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Linear Elastic Fracture Toughness (K_{Ic}) and Dynamic Tear Transition

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ABSTRACT

The design of a modern warship is a very complex task. Some of the greatest concerns in the design are the selection of proper materials and welding techniques. The aim of the selection is to reach a design, which enables the whole structure to have a ductile behaviour under all operating conditions.

This report concentrates on Linear Elastic (K type) tests at temperatures where the Dynamic Tear energy was less than 133 joules for a 16 mm specimen. 133 joules was selected since it has been suggested that nil ductility occurs at that point for a standard Dynamic Tear Specimen.

A background on the subject at hand and a proposed new transition curve interpretation is given. The materials composition and the dynamic tear transition behaviour of three weldments and a Grade A steel chosen for testing are shown. Precracking and fracture toughness procedures are given. The fracture toughness experimental results are shown for all temperatures. A proposed relationship between the shear lip size and the critical plastic zone size is used to determine the validity of the results.

The results show that the transition curve is a useful guide to establish a temperature range where a valid plane strain test will exist. Lower shelf is not necessarily plane strain. Using the shear lip size it is possible to establish a new criteria for a valid plane strain test (i.e. shear lip size (s) less than thickness (B) divided by 50)

$$s < \frac{B}{50}$$

Finally, it will be shown that the measured stress intensity at fracture, K_Q, only becomes a valid K_{Ic} at a temperature below the inflection point on the K_Q versus temperature graph.

INTRODUCTION

The design of a modern warship is a very complex task. Some of the greatest concerns in the design are the selection of proper materials and welding techniques. The aim of the selection is to reach a design, which enables the whole structure to have a ductile behaviour under all operating conditions. The prediction of the performance in welded structures requires the following knowledge: Structural transition behaviour for steels and weldments, environmental conditions such as temperatures, and external influences such as insulation and heat sources [1].

The transition curves of steels and welds are a good guideline to help the designer select the proper materials. If the minimum operating temperature corresponds with the upper shelf of the transition curve the structure will have a ductile comportment and this is a desirable situation for all ships. Designers should be concerned about steels and welds, which lie in the lower shelf section of the transition curve.

Dynamic Tear (DT) Transition Curves [1,2] were completed for a grade A steel and three welds examined in this paper in order to establish the appropriate temperature for quantitative fracture tests. This report concentrates on Linear Elastic (K type) tests at temperatures where the Dynamic Tear energy was less than 133 joules for a 16 mm specimen. 133 joules was selected since a report [3] suggested that nil ductility occurs at that point for a standard DT Specimen.

It was expected that valid linear elastic fracture toughness would occur near this nil ductility temperature point but as will be seen in this paper plane strain fracture toughness would be measurable only at a much lower temperature than anticipated.

The paper is divided into distinct sections. First, a background on the subject at hand and a proposed new transition curve interpretation is given. Second, the materials composition and the dynamic tear transition behaviour for the three weldments and the steel chosen for testing is shown. Third, the precracking procedure is given. Fourth, the procedure for the fracture toughness test is given. Fifth, a proposed relationship between the shear lip size and the critical plastic zone size is discussed. Sixth, the fracture toughness experimental results are shown for all temperatures. Seventh, the validity of the results are discussed by using the shear lip size and the critical plastic zone size. Eighth, a final discussion and overview graphs are given.

BACKGROUND

The plane strain linear elastic toughness (K_{Ic}) characterizes the resistance of a material to fracture in a neutral environment in the presence of a sharp crack under severe tensile constraint. The K_{Ic} value represents a limiting value of fracture toughness [4]. This property is used to estimate the relation between failure stress and defect size for materials in a high constraint condition.

The transition curve represented in Figure 1 shows the energy transition behaviour in relation to the temperature. The top shelf where there is full plastic shear, the material behaves in a ductile manner. The relevant material property in this top shelf zone is the flow stress in shear. The flow stress in shear($\hat{k}$) is approximately half the yield strength. In the elastic-plastic zone, failure can be evaluated using the J_{Ic} equations. In transition, the most relevant property, for shear lips between B/20 and B/2, is strain to fracture. Finally, the lower shelf corresponds to an elastic behaviour. This report focuses on determining the highest temperature at which a valid K_{Ic} value can be determined for 3 different weldments and a UK supplied Grade A steel and thus the establishment of the fracture transition elastic point on the transition curve. From our results it will be apparent that the temperature range for a valid K_{Ic} is much lower than initially thought. This is also true for J_{Ic} [5] and therefore the transition curve quantitative relationships are redefined.

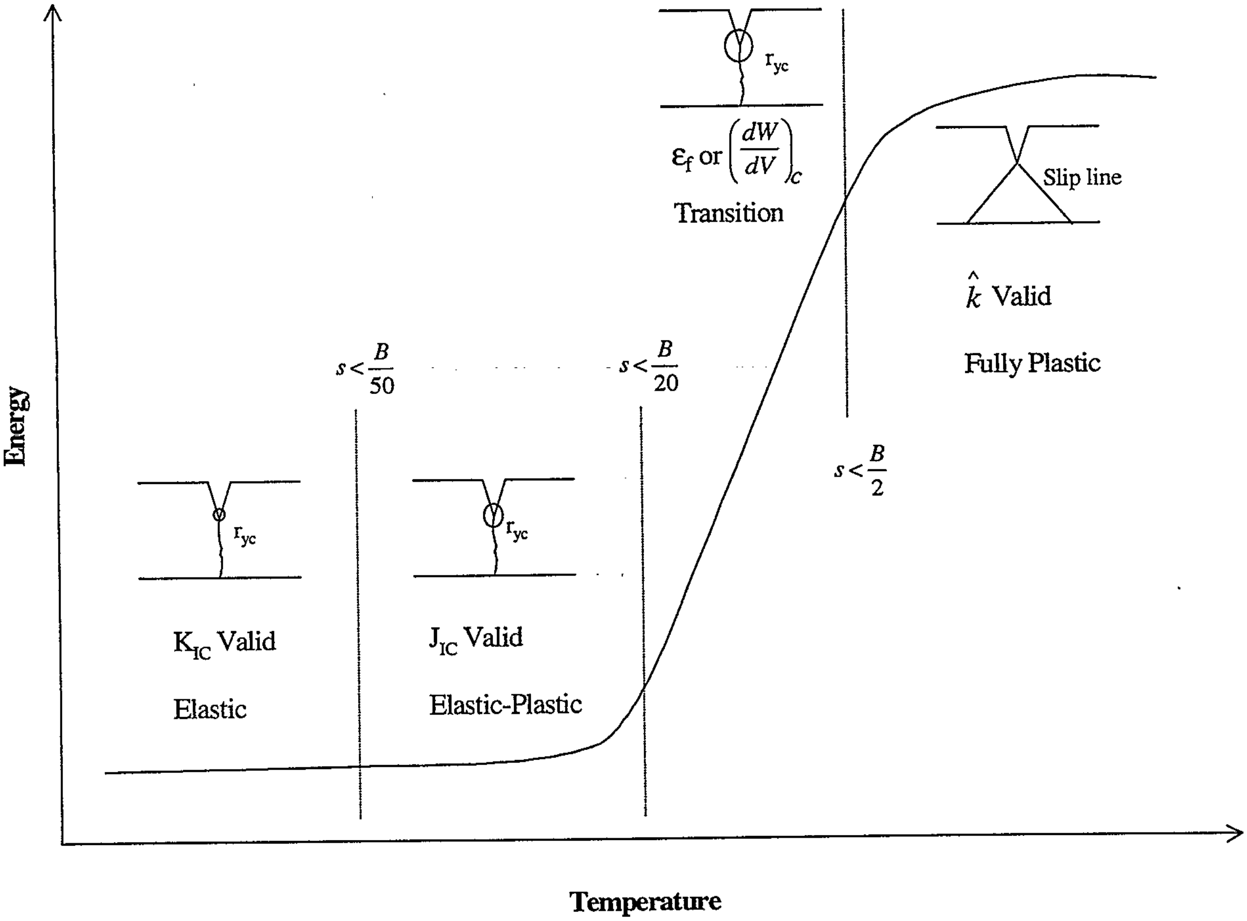

Figure 1. Transition curve.

MATERIAL

The materials mentioned in this paper include three weldments of a CSA G40.21 Gr 350WT steel and a British Grade A steel plate. Table 1a describes these three weldments and Table 1b describes the Grade A steel.

Table 1a. Weldment description for samples tested.

	Weldment #3	Weldment #11	Weldment #12
Base Material	350WT	350WT	350WT
Thickness	8 mm (0.31 in)	12 mm (0.47 in)	12 mm (0.47 in)
Weld Process	SAW	SAW	FCAW
Position	1G Ceramic	1G	1G Ceramic
Joint	SQ	SQ	SV
Root opening	0 mm (0 in)	0 mm (0 in)	6-8 mm (0.24 in)
Root Face	8 mm (0.31 in)	12 mm (0.47 in)	1 mm (0.04 in)
Bevel Details	Square	Square	60° included

Table 1b. Chemical composition of British Grade A Steel.

C	Mn	Si	P	S
0.15-0.16	0.85-0.90	0.20-0.27	0.016-0.025	0.017-0.020

The lower shelf K_{Ic} testing was performed on the three weldments with the worst transition performance in a series of 21 weldments in a materials data base study [1]. The lower shelf K_{Ic} testing was performed on the steel because it exhibited poor transition performance.

DYNAMIC TEAR TRANSITION BEHAVIOUR

The dynamic tear test results for the 3 weldments [1] studied in this paper are shown in Figure 2a. The results for the Grade A Steel, for both T-L and L-T directions, are shown in Figure 2b. For the K tests, the L-T direction was selected. Figures 2a and b are critical since the results helped select temperatures for the fracture toughness tests performed in this work. The dynamic tear tests were completed with ASTM E604 specimens in a drop tower.

From Figure 2a, it is evident that the 3 weldments tested are lower shelf below about 0°C according to the dynamic tear transition curve. It is evident that in the L-T direction, British Grade A Steel at 10 °C is lower shelf according to the dynamic tear transition curve. Does lower shelf mean valid K_{Ic}? This report attempts to answer that question.

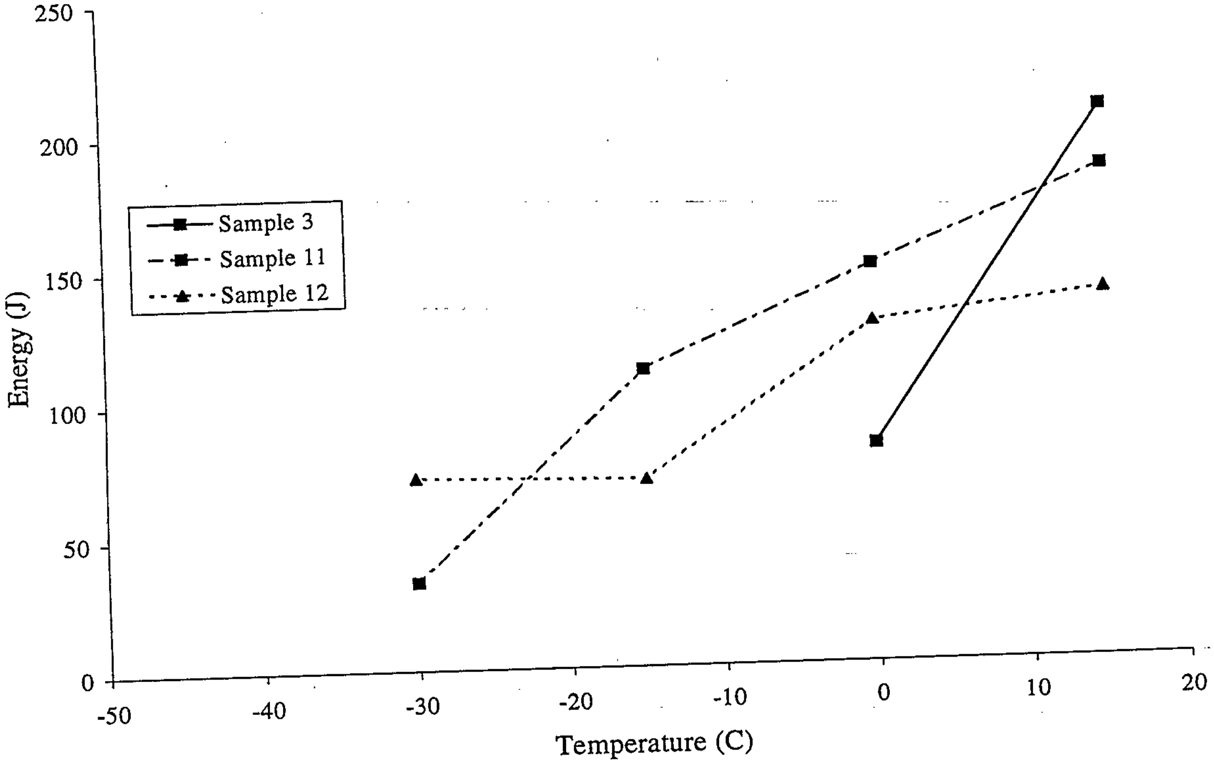

Figure 2a. Dynamic Tear Transition of Simulated Weldments #3, #11 and #12 [1].

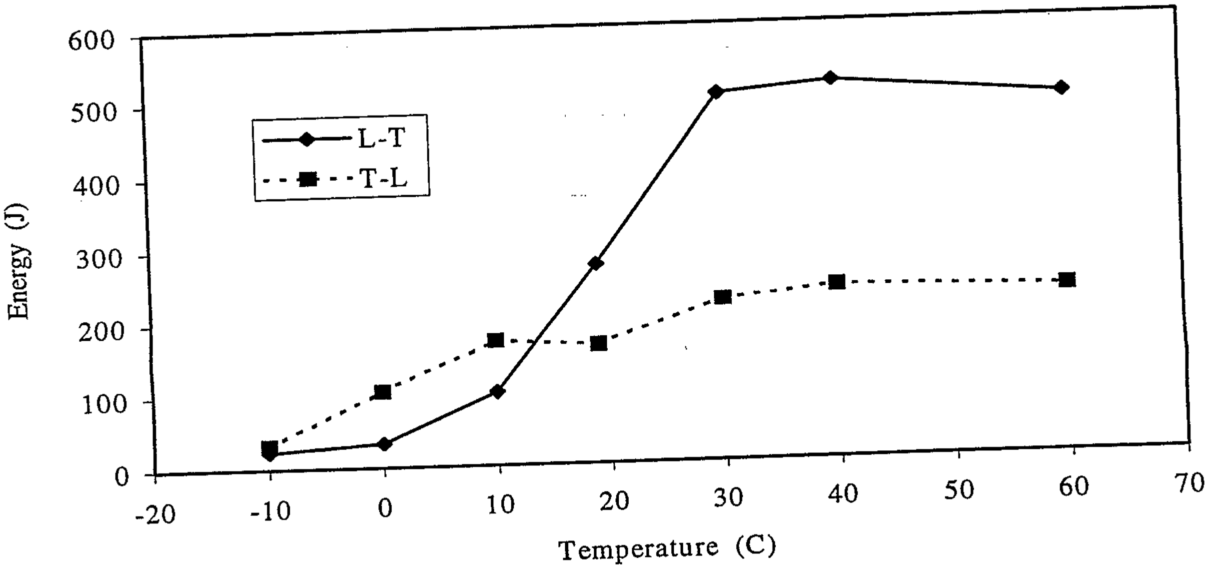

Figure 2b. Dynamic Tear Transition Curve of British Grade A Steel.

PROCEDURE FOR SPECIMEN PRECRACKING

Carefully controlled fatigue precracking [6] was used to obtain reproducible sharp cracks in well defined plastic zones for each K test [4]. Figure 3 represents the parameters for the specimens and also the sample configuration for the 3 point bend test [3].

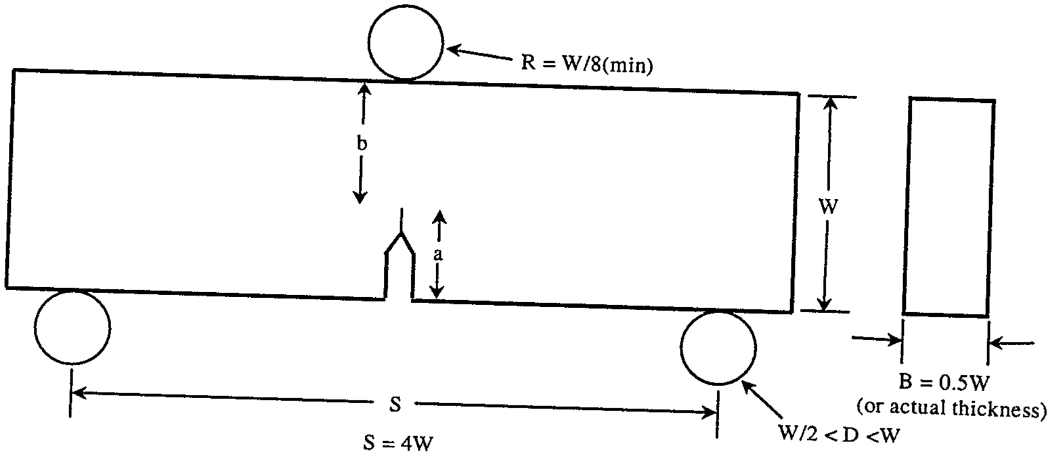

Figure 3. Set up for the 3 point bend with parameter representation.

The parameters of importance are defined as:

P_L	limit load (load at which permanent bending will occur)
a	crack length
W	specimen width
b	uncracked ligament (b = W - a)
B	thickness
σ_Y	yield strength
S	span between bottom rollers (4W)

The load ratio (min load/max load) R=0.1 was used to fatigue all the specimens. A fraction of the load P_L was used during the weldment precracking. For three point bend specimens Equation 1 was used to determine the P_L values [5].

$$P_L = \left[\left(\frac{4}{3} \right) \left(\frac{B b_o^2 \sigma_Y}{S} \right) \right] \qquad (1)$$

The yield strength values for the welds were determined from tensile tests performed by Fleet Technologies Limited [7]. The quasi-static yield stress at 0 °C averaged 469 MPa. The reported yield strength value for the British Grade A Steel is approximately 350 MPa (50.7 ksi). Since the yield strength does not vary much within our temperature testing range, these values were used for all tests.

The values of P_L were calculated for different crack lengths as the crack advances since P_L is crack length dependent. The P_L value had to be evaluated for each sample since the thickness and yield strength varies for each. Detailed information on precracking values can be found in references 6 and 8.

The maximum stress intensity level must not exceed 60% of the K_{Ic} value in the last 2.5 % of the fatigue crack length to have a proper precracking of the sample. If the fatigue level exceeds this value the K_{Ic} will not be valid.

Standard specimens have a crack length, a, equal to the thickness, B (but can be greater), and a/W is between 0.45 and 0.55. The ratio W/B is nominally equal to two [4]. Acceptable alternative samples are $1 \leq W/B \leq 4$. The dimensions for weldment specimen #3 is given in Table 2a. The dimensions for weldment specimens #11 and 12 and the grade A steel are given in Table 2b.

Table 2a. Specimen Dimensions (Weldment #3).

Width (W)		Thickness (B)		Crack Length (a)		Uncracked Ligament (b)	
(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)
40.6	1.6	8.9	0.35	12.7	0.5	27.9	1.1

Table 2b. Specimen Dimensions (Weldments #11 and #12 and grade A steel).

Width (W)		Thickness (B)		Crack Length (a)		Uncracked Ligament (b)	
(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)
40.6	1.6	12.7	0.5	12.7	0.5	27.9	1.1

PROCEDURE FOR FRACTURE TOUGHNESS (K_{IC}) TEST

The test method used for the determination of the plane strain fracture toughness (K_{Ic}) is covered in ASTM E399 [4]. The testing involves notched samples which are precracked in three point bend fatigue loading. During the test of a specimen, the load versus the displacement across the notch is measured. The point at which the load versus the displacement ceases to be linear (P_Q) can be established as the point representing a 2 % increase in crack length. This load is recorded and is used to determine the fracture toughness value. The equations established to calculate the K_{Ic} value are based on elastic stress analysis.

A sharp-crack condition at the tip of the notch had to be present in order to have a valid K_{Ic} test. Therefore the stress intensity level at which the specimen was fatigue cracked had to be limited to a relatively low value.

Specimens were loaded in a testing machine that had a proper fixture in order to minimize the frictional contribution to the measured load. The displacement gauge was installed to indicate the relative displacement of two precisely located gauge positions spanning the crack starter notch mouth [4]. Figure 4 gives a representation of the setup used in the K_{Ic} test.

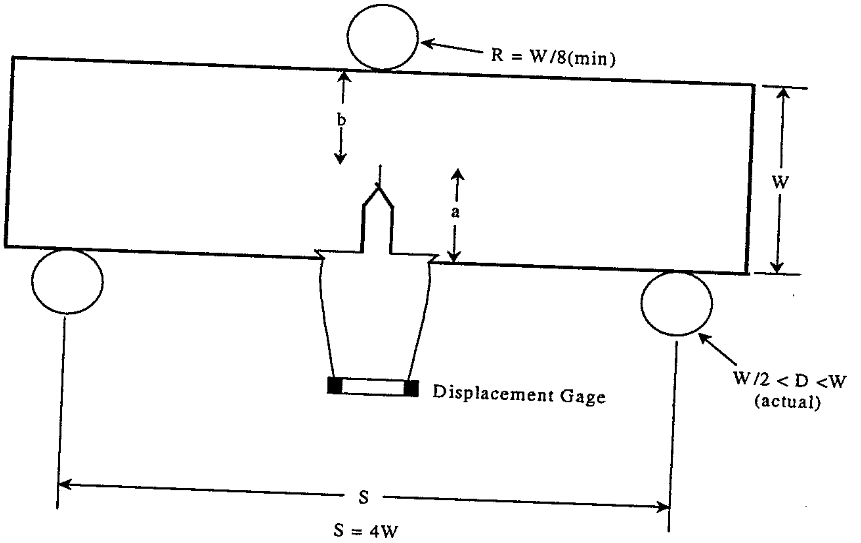

Figure 4. Bend Test Configuration.

Each gauge was checked for linearity using an extensometer calibrator. The gauge employed during the test was provided by Instron and had an initial gauge width of 7.5 mm. It was capable of measuring a displacement, from its initial position, to approximately 3 mm.

In order for the results to be valid Equations 2 and 3 must be satisfied [4]:

$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{YS}}\right)^2 \qquad (2)$$

$$a \geq 2.5\left(\frac{K_{Ic}}{\sigma_{YS}}\right)^2 \qquad (3)$$

where σ_{YS} is the 0.2 % offset yield strength of the material for the temperature and loading rate of the test [4]. Normally, the initial size of the specimen is selected so that valid results will be obtained. For this work the samples were already defined so it therefore remained to verify the results with Equations 2 and 3.

For the calculation of the plane strain toughness three measurements are necessary (B, a and W). The thickness of the three specimens was measured to the nearest 0.025 mm (0.001 in) and the average was calculated; the resulting value was B. The nine crack lengths were measured to the nearest 0.5 % on both sides of each specimen. A difference of more than 10 % on each side of a specimen was unacceptable [4]. Again, the average was calculated; the resulting value was a.

In order to establish if the results from a specimen were valid, it was necessary to calculate conditional results. P_Q is determined graphically from the output collected during the experiment. First, a tangential line is drawn from the linear part of the graph, ensuring it passes through the origin. The slope was then calculated. 95 % of the slope was calculated and was drawn on the same graph and the point at which it crossed the output was identified as P_Q. The procedure to find P_Q is demonstrated in Figure 5.

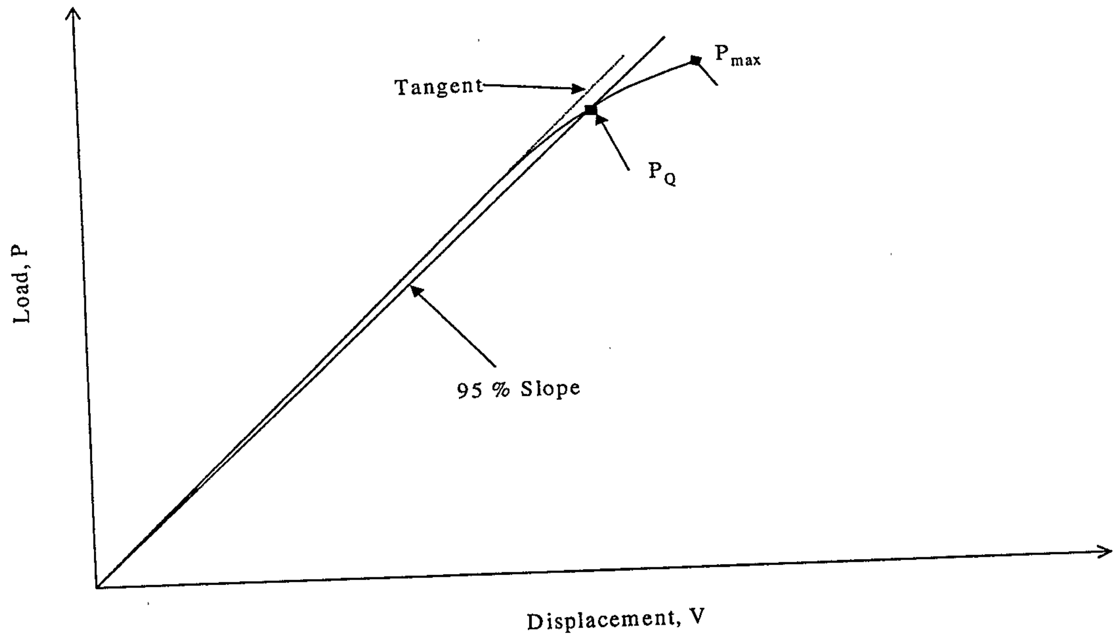

Figure 5. Graphical representation of P_Q.

If the ratio P_{max}/P_Q exceeded 1.1, then the test was not a valid K_{Ic} [4]. If the ratio was less than 1.1 then Equations 2 and 3 were used to confirm the validity of the test. If the test is valid then K_Q is equal to K_{Ic}. Accordingly, the plane strain fracture toughness, K_{Ic}, was calculated using Equations 4 and 5 [4].

$$K_Q = \left(\frac{P_Q S}{B W^{3/2}}\right) \cdot f\left(a/W\right) \qquad (4)$$

$$f\left(a/W\right) = \frac{3\left(a/W\right)^{1/2}\left[1.99 - \left(a/W\right)\left(1 - a/W\right) \cdot \left(2.15 - 3.93\,a/W + 2.7\,a^2/W^2\right)\right]}{2\left(1 + 2\,a/W\right)\left(1 - a/W\right)^{3/2}} \qquad (5)$$

The shear lip was also measured [9] for each sample at closest point of contact (x) of the two lips.

$$s = \frac{B - x}{2} \qquad (6)$$

SHEAR LIP SIZE AND CRITICAL PLASTIC ZONE SIZE

The critical plastic zone size (r_{Yc}) can be calculated with Equation 7 to give the size of the plastically deformed zone.

$$r_{Yc} = \frac{1}{6\pi}\left(\frac{K_{Ic}}{\sigma_Y}\right)^2 \qquad (7)$$

In order to have a valid test it is well known that a, b, and B must be greater than 50 times the critical plastic zone radius. For the plane strain case, Equation 8 shows that Equation 2 is found again.

$$a, b, B \geq \frac{50}{6\pi}\left(\frac{K_{Ic}}{\sigma_Y}\right)^2 = 2.5\left(\frac{K_{Ic}}{\sigma_Y}\right)^2 \qquad (8)$$

According to Matthews [9], it is estimated that the shear lip size, s, is approximately equal to the critical radius, r_{Yc}, in the elastic range. Using the previous relationship in Equation 8, it is therefore possible to establish Equation 9 as a requirement for a valid plane strain test.

$$s < \frac{B}{50} \qquad (9)$$

FRACTURE TOUGHNESS (K_{IC}) TEST RESULTS

The fatigued weldments were tested in the CO_2 cold chamber at various temperatures to give broad results in the elastic-plastic zone. The specimens were preloaded to 200 kg to ensure that the clip gauge was properly set in.

It was verified experimentally that one hour was sufficient time to assure that the core temperature was equal to the ambient chamber temperature at -40 °C.

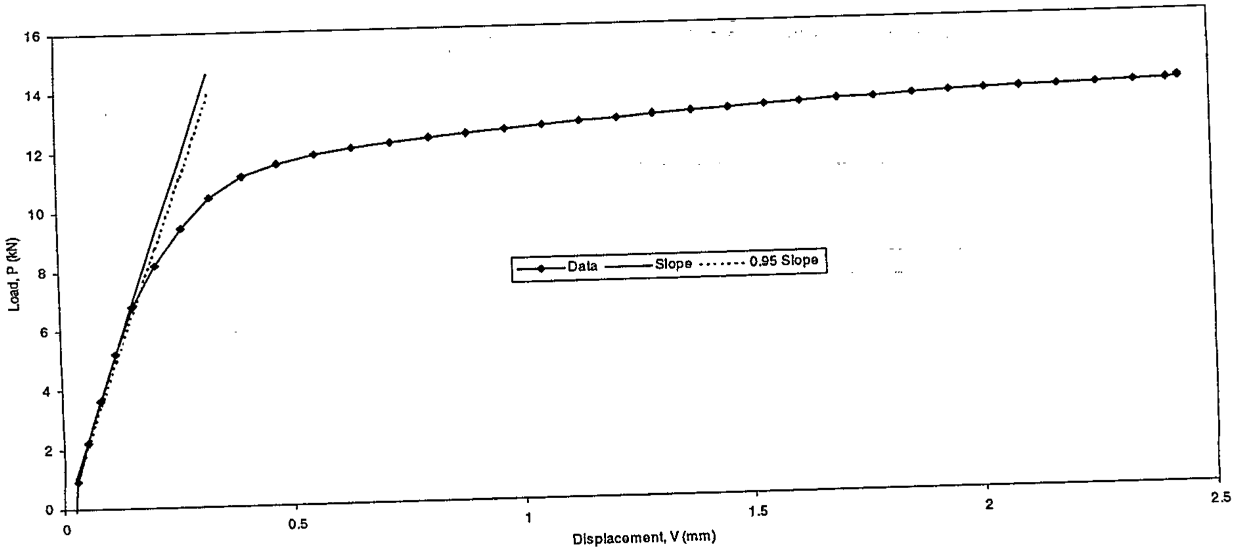

Figure 6a. Weldment #3 at Room Temperature (18 °C).

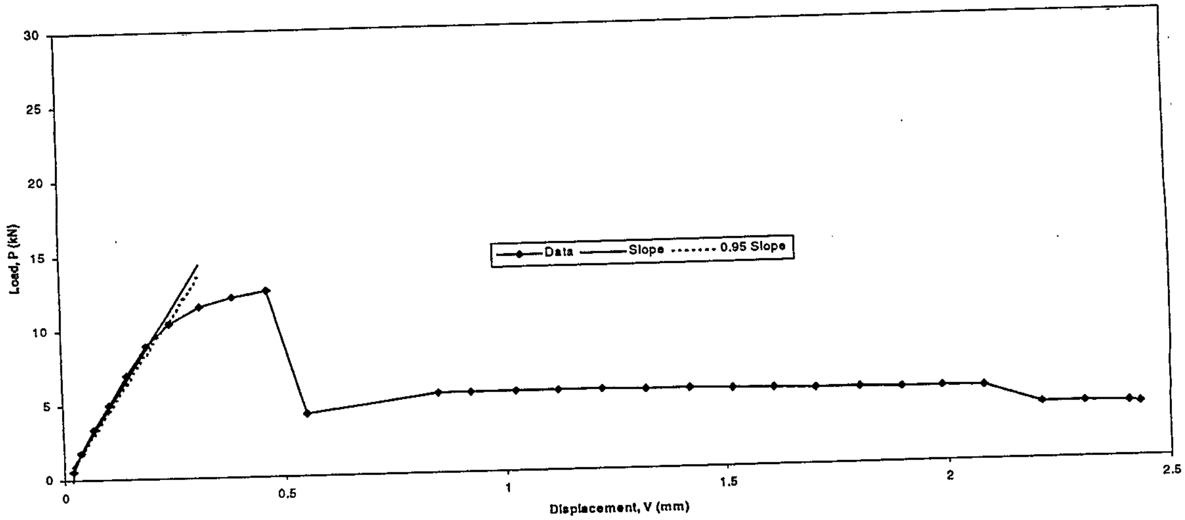

Figure 6b. Weldment #3 at -20 °C.

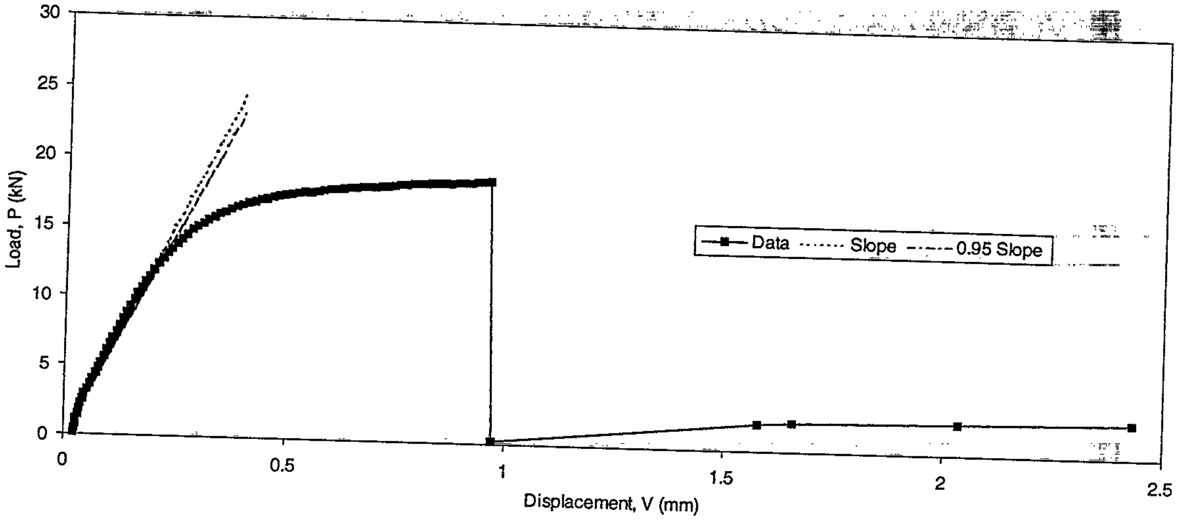

Figure 6c. Weldment #3 at -40 °C.

Figures 6a, b and c show the load in kilonewtons versus displacement in millimeters at various temperatures. The displacement V is the clip gauge opening. Two slopes are shown on each graph; the slope of the initial data points and the second slope 95% of that value. Also, the information in Table 3a was gathered from Figures 6a to c.

Table 3a. Calculated results from Weldment #3

Temperature (°C)	18	-20	-40
a/W	0.54	0.55	0.49
P_Q (kN)	7.25	10.0	13.1
P_{max} (kN)	13.5	12.5	18.8
P_{max}/P_Q	1.86	1.25	1.44
K_Q (MPa $m^{1/2}$)	49.2	69.4	76.3
$2.5(K_Q/\sigma_y)^2$ (mm)	27.6	54.7	66.2
B/50 (mm)	0.178	0.178	0.178
s (mm)	4.5	0.75	0.36

From the results at 18, -20 and -40 °C it is obvious that the tests were not valid K_{Ic}. The P_Q and P_{max} ratio, as shown in Table 3a, exceeds the allowed value in the ASTM standard. Weldment #3 displayed no ductility at -20 °C and below. This indicates that the material should have behaved elastically.

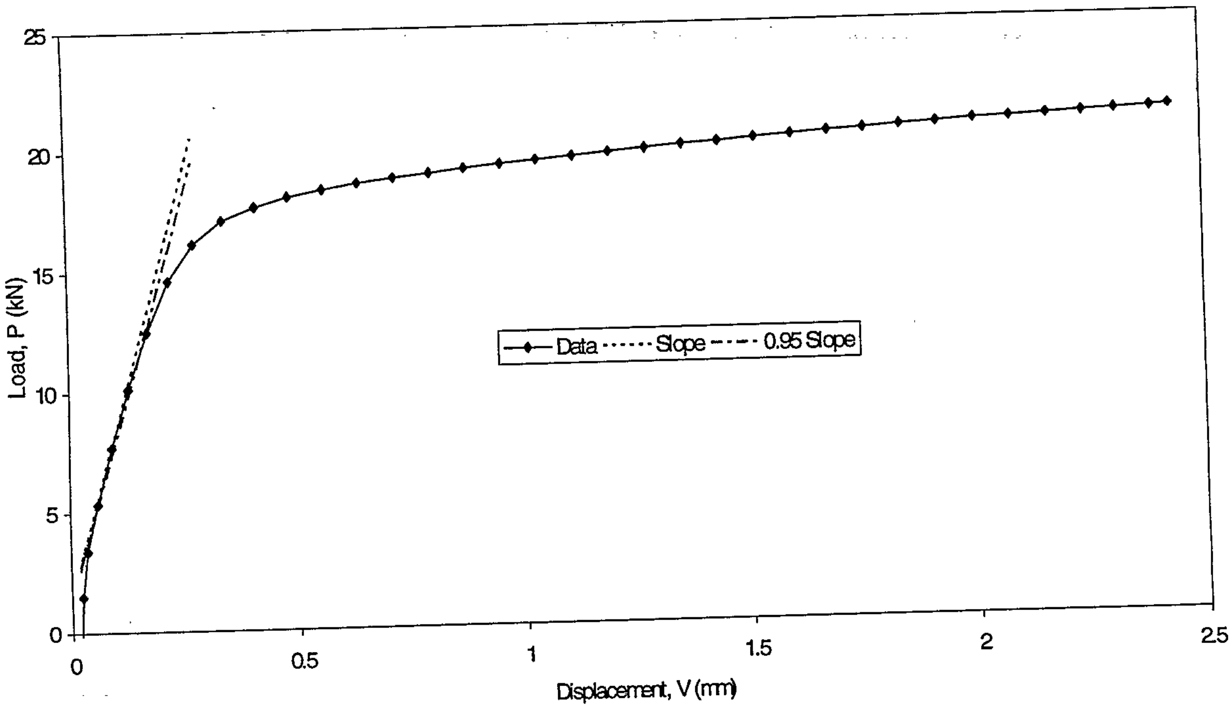

Figure 7a. Weldment #11 at Room Temperature (18 °C).

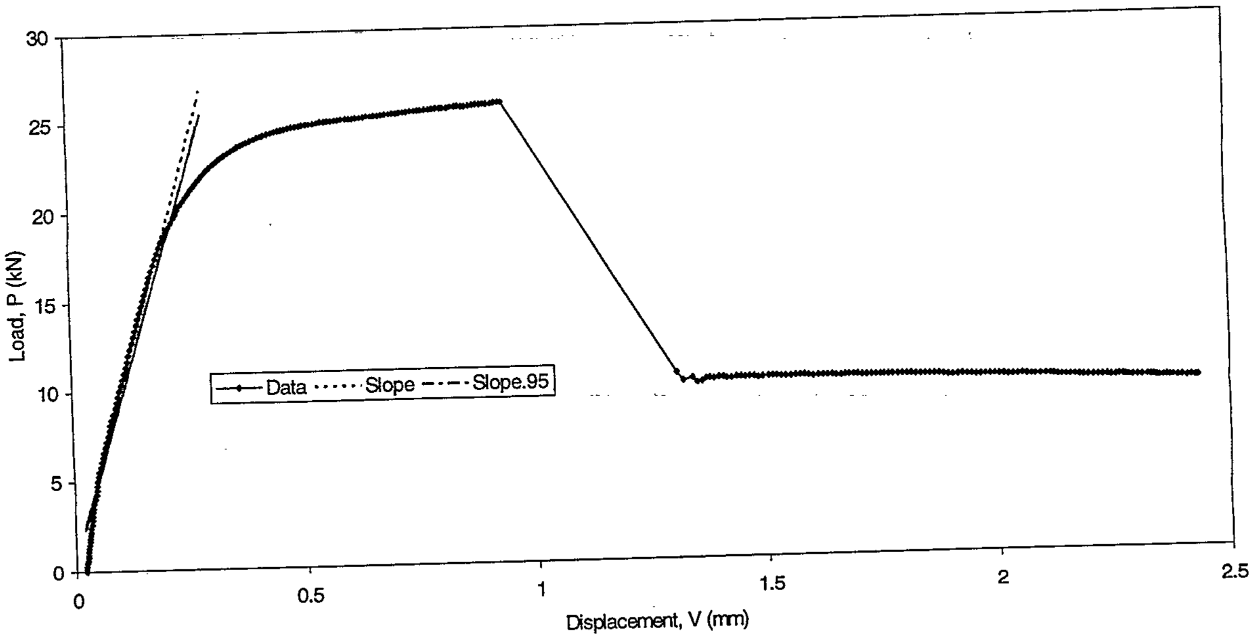

Figure 7b. Weldment #11 at -20 °C.

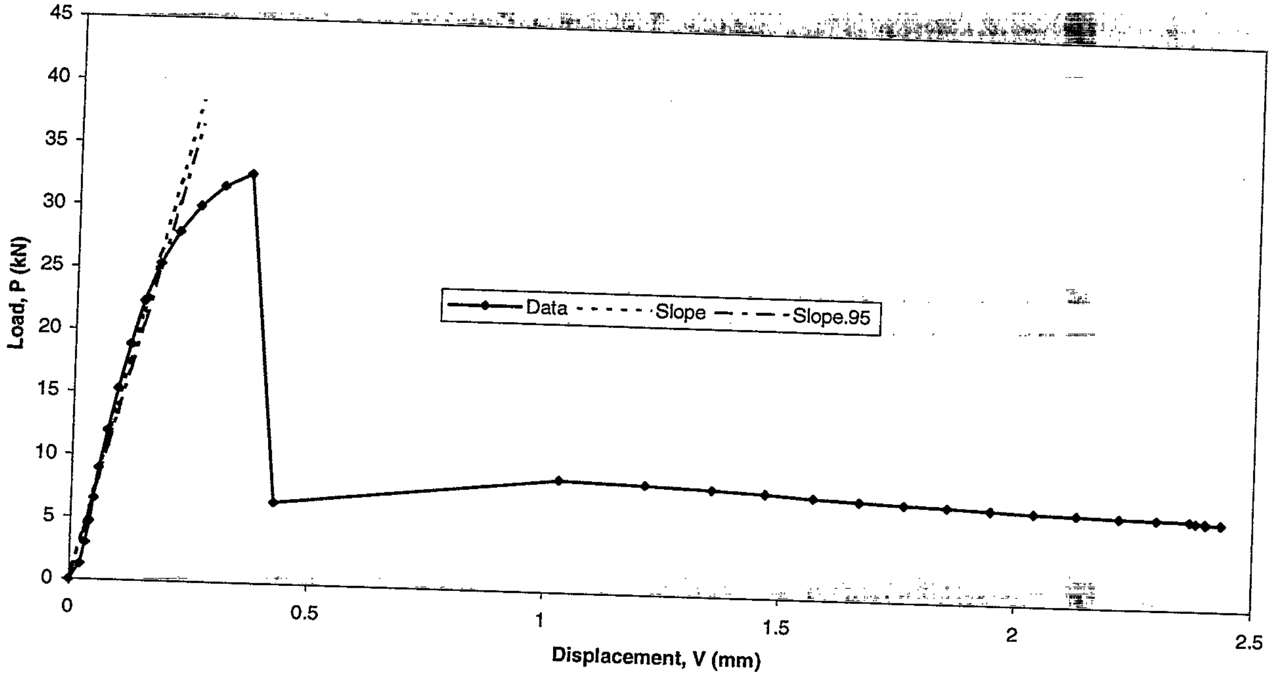

Figure 7c. Weldment #11 at -40 °C.

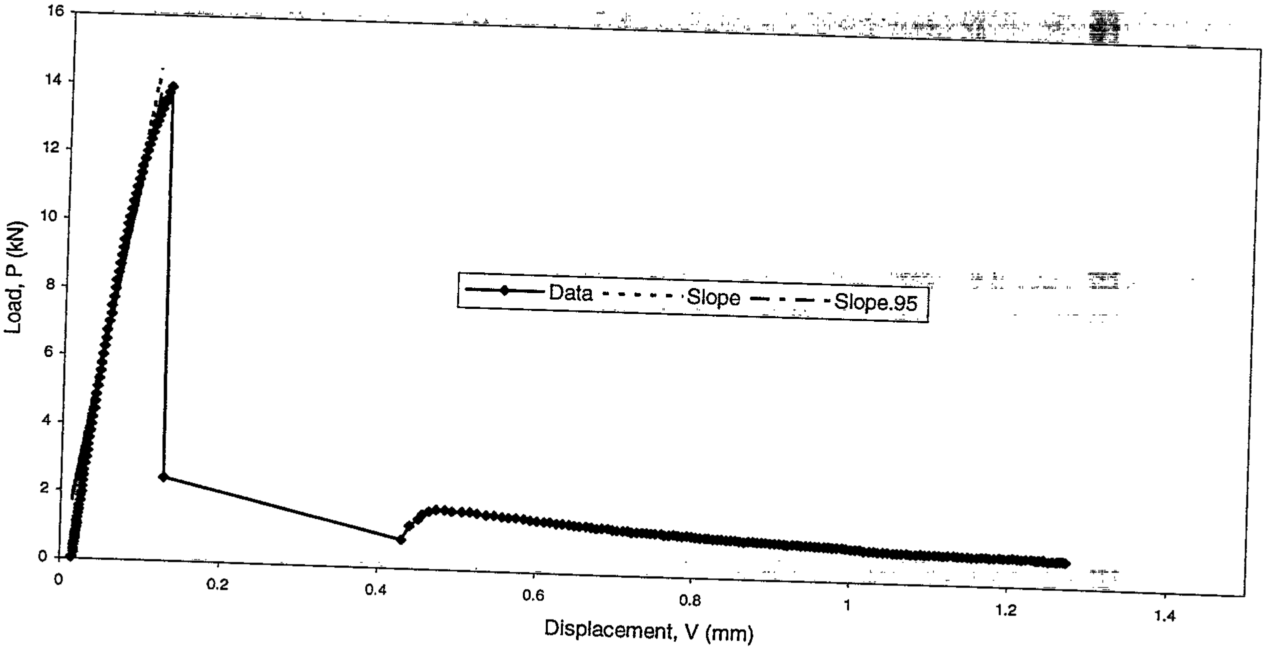

Figure 7d. Weldment #11 at -45 °C.

Figures 7a, b, c and d show the load in kilonewtons versus displacement in millimeters at various temperatures for Weldment #11. The displacement V is the clip gauge opening. Two slopes are shown on each graph; the slope of the initial data points and the second slope is 95% of that value. Also, the information in Table 3b was gathered from Figures 7a to d.

Table 3b. Calculated results from Weldment #11

Temperature (°C)	18	-20	-40	-45
a/W	0.53	0.47	0.43	0.41
P_Q (kN)	12.5	19.2	25.5	12.7
P_{max} (kN)	21	25.8	32.71	13.9
P_{max}/P_Q	1.7	1.3	1.3	1.1
K_Q (MPa $m^{1/2}$)	59.3	76.2	89.4	41.8
$2.5(K_Q/\sigma_y)^2$ (mm)	40.0	66.0	90.9	19.8
B/50 (mm)	0.244	0.244	0.244	0.244
s (mm)	4.45	1.0	0.64	0.3

From the results at 18, -20 and -40 °C it is obvious that the tests were not valid K_{Ic}. The P_Q and P_{max} ratio, as shown in Table 3b, exceeded the allowed value in the ASTM standard. Weldment #11 displayed no ductility at -20 °C and below. This indicates that the material should have behaved elastically. The fatiguing on the weldments at -40 and -45 °C did not meet the standard's requirements for shape but at -45 °C, the weldment displayed a fully elastic behaviour and met the P_Q and P_{max} ratio of 1.1.

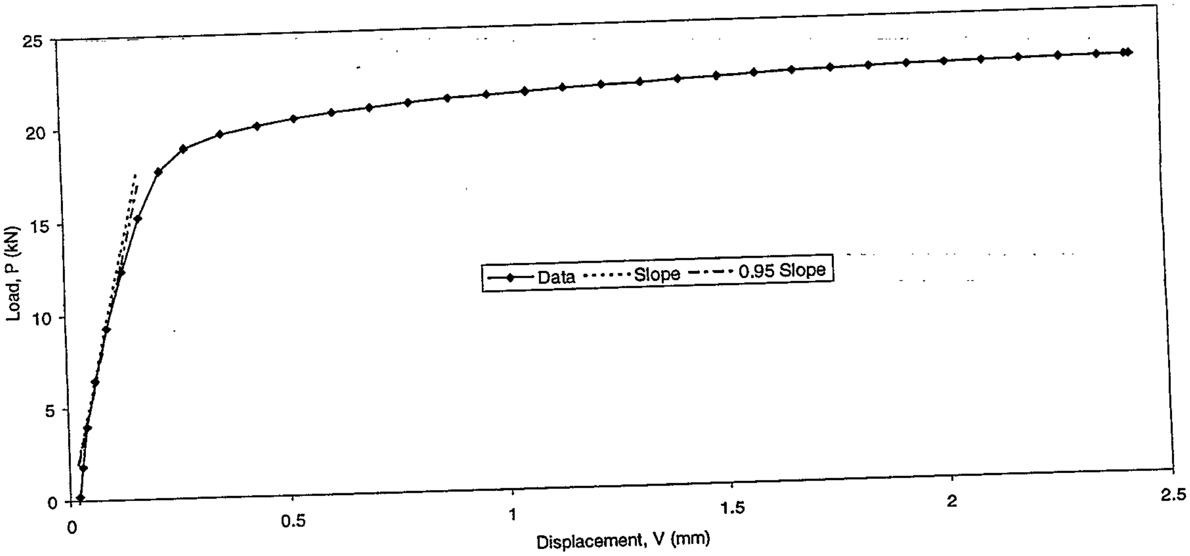

Figure 8a. Weldment #12 at Room Temperature (18 °C).

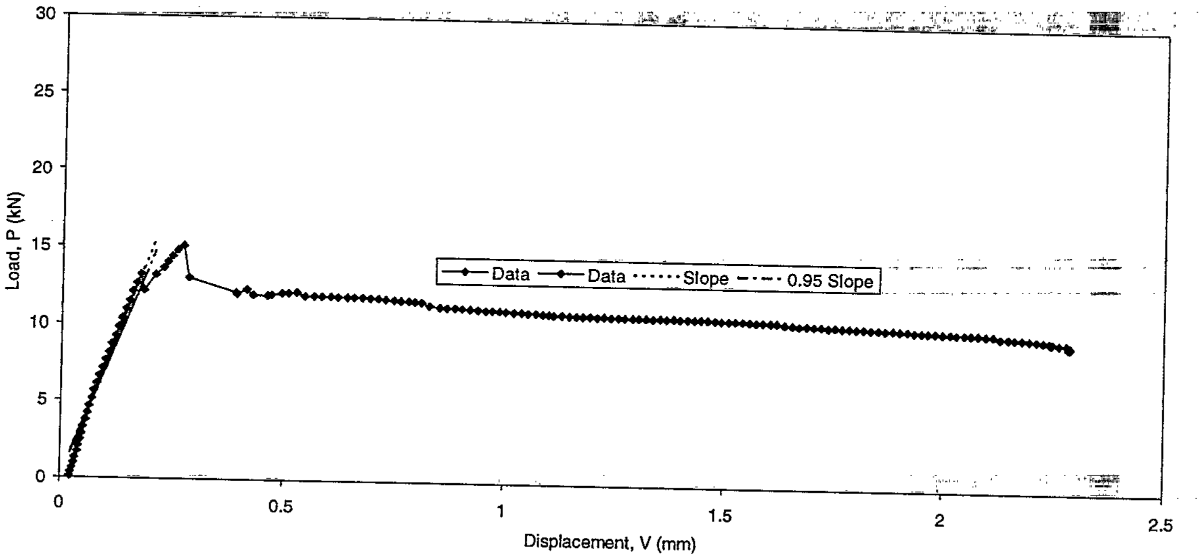

Figure 8b. Weldment #12 at -30 °C.

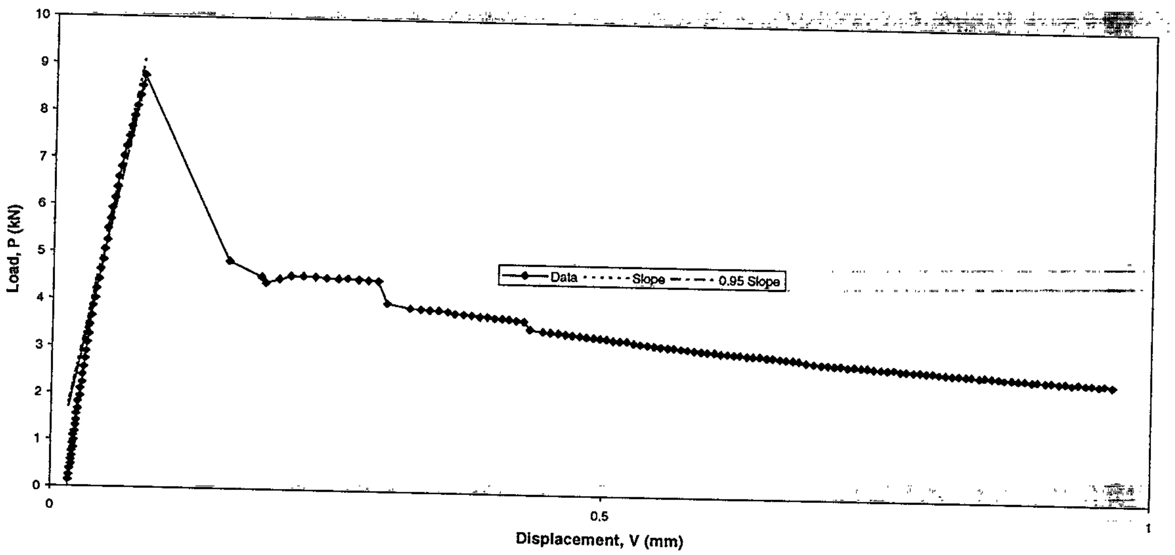

Figure 8c. Weldment #12 at -45°C.

Figures 8a, b and c show the load in kilonewtons versus displacement in millimeters at various temperatures for Weldment #12. The displacement V is the clip gauge opening. Two slopes are shown on each graph; the slope of the initial data points and the second slope is 95% of that value. Also, the information in Table 3c was gathered from Figures 8a to c.

Table 3c. Calculated results from Weldment #12

Temperature (°C)	18	-30	-45
a/W	0.49	0.51	0.42
P_Q (kN)	9.2	13.2	8.0
P_{max} (kN)	22.5	15.1	8.7
P_{max}/P_Q	2.5	1.14	1.1
K_Q (MPa $m^{1/2}$)	39.1	58.5	27.3
$2.5(K_Q/\sigma_y)^2$ (mm)	17.6	39.4	8.6
B/50 (mm)	0.244	0.244	0.244
s (mm)	2.7	1.9	0.45*

*At a/W = 0.5. At a/W = 0.7, the shear lip size was 1.54mm.

From the results at 18 and -20 °C it is obvious that the tests were not valid K_{Ic}, according to the ASTM standard. The P_Q and P_{max} ratio, as shown in Table 3c, exceeds the allowed value in the ASTM standard, although not much in the case at -30 °C. Weldment #12 displayed no ductility at and below -30 °C, and except for crack shape met the validity requirements at -45 °C.

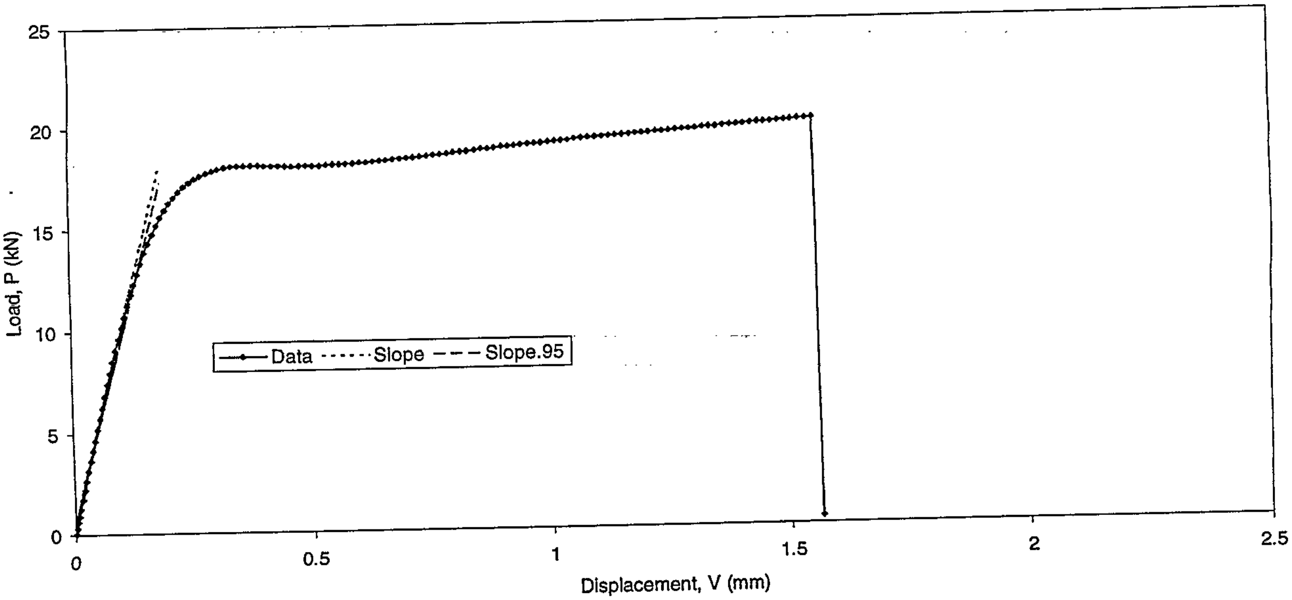

Figure 9a. Steel Specimen #15 at –40 °C.

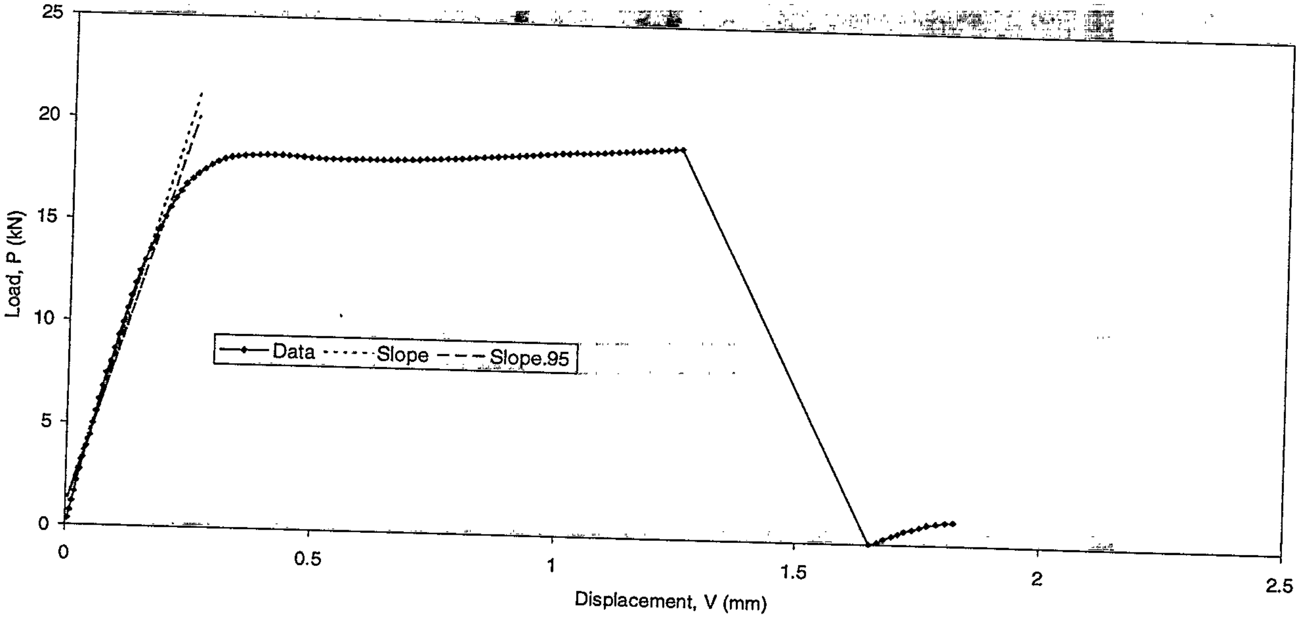

Figure 9b. Steel Specimen #18 at -55 °C.

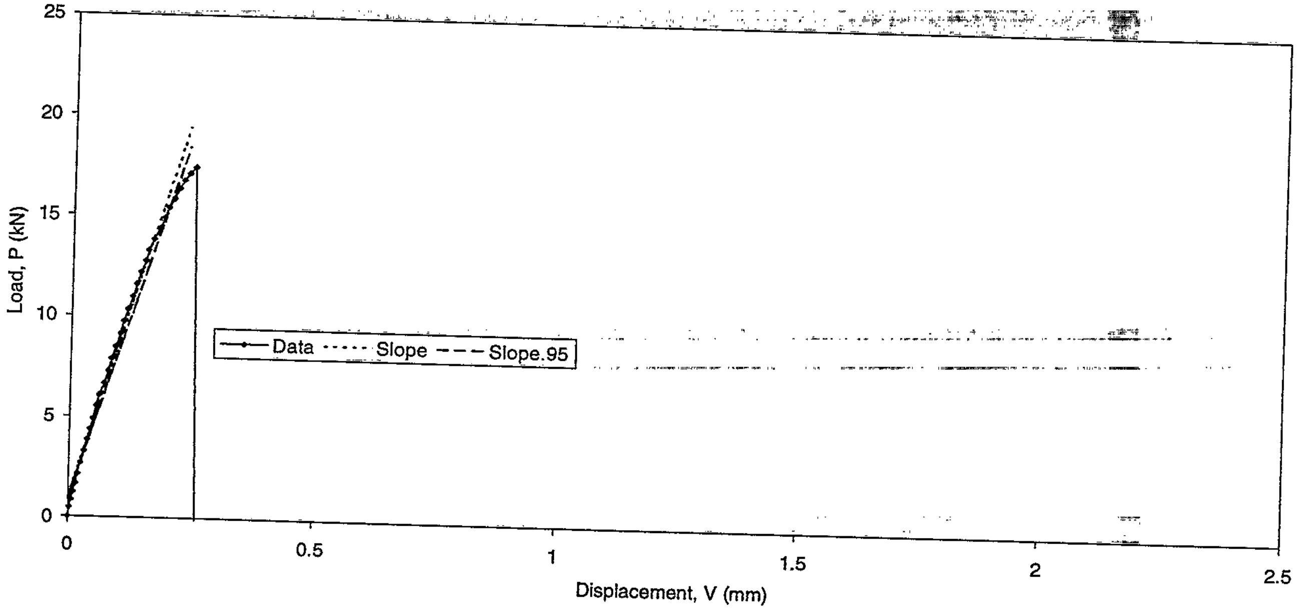

Figure 9c. Steel Specimen #17 at -65 °C.

Figures 9a, b and c show the load in kilonewtons versus displacement in millimeters at various temperatures for the Grade A steel. The displacement V is the clip gauge opening. Two slopes are shown on each graph; the slope of the initial data points and the second slope 95% of that value. Also, the information in Table 4 was gathered from Figures 9a to c.

Table 4a. K_Q vs Temperature results for British Grade A Specimens.

Temperature (°C)	-70	-65	-55	-40	-20	0
K_Q	52.6	63.4	62.4	51.0	48.7	48.6

Table 4b. Detailed results from select British Grade A specimens (near inflection point).

Temperature (°C)	-40	-55	-65
a/W	0.46	0.48	0.48
P_Q (kN)	13.5	15.6	15.9
P_{max} (kN)	20.1	19.1	17.4
P_{max}/P_Q	1.49	1.22	1.10
K_Q (MPa $m^{1/2}$)	51.0	62.4	63.4
$2.5(K_Q/\sigma_y)^2$ (mm)	53.2	79.5	82.2
B/50 (mm)	0.25	0.25	0.25
s (mm)	0.42	0.33	0.04

From the results at -40 and -55 °C it is obvious that the tests were not valid K_{Ic}. The P_Q and P_{max} ratio, as shown in Table 4b, exceeded the allowed value in the ASTM standard. British Grade A displayed no evident ductility except for a small band near the fracture initiation area at -40 and -55 °C. At -65 °C, the band was non-existent, which perhaps explains the lower P_{max}/P_Q ratio and why the specimen displayed a fully elastic behaviour.

VALIDITY OF PLANE STRAIN FRACTURE TOUGHNESS RESULTS

According to [9], shear lip size, s, is approximately equal to the critical radius, r_{Yc}, in the data range. Based on this relationship, Equation 9 can be a criteria to determine the validity of a test. Tables 5a and b evaluate B/50 and give the results on the Equation 9 criteria.

Table 5a. Validity of Plane strain Fracture Toughness Based on Shear Lip Size for Weldments.

Weldments	Temperature (°C)	Shear Lip Size (mm)	B/50 (mm)	$S \leq B/50$
#3	18	4.5	0.178	NO
	-20	0.75		NO
	-40	0.36		NO
#11	18	4.45	0.244	NO
	-20	1.0		NO
	-40	0.64		NO
	-45	0.3		YES*
#12	18	2.7	0.244	NO
	-30	1.9		NO
	-45	0.45		NO

* Within 20% of B/50.

Table 5b. Validity of Plane Strain Fracture Toughness Based on Shear Lip Size for Steel.

Specimens	Temperature (°C)	Shear Lip Size (mm)	B/50 (mm)	$s \leq B/50$
Steel 15	-40	0.42	0.25	NO
Steel 18	-55	0.33		NO
Steel 17	-65	0.04		YES

DISCUSSION

There is some ambiguity in the E399 standard for line construction used to determine P_Q. Determining the correct secant line through the origin is very difficult when the initial slope is curved. It is stated in the ASTM standard that the slope has to be determined with high precision. This of course is essential to obtain meaningful results. The results can vary greatly as a function of choice of line position and it was chosen for this report to be conservative with the choice of the secant line positioning, passing close to the origin.

It is well known that by making thicker (larger B) specimens constraint and brittleness is increased. This was verified with Weldments #11 and #12 when they were compared with Weldment #3. This fact was also confirmed by using the B/50 ratio to evaluate the validity of plane strain fracture toughness. As shown in Table 5a, the size of the shear lips required for a valid test with Weldment #3 are much smaller than with Weldments #11 and #12.

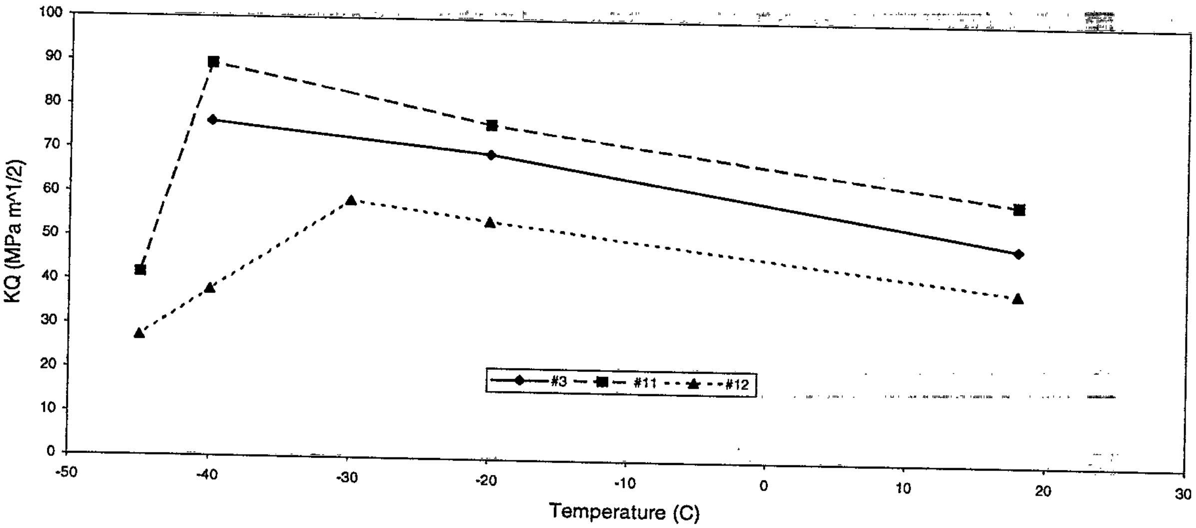

Figure 10a. K_Q Results as a Function of Temperature for the Weldments.

The plot of K_Q with temperature, Figure 10a, shows increasing K_Q with decreasing temperature until the point of inflection is reached. Below this point the K_Q value decreases. At -45 °C, Weldments #11 and #12 both displayed valid or very near valid testing. This suggests that for a temperature colder than the inflection point the test is valid. For a temperature warmer than the inflection point the test is not valid and is indicative of testing outside the valid range. What is seen is a phenomenon of size effect and decreasing constraint opposing one another.

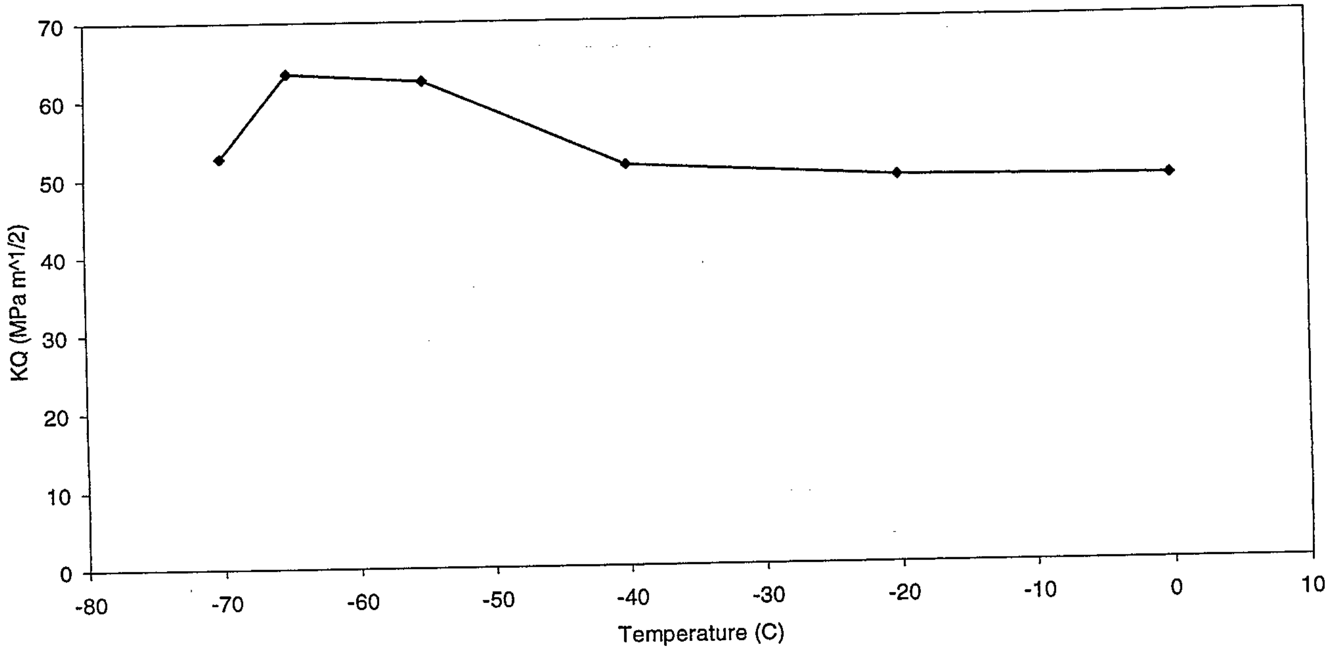

Figure 10b. K_Q Results as a Function of Temperature for the Steel.

The plot of K_Q with temperature, Figure 10b, for the steel, also shows increasing K_Q with decreasing temperature until the point of inflection is reached. Below this point the K_Q value decreases. At -65 °C, Specimen #17 displayed a valid K_{Ic} test. This suggests, as in the case for the weldments above, that for a temperature colder than the inflection point the test is valid. For a temperature warmer than the inflection point the test is not valid and is indicative of testing outside the valid range.

The goal, as depicted in Figures 10a and b, is to decrease testing temperature until elastic conditions prevail and a valid K_{Ic} result occurs. When this point is reached the maximum valid K_{Ic} value is found and the K_{Ic} value will decrease thereafter as the test temperature is lowered.

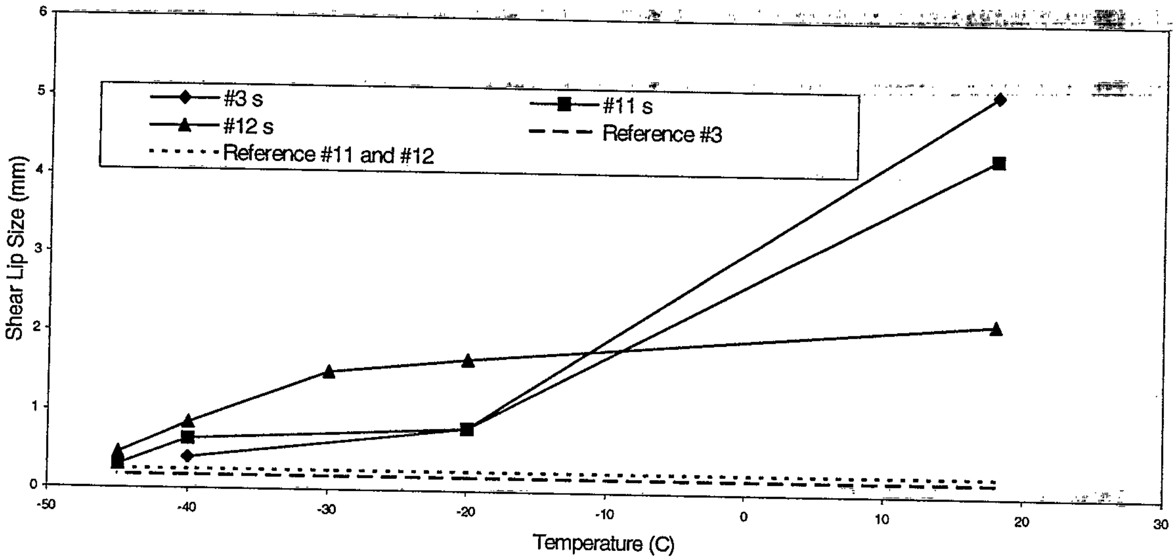

Figure 11a. Shear Lip Size as a Function of Temperature from K Tests on the Weldments.

The results of Figure 11a clearly show the decreasing toughness and increasing constraint with lowering temperature. It also shows that it was not possible to get a valid plane strain toughness test above a temperature of -45°C. At that temperature the shear lip sizes of Weldments #11 and #12 reached or were very close to their respective reference levels (B/50 lines). Using the B/50 reference lines, the test becomes valid at -45°C.

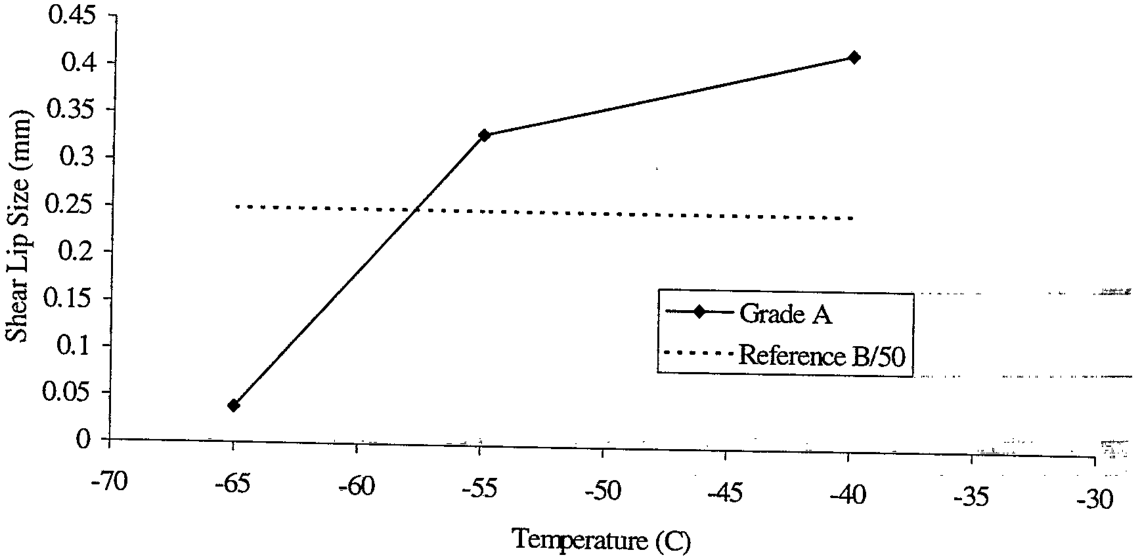

Figure 11b. Shear Lip Size as a Function of Temperature from the K Tests on the Steel.

The results of Figure 11b clearly show the decreasing toughness with lowering temperature (smaller shear lips equate to smaller plastic zones which give rise to greater constraint). It also shows that it was not possible to get a valid plane strain toughness test above a temperature of -55°C. At -65 °C the shear lip size of Specimen #17 was smaller than the reference level (B/50 dashed line). Using the B/50 reference line, the test becomes valid at -57°C.

CONCLUSIONS

1. The transition curve is a useful guide to establish a temperature range where a valid plane strain test will exist. Lower shelf is not necessarily plane strain.

2. The method suggested in reference [9] to estimate the critical plastic zone size from shear lip size seems very dependable. Using this relationship it is possible to establish a new criteria for a valid plane strain test.

$$s < \frac{B}{50} \qquad (9)$$

3. The measured stress intensity at fracture, K_Q, only becomes a valid K_{Ic} at a temperature below the inflection point on the K_Q versus temperature graph.

4. The technique proposed in the ASTM standard [4] to determine P_Q is imprecise.

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