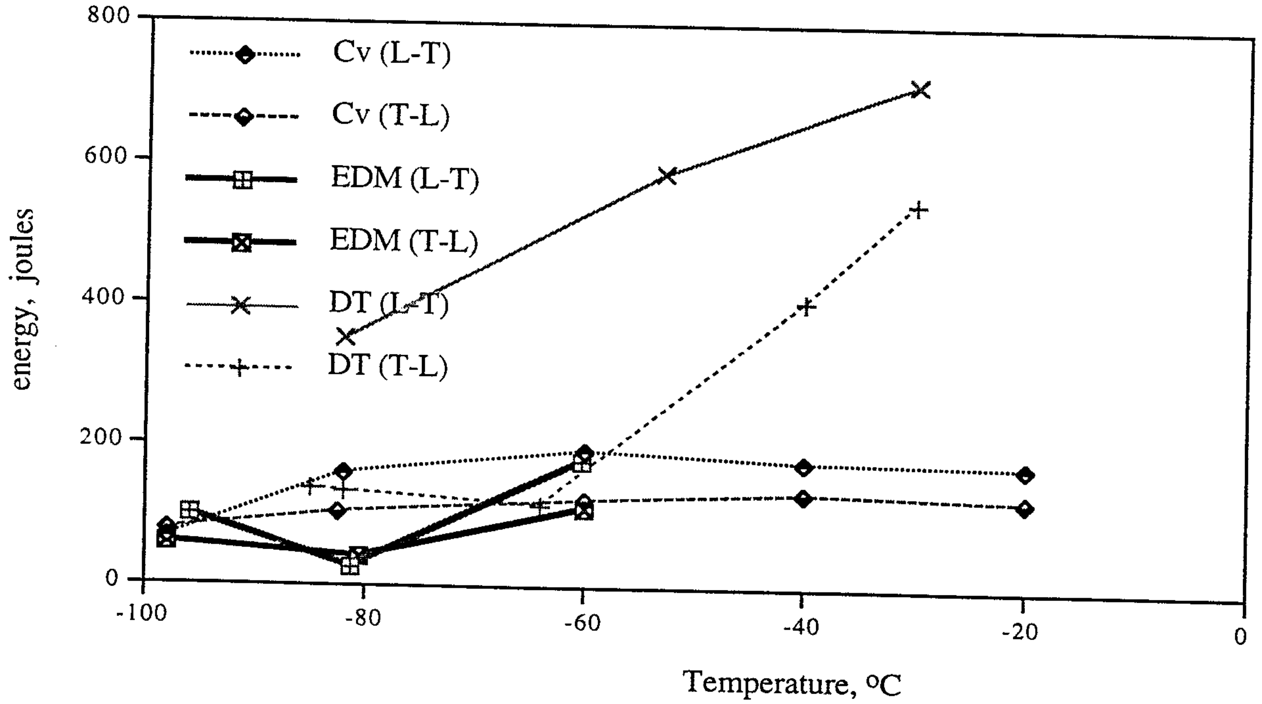

Figure 3b: Lower Bound Cv, EDM (Cv) and DT Transition Curves for A517.

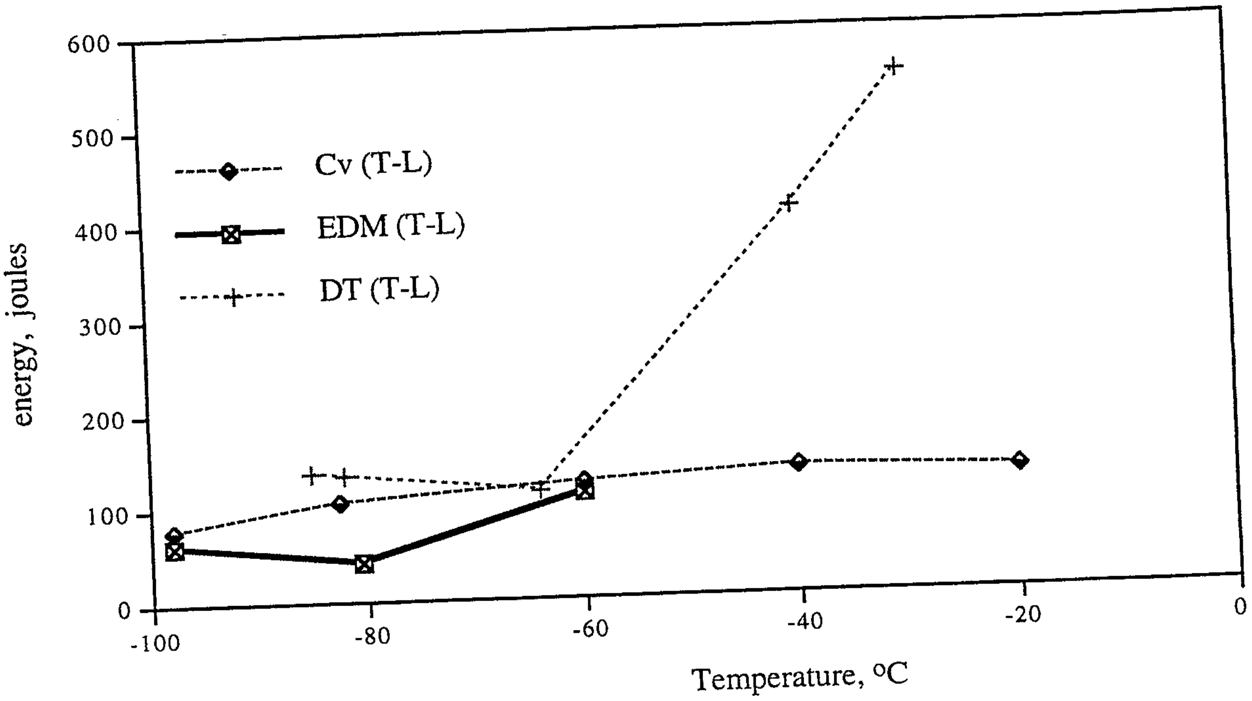

Figure 3c: Lower Bound Cv, EDM (Cv) and DT Transition Curves for A517 (T-L).

Shear Lip Transition Curves

One of the main road blocks to specifying a DT requirement in place of a Charpy requirement is the increased cost of the DT test. The cost comes from the cost of machining, the cost of a tower and the cost of the electronics for load capture and computer analysis. The last cost which is perhaps the greatest can be eliminated by relying on shear lip [8,9] in place of energy to produce transition curves. In addition to reduced cost, the perpetual preservation of results and the potential for elimination of errors that can show up (sometimes undetected) with strain gage instrumentation and computer data logging, plus the elimination of notch effects [8] make shear lip transition curves a very attractive alternative.

Morphology of fracture surfaces has long been used as an indication of how brittle or ductile a material is at a given temperature[10]. The morphology can range from flat when no shear lips are present, to a shear index of one, when the shear lips on either side of the specimen are developed to the point of touching each other, Figure 4. In many fracture tests such as the Charpy V notched (Cv)[1] and Dynamic Tear (DT)[3] standard test methods, measurement of percentage shear which is somewhat related to the shear lip size is optional, while in the Drop Weight Tear Test (DWTT)[11], it is the basic physical measurement required.

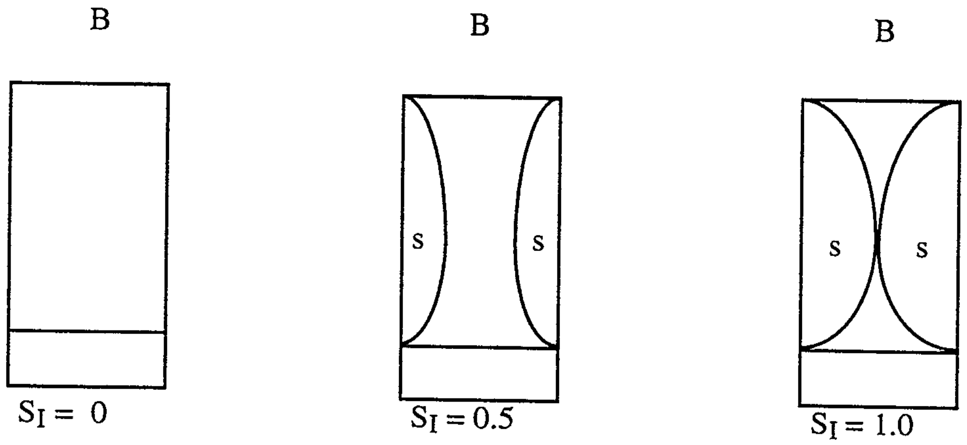

Figure 4: Typical morphologies for dynamic tear impact samples (shear index is measured at the point of the closest contact between the two shear lips: $S_I = 2s/B$).

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 (W). Accordingly, it was decided in our earlier work[8] 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 distance between the two shear lips was measured, subtracted from the original width and divided by two to obtain an average shear lip estimate.

DT Data for HY80, HY100 and a lower strength low alloy steel taken over a wide range of temperatures were used to determine the relationship between energy and shear lip size, Figure 5.

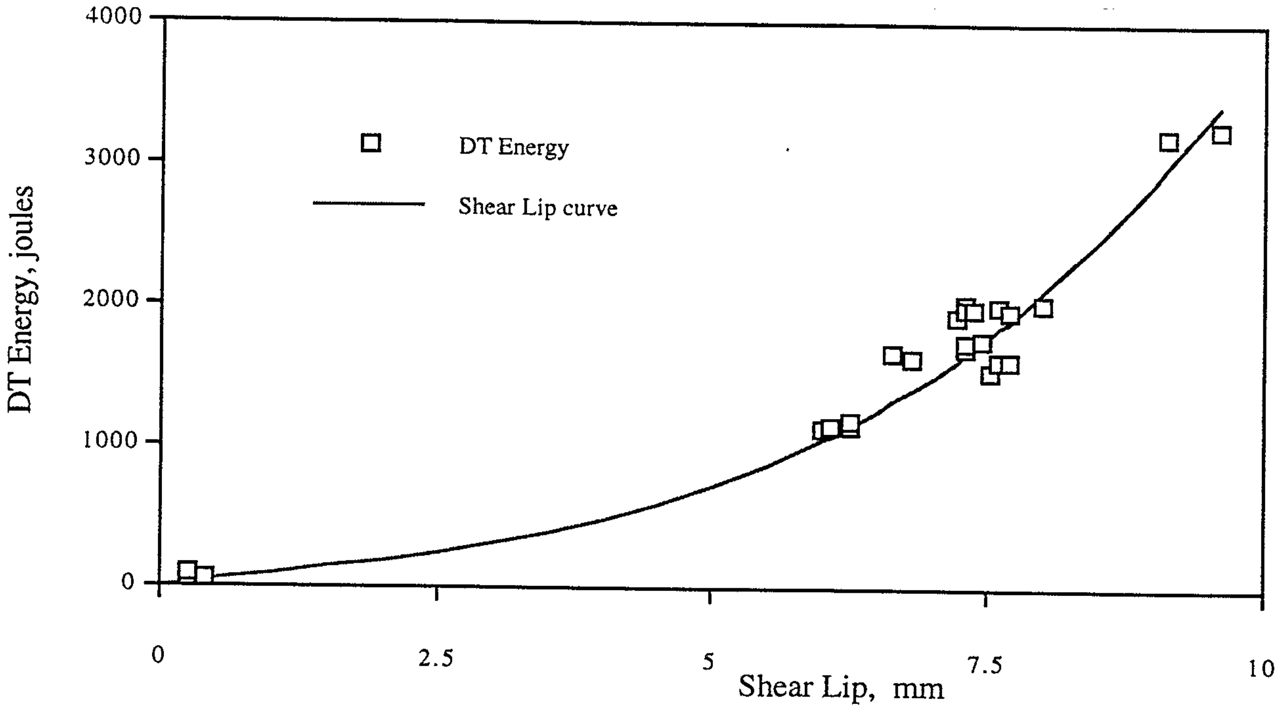

Figure 5: Graph of Shear Lip "s" vs DT Energy.

The influence of yielding on the relationship between shear lip "s" and energy is generally nonlinear except at low values of toughness, in the elastic range, where it is linear. It was found [8] that DT_E in joules can be determined from shear lip in mm by the following:

$$DT_E = 105\,s - 12.96\,s^2 + 4.096\,s^3. \tag{1}$$

This curve is shown with basic data in Figure 5. It was found that this curve fits equally well for steel and weldments. With weldments there is more scatter but this is due to the inherent variability of the welds and weld defects. Scatter caused by notch variability was isolated to be showing up in the energy values only. The shear lip size was independent of the notch acuity.

Attempts to produce an analytical relationship between energy, toughness and shear lip size is extremely complex and covers the whole range of mechanics, elastic through plastic. 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 effectively requiring elastic, elastic-plastic and plastic analysis at some stage in the fracture analysis of all but the most brittle samples.

In previous work [8,9] we noted the following

(i) *Elastic*

For plane strain elastic conditions to exist in a DT specimen, just after crack advance at least, the following would apply:

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

Estimating shear lips to be of the order of the critical plastic zone size gives:

$$s = r_{yc} = \frac{1}{6\pi}\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \tag{3}$$

(ii) *Elastic-plastic*

For elastic-plastic conditions to exist in a DT specimen, just after crack advance, the following conditions would apply:

$$a, b, B > 50\, \frac{J_{Ic}}{\sigma_{flow}} \tag{4}$$

Critical crack blunting could be calculated from

$$\Delta ac = \frac{J_{Ic}}{2\,\sigma_{flow}} \tag{5}$$

The shear lip size would be related to this critical blunting but not to the specimen size as originally suggested[8]. The shear lip would be about 50 times the critical crack blunting.

$$s = 50\,\Delta_{ac} = \frac{25\,J_{Ic}}{\sigma_{flow}} \qquad (6)$$

Slightly larger values would exist for thicker specimens but shear indexes of one would not be expected as specimens get larger and larger. This explains why the shear lips in thicker specimens that we tested (25 mm) tended to peak out at 8 to 9 mm.

(iii) *Plastic*

When the elastic-plastic toughness is exceeded the mode of failure appears to be plastic. 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 indexes of 0.90 to 1.00 (or shear lips of 7 to 8 mm) for our materials.

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 previous studies [8,9] 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 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.

In Figures 6a and 6b energy and shear lip data are presented for 350WT. It is clear that both measurements tell the same thing about the transition behaviour. Figures 7a and 7b show energy and shear lip data for A517. Once again both measurements tell the same thing about the transition behaviour.

In Figures 8,9 and 10 data for gas metal arc welds of HY80 and HY100 steels show that the energy and shear lip curves impart the same knowledge about the material performance. Also, these three figures show that the relationship between shear lip and energy is independent of specimen thickness between 16 mm and 25 mm thickness.

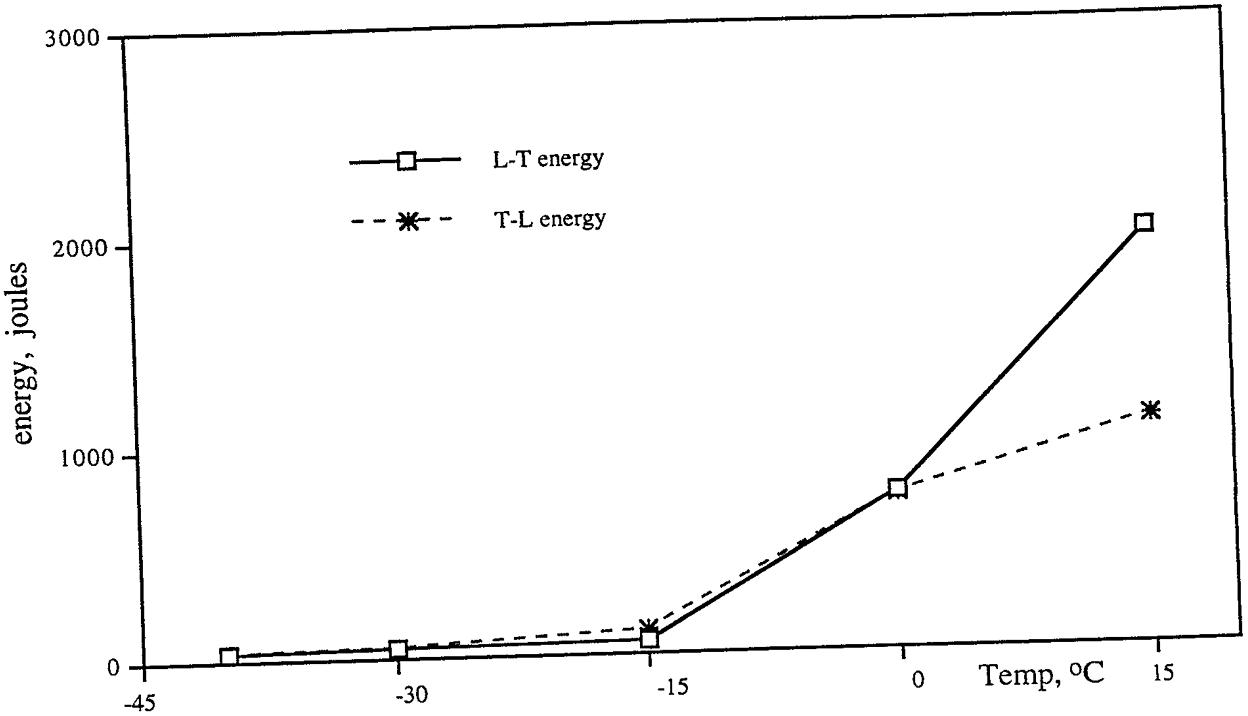

Figure 6a: Dynamic Tear Energy for 15 mm 350WT steel.

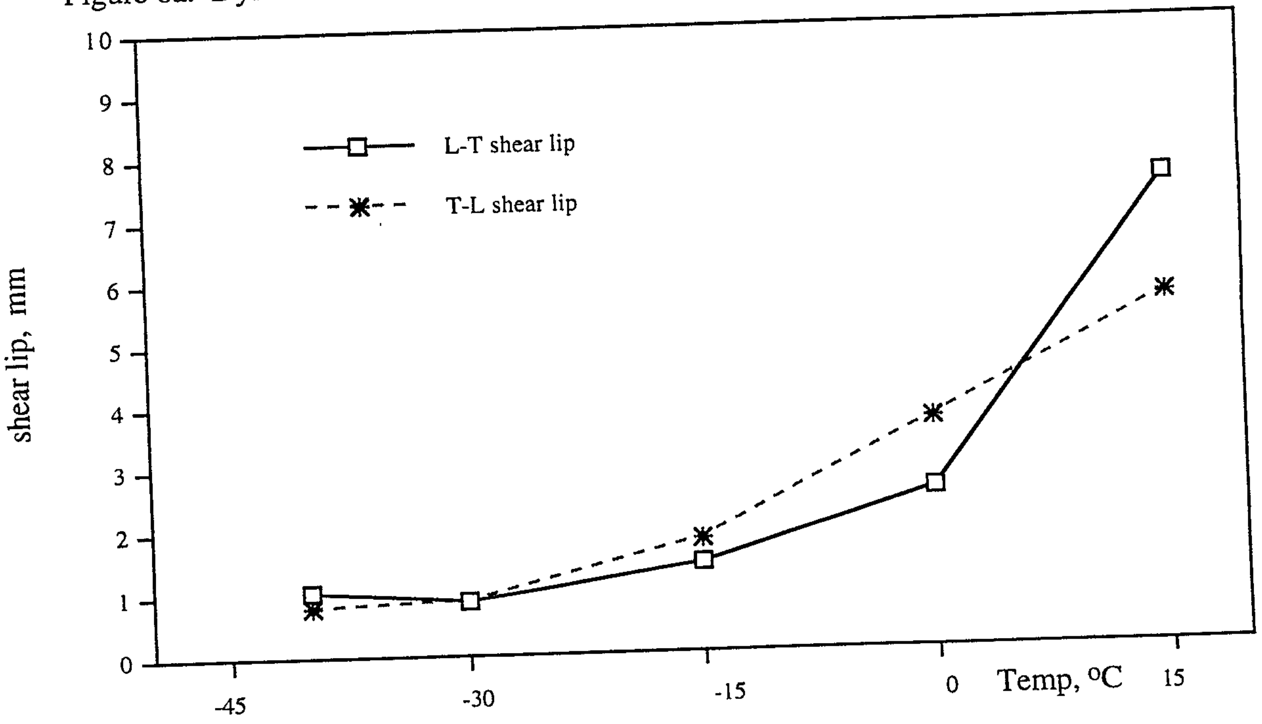

Figure 6b: Shear Lip Transition Curves for 15 mm 350 WT steel.

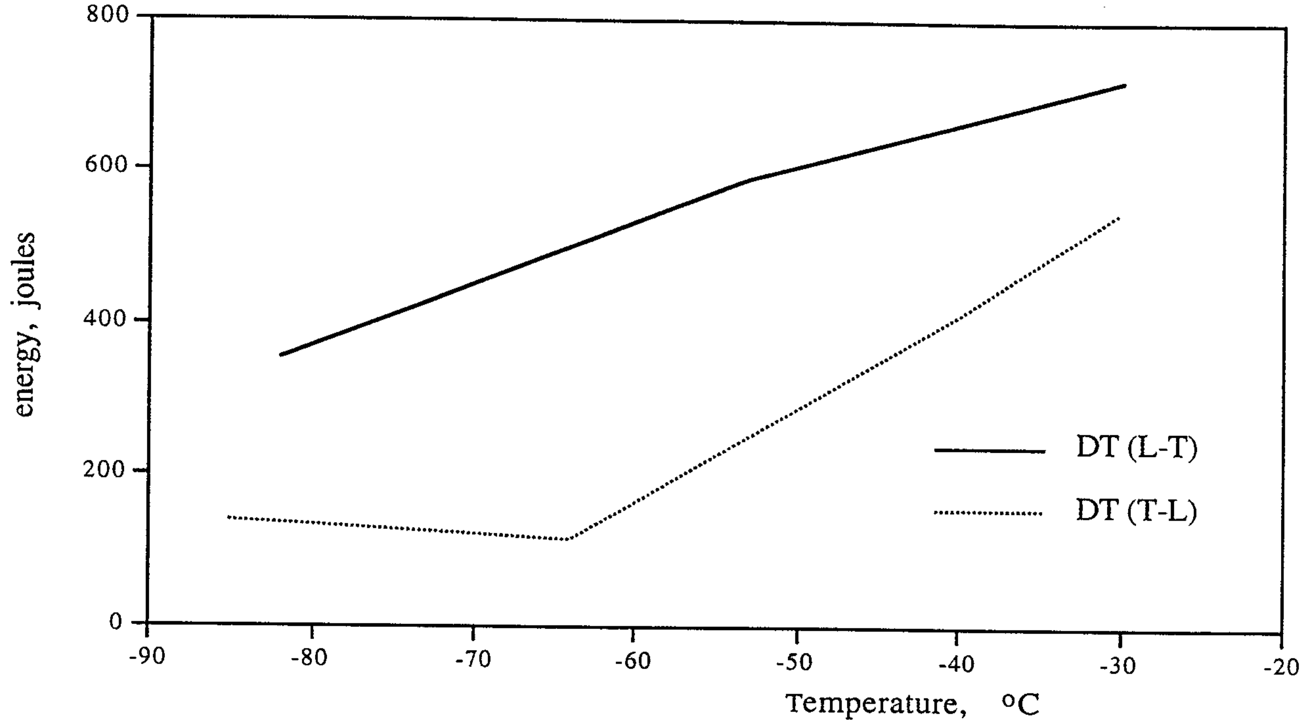

Figure 7a: Dynamic Tear Energy for 9.3 mm Thick A517 grade F steel.

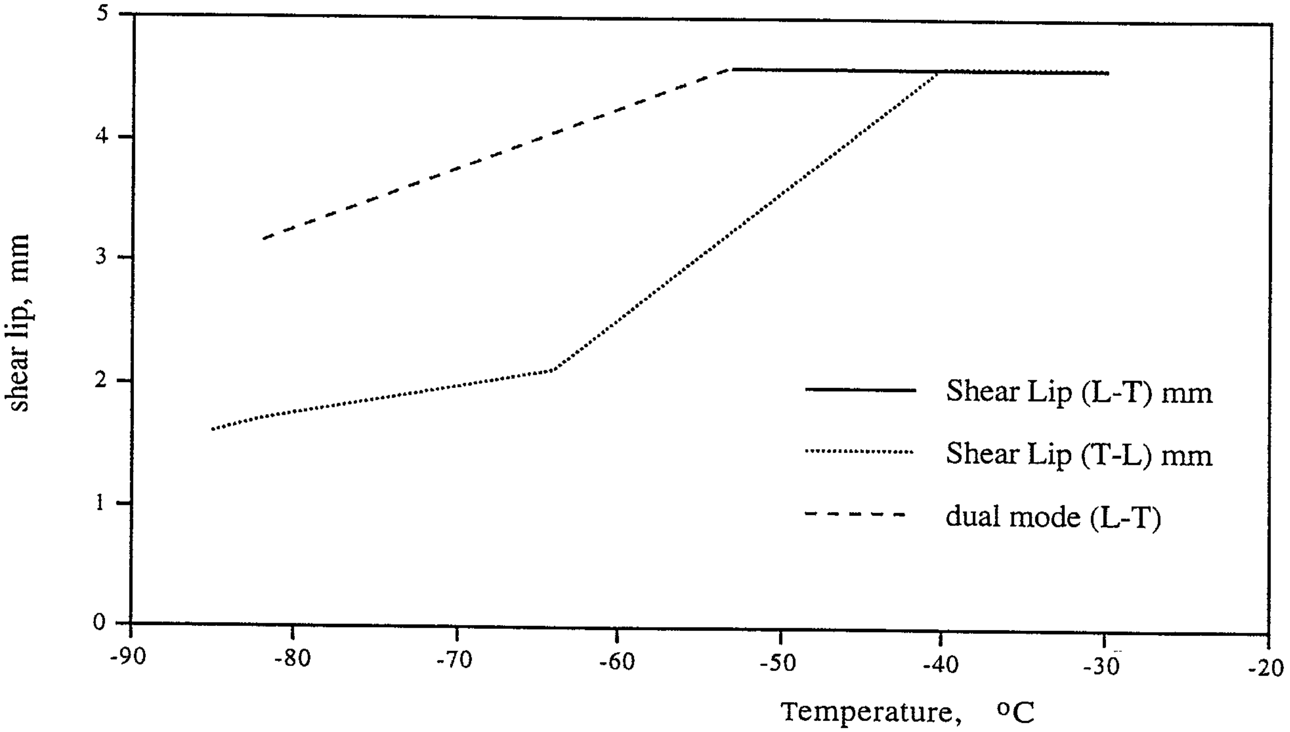

Figure 7b: Shear Lip Transition Curves for 9.3 mm Thick A517 grade F steel.

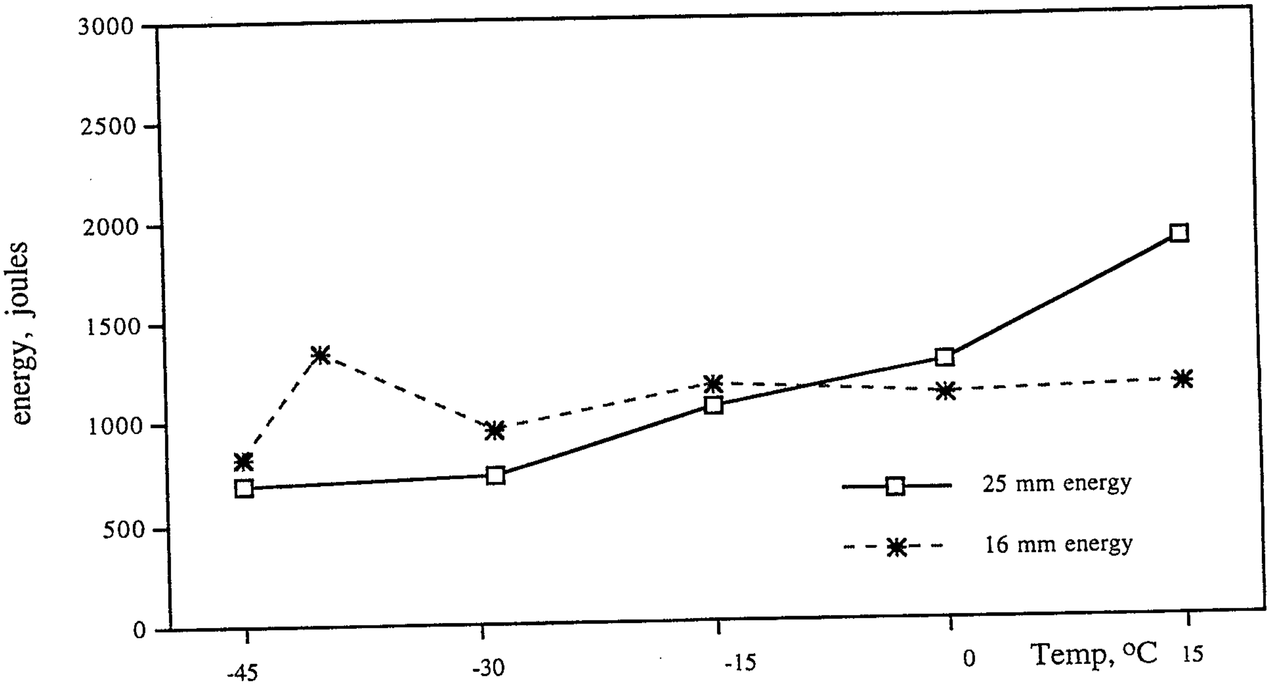

Figure 8a: Dynamic Tear Energy for HY80 GMAW Weld Produced With Standard L-Tec Machine, TIME gas, in the Vertical Position.

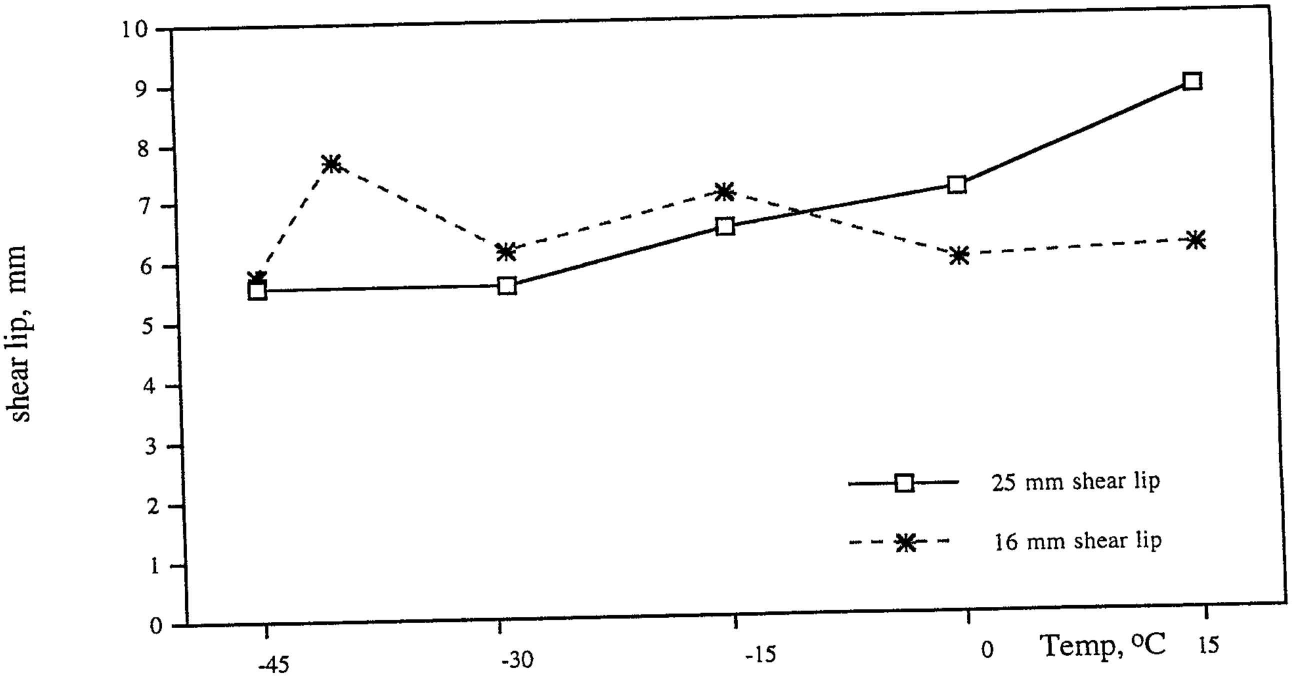

Figure 8b: Shear Lip Results for HY80 GMAW Weld Produced With Standard L-Tec Machine, TIME gas, in the Vertical Position.

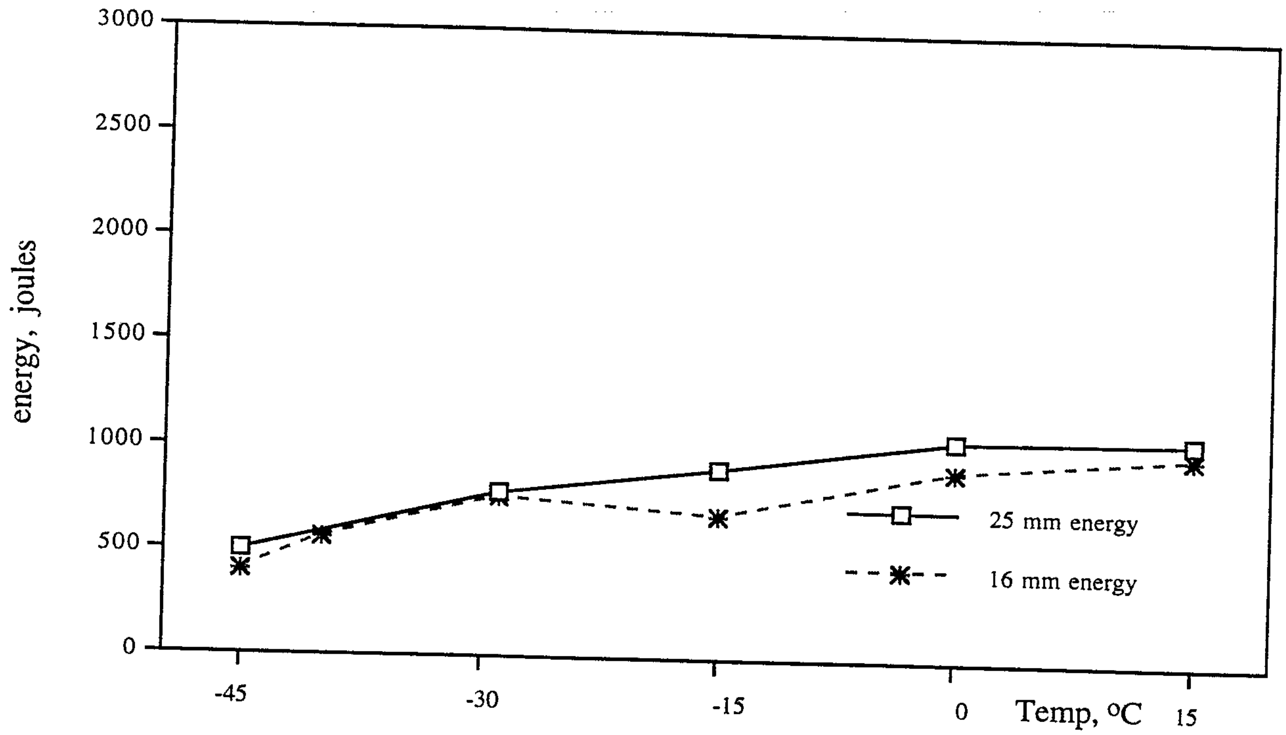

Figure 9a: Dynamic Tear Energy for HY100 GMAW Weld Produced With Standard L-Tec Machine, TIME gas, in the Overhead Position.

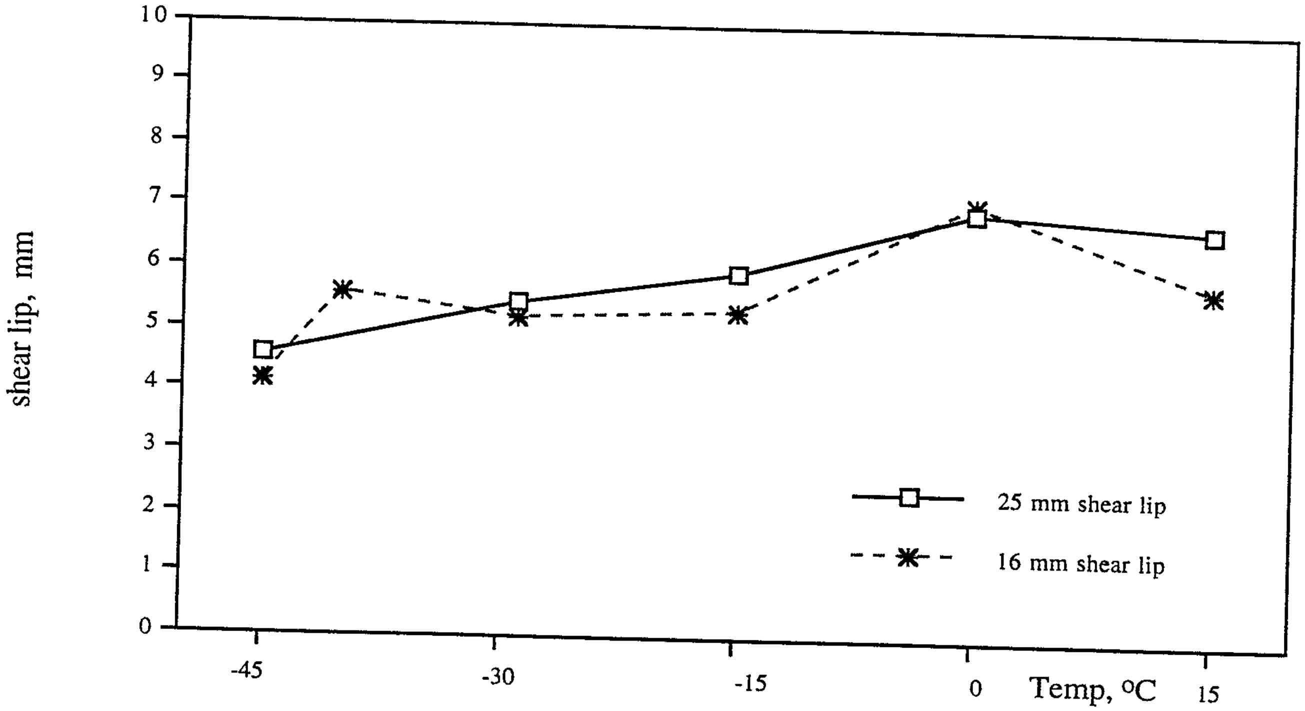

Figure 9b: Shear Lip Results for HY100 GMAW Weld Produced With Standard L-Tec Machine, TIME gas, in the Overhead Position.

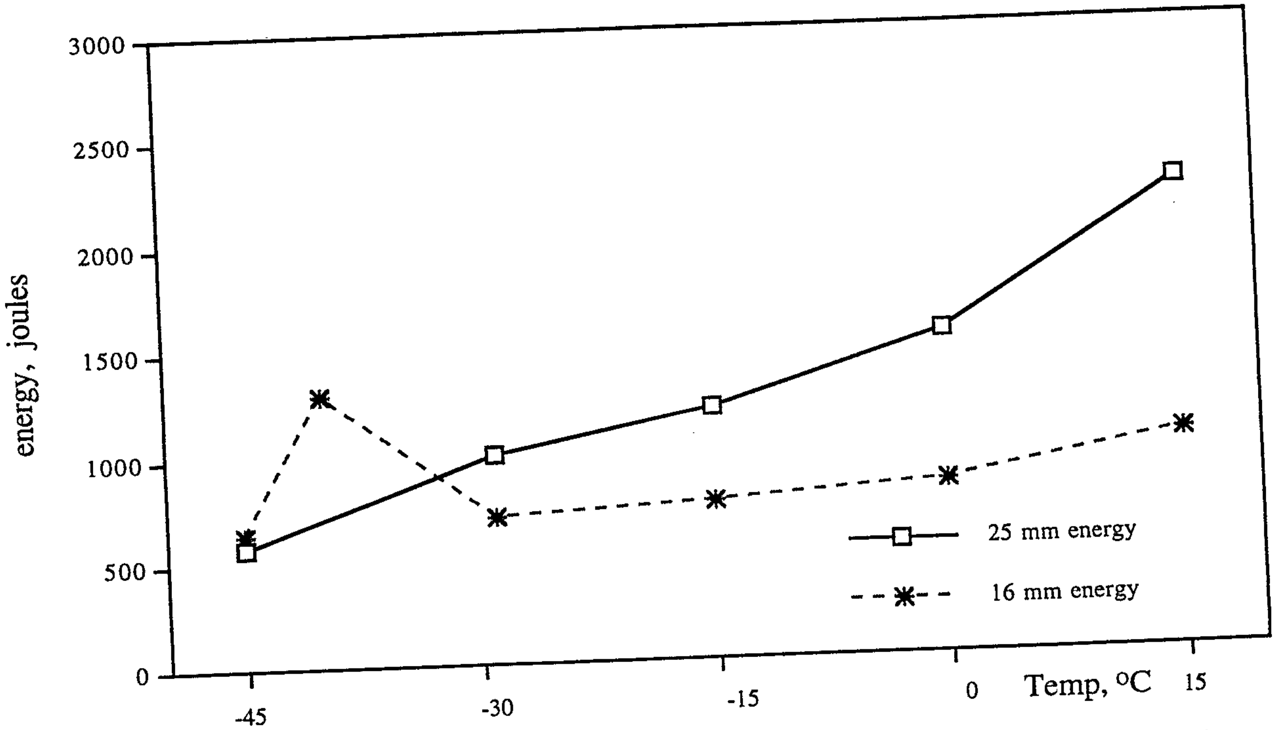

Figure 10a: Dynamic Tear Energy for HY100 GMAW Weld Produced With Pulsed Fronius Machine, 95/5 gas, in the Overhead Position.

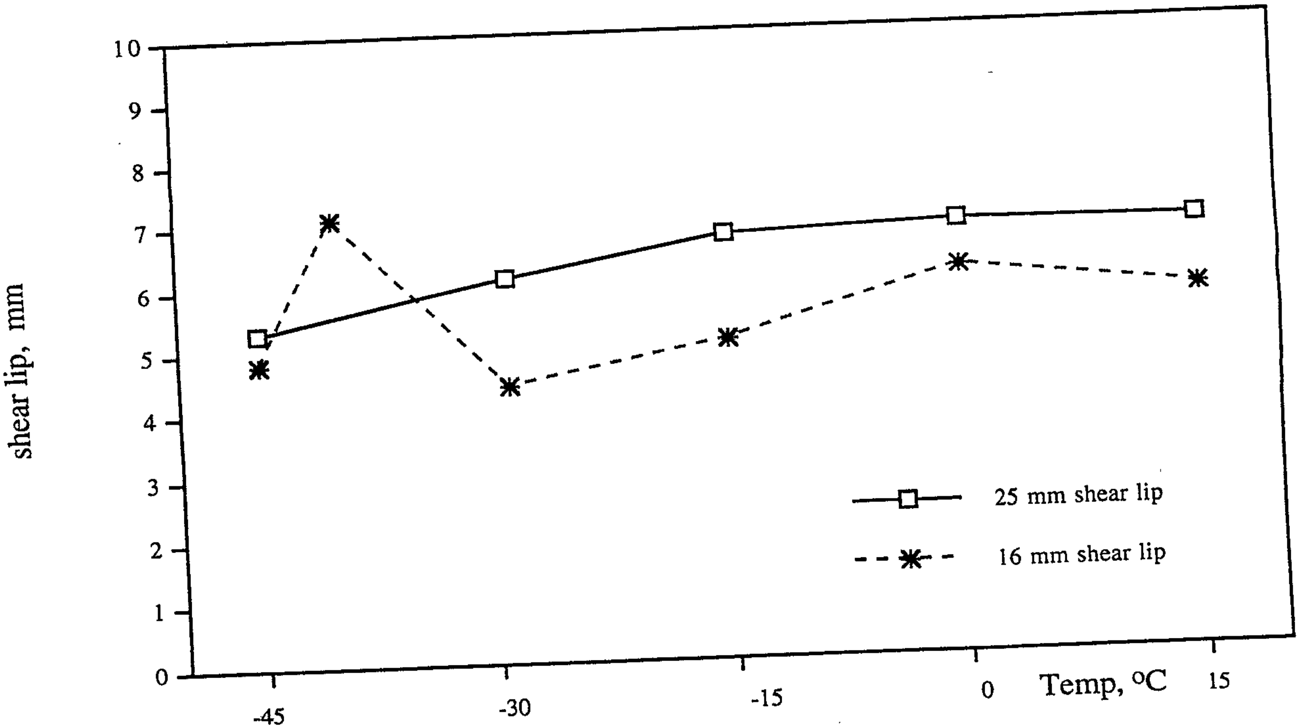

Figure 10b: Shear Lip Results for HY100 GMAW Weld Produced With Pulsed Fronius Machine, 95/5 gas, in the Overhead Position.

CONCLUSIONS

1. Prediction of ductile behaviour in welded structures starts with selection of material and fabrication control that guarantee the structure will exhibit upper shelf behaviour at the lowest service temperature.

2. The Cv specimen is too small to effectively and economically serve as a test vehicle to control structural quality.

3. DT is the simplest existing specimen whose transition behaviour approximates that of a structure.

4. The data presented shows that shear lip information is equivalent to energy information for characterizing the toughness of carbon and low alloy steel and their weldments. As the shear lip data is considerably cheaper to acquire and permanently available for accurate re-examination it is considered the preferential test for transition behaviour evaluation of ship steel and weldments.

5. The correlation between shear lip and energy is independent of thickness for 16 mm and 25 mm specimens of low alloy steels and their weldments. The 25 mm size test specimen shows no increase in energy over the 16 mm specimen except on the extreme upper shelf. Therefore the two tests can be used interchangeably dependent solely on machining costs. Toughness requirements for the one inch specimen will be identical to the 16 mm specimen.

6. The shear lip criterion for determination of toughness does not appear to be affected by poorly pressed notches in DT tests.

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