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FRACTURE PROPERTIES OF GRADE 'A' SHIP PLATE

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SUMMARY

A programme of work was undertaken to generate fracture property data, including a measure of the degree of scatter, from as rolled ship plate material, nominally Lloyd's Grade 'A', representing the lower end of the Charpy toughness spectrum. This was in response to concerns regarding the safety of sea going vessels, particularly when an extension of the service life is envisaged or a change of use, for example to offshore production or storage vessels, is considered which would require structural integrity assessments.

Seven plates, which were not necessarily certified Grade A plates but were offered by stockists as suitable alternatives, were examined. The selection was dictated by the desire to include plates at the lower end of the toughness spectrum. These, therefore, originated from a number of steel suppliers and had widely differing chemistries.

The test certificates did not always reflect the actual chemistries or mechanical properties. Some of the plates exhibited strength levels which were outside the limits for Grade A. All of the plates were homogeneous and the material properties were not influenced by sampling positions.

In general there is no minimum Charpy impact energy value specified for Grade A, although the 1997 amendments to the Lloyd's Register rules and regulations for Classification of Ships now include a Charpy impact energy requirement for Grade A plates of 27 J in the longitudinal direction and 20 J in the transverse direction at +20°C. The Charpy impact energy for the plates in this current test programme exceeded 27 J at +20°C in both orientations.

Pellini Drop weight tests were carried out on some of the plates, fully recognising that three of the four plates were less than the minimum plate thickness covered by the Drop Weight test standard thus yielding non-standard specimens.

The fracture toughness of four plates was measured using high loading rate and results compared with the criterion, proposed by Sumpter, that the toughness K_{mat} must exceed a value of 125 MPa√m at a loading rate of 10^4 MPa√m/s or higher at a test temperature reflecting operating conditions for ships. Three plates with thickness up to 15 mm had adequate toughness such that K_{mat} exceeded the minimum stated above at a test temperature of -10°C which is the minimum operating air temperature for the North Sea. The only 20 mm thick plate in this study failed to meet the minimum toughness level as described above.

The effect of strain ageing treatment on toughness properties was measured on one plate and the Charpy toughness of strain-aged specimens was, as expected, worse than the corresponding parent plate material with the 50% FATT approximately 50°C higher.

The effect of welding on HAZ toughness was studied by applying thermal simulation treatment. The coarse grained HAZ was simulated by using single cycle thermal treatments corresponding to nominally 1.5 and 5.0 kJ/mm heat input welds and the toughness was characterised by the Charpy impact toughness test. 50% FATT increased by up to 15°C for the lower heat input and 40°C for the higher heat input welds for the two plates studied. It is likely that this will be the worst case view of the toughness compared to this region in a real weld because the thermally simulated specimens contain uniform microstructure of low toughness through the specimen cross-section. A specimen taken from a real weld is likely to contain a mixture of microstructure ranging from low to relatively high toughness.

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1. INTRODUCTION

Grade 'A' steel is the most common grade of ship plate used in the construction of merchant ships. However Charpy impact energy and fracture toughness data are not generally available for this grade mainly because it is not generally required to meet a Charpy toughness specification. (Note: This changed in 1997 when Lloyd's Register rules and regulations for Classification of Ships were amended to include a Charpy impact energy requirement of 27 J in the longitudinal direction and 20 J in the transverse direction at +20°C for Grade A plates). There are many ships now in use which are beyond their original design life and consequently may contain an increasing number and size of defects which may initiate a catastrophic fracture. In these circumstances the base toughness of steel plate is an important consideration and raises concerns about the safety of sea going vessels. The toughness of the plate used in the fabrication of such vessels is one of the principal areas of concern.

In recent years some sea-going vessels have been subjected to a change of use to floating production storage and offloading (FPSO) vessels for oil field development. This involves the ships being moored in the vicinity of an offshore production platform which has the effect of changing the wave loading pattern on the ship as it is subjected to wave impact from predominantly one direction instead of the more random loading pattern which arises from normal use. This change in loading pattern will also have an effect upon the applied stresses and therefore the structural integrity of the vessel.

2. BACKGROUND

In order to address the concerns noted above, a literature review of the fracture properties of Grade A ship plate was carried out and reported(1). The principal objectives of the review were to:-

- review the concepts of fracture control in ship structures.
- review the available data on the fracture properties of Grade A ship plate in terms of fracture initiation (Charpy toughness, fracture toughness) and fracture propagation resistance (Pellini Nil Ductility Transition Temperature, Drop weight tear test).
- provide recommendations on the minimum requirements for fracture control plans.

This review found a significant variability in the fracture initiation toughness of Grade A plates although the level of toughness was considered generally adequate. The crack arrest toughness for these plates appeared to be less variable but the review concluded that it was probably insufficient to guarantee structural integrity in the event of the initiation of a large fast running crack.

As noted above the amount of fracture toughness data on Grade A is very limited and do not fully address the concerns associated with the use of ship structures for offshore oil production and storage.

A programme of work was undertaken to build upon the data currently available and to further study the variability of toughness within a plate. The aim of the programme was to generate mechanical property and fracture data from steel plates which conform, in general terms, to the Grade A ship plate requirements manufactured by a variety of steel producers. It was thought that this approach would not only permit the evaluation of the effect of different steel-making and processing conditions but would also provide an indication of the lower bound toughness values relevant to such steels.

The work was carried out at Swinden Technology Centre, British Steel and the University of Gent, Belgium and has been funded by Lloyds Register of Shipping and the Offshore Division of the Health and Safety Executive. Full details of the work have been reported elsewhere(2,3) and the current report is a synthesis of these data with some additional analyses.

3. MATERIALS

Seven plates, originating from different countries, were purchased from stockholders. The plate details are given in Table 1 and each plate has been ascribed a letter which is used throughout the report to identify that plate.

A desired aim of the project was to investigate plates with toughness at the lower end of the spectrum for this grade of steel. It was thought that restricting the search to pedigreed Grade A plates may not unearth such plates within the envisaged time-scale with the available resources. By including other plates in the search which, on the basis of information given in the associated tests certificates, met the composition and the mechanical property requirements of Grade A without being classified as such, it was possible to select plates with varying steel chemistries from a variety of steel producers.

4. TEST PROGRAMME

The following tests were carried out at several locations on plates in order to evaluate the variability in properties. The test positions for all of the plates are listed in Table 2.

- Chemical analysis.
- Tensile testing to EN10002-1 (1990) in both the transverse and longitudinal (relative to the plate rolling direction) directions.
- Longitudinal and transverse Charpy tests to EN 10045-1 (1992). These tests were used to establish ductile - brittle transition temperatures.
- Pellini Drop Weight Tests on longitudinal specimens to ASTM E208-87 (for specimen thicknesses of 19 mm (P2) and 16 mm (P3)) or Stahl-Eisen Test Specification 1325 (1982) (for 13 mm thick specimens (P4)) to determine Nil Ductility Transition Temperatures (NDTT). (Note: tests conducted on plates less than 13 mm thick did not strictly conform to these specifications).
- Fracture toughness properties were measured on longitudinal specimens for four of the plates over a range of temperatures and stress intensity rates.

In order to measure the effect of welding on the heat affected zone (HAZ) toughness, a Gleeble 1500 thermal simulator was used to simulate the coarse grained HAZ microstructure for 1.5 and 5.0 kJ/mm heat input welds in two of the plates, plates C and H. Charpy impact transition curves were determined for this region and compared with the corresponding parent plate data.

One of the plates, plate C, was given a strain ageing treatment of 5% strain followed by ageing for 1 h @ 250°C and the effect was characterised by generating Charpy transition curves and comparing the same with the corresponding plate properties.

5. RESULTS AND DISCUSSION

5.1 GRADES AND CHEMICAL COMPOSITION

Plate A was purchased from a stockist in the UK as Lloyd's grade A. The other plates, obtained from steel stockholders in other European countries, were not classified as Grade A. Most of these, except plates G and I, conformed to S235 or equivalent as per German standards as shown in Table 1. Plate G carried a similar specification but to a Chinese standard. There was no grade indicated for the plate I.

Chemical compositions of these plates are shown with the Grade A specification and the analysis values quoted on the release certificates in Table 3. It can be seen that all of the plates conformed to the requirements for this grade of steel. All of the plates, except for G and I, were unalloyed or low alloyed structural steels with low carbon equivalents for good weldability. Plate G had high C, Si and Mn contents and was typical of 'old' structural steels with moderate weldability as a consequence of it's high hardenability. Plate I with its low carbon content and low tensile strength is typical of more modern steels.

Plates G and I showed substantial discrepancies in information between that contained on their respective test certificates and the results of the laboratory tests. Si and Mn contents were significantly understated for plate G and the values of C, Mn, P and S given for plate I were all different to those determined in the laboratory, particularly the carbon content which was grossly overstated on the test certificate.

5.2 MECHANICAL PROPERTIES

The results for all of the tensile tests carried out are contained in Table 4 along with the relevant test certificate information and the requirements for Lloyd's grade A (it should be noted that all comparisons are with Lloyd's rules dating before the 1997 amendments). Plates D, G and I did not meet the tensile strength specification. The tensile strength of plate G was above the maximum, although the certificate did not show this. For Plates D and I some of the values were marginally outside the limits set by Lloyds Register. Apart from these discrepancies the remaining plates were in reasonable agreement with the information on the test certificates.

The tensile and yield strength properties are shown in Figs. 1-4 in order to compare the results from the various locations sampled. Figures 1 and 2 demonstrate that all of the results obtained from plate A are very similar, a feature which is repeated with the more limited data from the other plates. Specimen orientation (longitudinal versus transverse) also did not have a noticeable effect suggesting the plates were essentially isotropic in terms of strength.

5.3 CHARPY IMPACT ENERGY

The Charpy impact energy data are presented in graphical form in Figs. 5-16. The tests were carried out on each plate using specimens from several positions across and along the plate and for both longitudinal and transverse orientations. The most commonly used measures of Charpy performance, 27 J transition temperature ($T_{27\,J}$) (20 J for transverse specimens) and 50% brittle fracture appearance transition temperature (50% FATT), were derived from the data in Figs. 5-16 and these are presented in Table 5 and Fig. 17.

All of the plates examined here had $T_{27\ J}$ temperatures ($T_{20\ J}$ for transverse tests) of 0°C or lower. Plate I was found to be the toughest and plate C the least tough. The 50% FATT for these plates varied between 25°C and -60°C.

The sampling position did not have any pronounced effect on the Charpy impact energies indicating that the plates were quite homogeneous. Transverse Charpy toughness was worse than the longitudinal Charpy toughness which is typical of as rolled plates.

5.4 PELLINI NIL DUCTILITY TRANSITION TEMPERATURE

The Pellini drop-weight test is widely used to infer the crack arrest properties of steel plates. However ship plates have not been traditionally subjected to this test, mainly because the majority of these plates are thinner than 15.9 mm which is the minimum specimen thickness accepted in the Drop-Weight test standard, ASTM E208. Nevertheless the tests were performed on plates A, C, G and H and Nil Ductility Transition temperatures determined though it was recognised that most of the plates were below the thickness range for valid drop-weight tests. Specimen dimensions for thinner plates conformed to those specified for P3 specimens. The deflection stop distance for the 9.5 mm thick plate was set in accordance with a German standard (Stahl Eisen Prufblatt 1325) which extends the scope of the drop-weight test to 13 mm thick plates (specimen P4). Results from the drop-weight tests are given below;

Plate Code	Position	Specimen Type	NDTT
A	End B - ½ Width	15 mm	-20°C
C	Mid-length - Edge	19 mm P2	0°C
G	Mid-length - ¼ Width	9.5 mm	-50°C
H	Mid-length - Edge	15 mm	-10°C

5.5 HIGH RATE FRACTURE TESTS

Sumpter has suggested$^{(4)}$ that a dynamic fracture mechanics toughness (K_{mat}) of 125 MPa√m (K_{crit}) at the operating temperature is needed to avoid risk of brittle fracture. This criterion must be met at loading rates of 10^4 MPa√m/s to represent dishing of a hull plate under local slamming in a ship's bottom and 10^2 MPa√m/s to represent the effect of slamming at mid-ship's deck. The operating temperatures for the North Sea is 0°C for below the water line and -10°C for above the water line.

Bx2B pre-cracked longitudinal specimens from plate A were subjected to high strain rate fracture tests at test temperatures of 0°C and -10°C at the two loading rates described above and these results in terms of stress intensity factor (K_{mat}) are presented in Fig. 18. Stress intensity factors were calculated from the measured CTOD values using the following relationship;

$$K = \sqrt{\frac{1.5 \times \text{CTOD} \times \text{Yield strength} \times \text{Young's modulus}}{0.91}} \qquad \ldots (1)$$

This plate met the criterion for K_{mat} of 125 MPa√m at 0°C and therefore could be considered to posses adequate toughness for a ship operating in the North Sea environment.

Subsequently plates C, G, and H were selected from the remaining plates and longitudinal specimens from these were tested slightly differently. Tests were conducted over a range of temperatures using a high (>10^4 MPa√m/s) stress intensity rate to establish the temperature at which K_{mat} values fall below the K_{crit} value of 125 MPa√m. Subsequent tests were done at a fixed temperature just below the 125 MPa√m transition temperature using a range of stress intensity rates to establish a stress intensity rate transition for K_{mat}. These results are presented in Figs. 19-24.

Transition temperatures for meeting Sumpter's criterion at the higher of the two loading rates are presented below. It has been suggested(4) that 50% FATT temperatures can be used in the absence of fracture toughness data, therefore these are also included. The 50% FATT values shown are the highest values for longitudinal tests including all test positions and although the fracture toughness test samples were taken from a corresponding position for plate A this was not the case for the other plates.

	K_{crit} Transition T, °C	50% FATT T, °C
Plate A	0	+10
Plate C	+18	+10
Plate G	-16	+5
Plate H	-10	-10

Plates A, G and H having met the Sumpter criterion could be considered to have adequate toughness for use in ships operating in conditions existing in the North Sea. The K_{crit} transition temperature for plate C was above 0°C and so did not satisfy the more stringent of the two criteria set by Sumpter. Tests done at 10°C to establish the strain rate transition curve for the material fracture toughness showed K_{mat} exceeding K_{crit} only when loading rates were around 10^2 MPa√m/s or lower, Fig. 20. These results were insufficient to categorically state whether this plate is capable of satisfying the Sumpter criterion at the lower of the two loading rates at a temperature of -10°C. Therefore additional tests were done to establish a fracture toughness ductile-brittle transition curve using the lower of the two loading rates. These results are included in Fig. 19 which reaffirmed that +10°C is the lowest temperature at which the fracture toughness, K_{mat}, for this steel exceeds the critical value of 125 MPa√m. In order to establish the maximum loading rate at which K_{mat} would exceed K_{crit}, further tests were done at 0°C and -10°C and these results are shown in Fig. 20. It is clear that the fracture toughness of this plate does not exceed the critical value at -10°C even for very slow loading rates. It, therefore, does not possess sufficient toughness for use as ship plate for the North Sea environment according to the criterion set by Sumpter.

Plate C was also unusual in the fact that its FATT was less than the K_{crit} transition temperature. A large volume of results from 5-15 mm thick plates contained in reference 4 showed the FATT to be invariably higher. Plate C at 20 mm was thicker and it is possible that the consequent increased thickness of the fracture mechanics test, whilst keeping the Charpy thickness constant at 10 mm, caused an upward shift in the K_{crit} transition temperature relative to Charpy toughness. The other results are within the scatter band established by Sumpter for 5-15 mm thick plates(4).

There is only a limited amount of data on the fracture toughness of steel plates at high strain rates as only DERA appear to be using this method. They apply it to assess the suitability of steel plates for warships and have published results from six different steel plates conforming to Grade A specification(4). These show variations in K_{crit} transition temperatures ranging from +30°C to -30°C and only four plates had satisfactory toughness as per the Sumpter criterion, a ratio similar to the present results which showed that three out of four plates had satisfactory toughness on this basis.

5.6 HAZ THERMAL SIMULATION

In order to assess the effect of welding on HAZ toughness, specimens with a cross section of 11 x 11 mm from plates C and H were subjected to thermal cycles on a Gleeble 1500 thermal simulator to simulate the HAZ such that one set of specimens from each plate was subjected to a thermal cycle representing a low heat input weld (~1.5 kJ/mm) and another set to one representing a high heat input (~5.0 kJ/mm) weld. In both cases the specimens were heated to 1350°C in two seconds followed by controlled cooling such that the cooling times between 800°C and 500°C ($\Delta t_{8/5}$) were 10 seconds and 125 seconds respectively for the lower and the higher heat input values.

Charpy specimens machined from the thermally simulated specimens were tested and the Charpy transition curves and fracture appearance transition curves for the two plates are shown in Fig. 25. 27 J transition temperatures and 50% FATT from these curves are given below;

	27 J Transition Temperature, (°C)			50% FATT (°C)		
	Plate	Weld Heat Input		Plate	Weld Heat Input	
		1.5 kJ	5.0 kJ		1.5 kJ	5.0 kJ
Plate C	-10	-5	+10	+15	+25	+30
Plate H	-10	+5	+15	-5	+20	+30

There is a deterioration in the Charpy impact toughness after the thermal simulation treatment compared to the plate properties. The HAZ of the higher heat input weld suffered greater deterioration in toughness compared to the lower heat input weld. However, the performance of the HAZ in real welds may be better because the HAZ usually contains a mixture of grain sizes and microstructures with toughness properties for the individual constituents ranging from low to relatively high values, whereas the thermally simulated specimens present a fairly uniform coarse grain microstructure of low toughness in the crack path and thus represent the worst case.

5.7 STRAIN AGEING

Longitudinal specimens from plate C, taken from ¼ width position on the full plate, were subjected to 5% strain followed by 1 h @ 250°C ageing treatment. Results of the Charpy tests are presented in Fig. 26 which also includes the original plate Charpy impact energy data for comparison. 27 J transition temperatures and 50% FATTs given below;

27 J Transition Temperature (°C)		50% FATT (°C)	
As rolled	Aged	As rolled	Aged
-10	+35	+20	+70

There is an increase in the Charpy toughness transition temperature of about 50°C. Even though no comparative data could be found for as rolled grade A steels, an earlier work(5) on BS4360:Grade 50E showed a deterioration in the impact transition temperature of about 40°C on a similar strain ageing treatment. This difference in results from the two steel plates are within the scatter in results normally associated with Charpy testing.

6. CONCLUSIONS

A total of seven plates which either conformed to the Lloyd's Grade A requirements in full, or had matching chemistries and strengths, has been examined. The plates were obtained from stockists and originated from several steel makers and had different steel chemistries. The aim of the work was to examine the variability in properties which could be obtained from this steel type, both within and between plates. A variety of tests was carried out and the main findings are given below.

Test certificates from stockists do not necessarily guarantee that the plate to which they refer conform with the information contained in them. Subsequent product testing, in some instances, gave significantly different values from those quoted on the test certificate.

The material properties for all of the plates examined were not markedly influenced by sampling positions.

All of the steels exceeded a Charpy impact toughness of 27 J at +20°C in all specimen orientations and test positions. Overall the 20 mm thick plate had the lowest Charpy impact energy.

Four out of seven plates met the strength requirements for Grade A plates and a further two plates were only marginally outside the specification limits. One plate was significantly stronger than the upper specification limit for tensile strength on the basis of actual test results which were at considerable variance with the relevant test certificate data.

Plate chemistries for most plates suggested a low risk of cracking during welding. The one exception was the chemistry of the 10 mm thick plate originating from China which, because of it's high carbon content, suggested relatively high hardenability.

Four plates were tested under high loading rate using pre-cracked specimens. Two 15 mm plates and one 10 mm thick plate, had adequate fracture toughness according to the criterion, suggested by Sumpter for ships operating in the North Sea, of a fracture toughness value (K_{mat}) exceeding 125 MPa/m at a loading rate of 10^4 MPa/m/s or higher. The 20 mm thick plate did not meet this requirement.

Pellini Drop Weight test results have been presented for four plates. Although three of these were outside the thickness limit covered by the relevant test standard they provide an indication of the relative NDTT between plates.

A strain ageing treatment of specimens from the 20 mm thick plate raised the 50% FATT values in the Charpy test by 50°C as compared to the as-rolled parent plate.

Thermal simulation technique was used to reproduce the coarse grained HAZ of nominally 1.5 and 5.0 kJ/mm heat input welds. Charpy tests performed on specimens from these showed that the 27 J transition temperature and the 50% FATT were increased for the two plates tested. This is argued to be the worst case and the HAZ from real welds of comparable heat inputs could be tougher as measured by Charpy impact energies.

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Table 1
Plate details

Plate Identity	STC Plate Code (if any)	Grade (actual) (Note 1)	Country of Origin	Thickness (mm)	Plate dimensions (mm) (Note 2)	
					Length	Width
A	Y7D2-10	A	Romania	15	12,000	3,000
B		S235JRG2 RST37-2	Bulgaria	10	2,000	2,000
C	H7E2	S235JRG2 RST37-2	Bulgaria	20	2,000	2,000
D		S235JRG2 RST37-2	Bulgaria	12	2,000	2,000
G	H7E3	Q235A	China	10	6,000	2,000
H	H7E4	RST37-2	Romania	15	6,000	2,000
I		Unknown	India	10	6,000	2,000

Note 1: Grade S235JRG2 according to DIN 1543/91.
Grade RST37-2 according to DIN 17100/80.
Grade Q235A according to a Chinese specification - identity not known.
Note 2: Plate A was a full rolled plate. Other plates were pieces as available from stockists.

Table 2
Sampling positions

Plate	Sampling Positions		
	Edge	¼ Width	½ Width
A	Plate end 'A'	Plate end 'A'	Plate end 'A'
	Plate mid-length	Plate mid-length	Plate mid-length
	Plate end 'E'	Plate end 'E'	Plate end 'E'
B	Plate mid-length	Plate mid-length	-
C	Plate mid-length	Plate mid-length	-
D	Plate mid-length	Plate mid-length	-
G	Plate end	Plate end	-
	-	Plate mid-length	Plate mid-length
H	Plate end	Plate end	-
	-	Plate mid-length	Plate mid-length
I	Plate end	Plate end	-
	-	Plate mid-length	Plate mid-length

Table 3
Chemical compositions of the plates

Element	Lloyd's Gr. A	Plate A		Plate B		Plate C		Plate D		Plate G		Plate H		Plate I	
		Certificate	Measured	Certificate	Measured	Certificate	Measured	Certificate	Measured	Certificate	Measured	Certificate	Measured	Certificate	Measured
C	0.23 max.	0.120	0.130	0.140	0.143	0.130	0.148	0.110	0.123	0.170	0.186	0.120	0.128	0.130	0.068
Si	0.5 max.	0.23	0.24	0.28	0.29	0.25	0.26	0.22	0.23	0.18	0.45	0.23	0.26	0.15	0.17
Mn	Note 1	0.63	0.66	0.43	0.42	0.54	0.52	0.71	0.72	0.42	1.45	0.44	0.47	0.65	0.99
P	0.04 max.	0.016	0.015	0.017	0.019	0.020	0.023	0.027	0.033	0.019	0.019	0.022	0.017	0.024	0.016
S	0.04 max.	0.018	0.016	0.042	0.043	0.022	0.026	0.023	0.023	0.022	0.030	0.016	0.009	0.025	0.012
Cr	-	-	<0.02	0.11	0.10	0.16	0.16	0.11	0.11	-	0.01	-	0.01	-	0.02
Ni	-	-	<0.02	0.10	0.09	0.13	0.12	0.09	0.09	-	0.01	-	0.00	-	0.02
Mo	-	-	<0.005	-	0.01	-	0.01	-	0.01	-	0.00	-	0.00	-	0.01
Al	-	-	0.006	-	0.011	-	0.019	-	0.010	-	0.015	0.012	0.068	-	0.037
V	-	-	<0.005	-	0.002	-	0.003	-	0.005	-	0.004	-	0.001	-	0.006
Nb	-	-	<0.005	-	0.002	-	0.002	-	0.003	-	0.004	-	0.001	-	0.003
Cu	-	-	<0.02	0.23	0.21	0.29	0.26	0.26	0.23	-	0.03	-	0.02	-	0.01
Ti	-	-	<0.005	-	0.002	-	0.002	-	0.002	-	0.003	-	0.003	-	0.003
CE(IIW)	-	0.230	0.243		0.255		0.295		0.289		0.433		0.210		0.242
P_{cm}	-	-	0.172		0.192		0.207		0.186		0.276		0.162		0.126

Note 1: For thickness >12.5 mm Mn must not be less than 2.5x (the carbon content).

Table 4
Tensile test results

Plate Code	Test Position	Longitudinal				Transverse			
		Tensile Strength (N/mm²)	Yield Strength		Elong-ation (%)	Tensile Strength (N/mm²)	Yield Strength		Elong-ation (%)
			Upper (N/mm²)	Lower (N/mm²)			Upper (N/mm²)	Lower (N/mm²)	
Lloyd's Grade A		400-490	235 min.		22 min.				
A	Certificate	453	321		24				
	End A - Edge	442/438	285	283/288	37/37	445/446	285/292	280/290	34/35
	End A - ¼ width	445/446	282/282	276/276	37/36	447/447	284/286	283/283	35/34
	End A - ½ width	446/445	288/291	281/278	36/37	444/440	288	283/289	33/34
	Mid-length - Edge	445,444	295,289	288/281	37/36	441/441	273/273	272/271	35/35
	Mid-length - ¼ width	441/441	274/273	272/268	37/34	441/442	271	270/270	35/36
	Mid-length - ½ width	442/444		272/272	37/37	441/441	284/276	283/273	33/34
	End B - Edge	441/435	286/284	275/276	32/34	437/437	277/284	273/276	35/34
	End B - ¼ width	444/440	278/273	275/271	35/34	447/451	283/293	280/282	35/34
	End B - ½ width	444/445	277/289	273/286	36/37	448/443	289/275	287/273	34/35
B	Certificate	470	304		29.5				
	Mid-length - Edge	462	326	309	37.0	463	308	303	29.8
	Mid-length - ¼ width	463	327	311	33.9	464	327	313	30.7
C	Certificate	461	289		28.5				
	Mid-length - Edge	462	271	269	32.6	454	284	268	32.7
	Mid-length - ¼ width	454	272	266	34.1	455	276	260	30.6
D	Certificate	456	299		32.5				
	Mid-length - Edge	477	317	313	31.0	482	328	321	31.1
	Mid-length - ¼ width	513	347	345	32.2	520	371	352	31.0
G	Certificate	430	255						
	End - Edge	569	402	379	31.7	561	388	369	27.8
	End - ¼ width	564	387	375	27.6	562	398	376	29.0
	Mid-length - ¼ width	572	386	383	24.9	567	378	375	26.0
	Mid-length - ½ width	558	385	376	24.5	568	384	377	32.0
H	Certificate	412	242		32.0				
	End - Edge	411	277	263	40.8	411	261	257	36.2
	End - ¼ width	414	271	260	39.2	417	285	256	39.1
	Mid-length - ¼ width	414	269	265	37.2	411	268	253	38.8
	Mid-length - ½ width	416	277	263	37.6	413	274	264	39.0
I	Certificate	412	310		25.0				
	End - Edge	402	292	275	40.5	408	282	280	39.4
	End - ¼ width	398	306	297	39.8	405	292	285	37.8
	Mid-length - ¼ width	403	304	289	35.9	402	307	294	38.5
	Mid-length - ½ width	397	302	282	37.2	405	286	286	35.8

Notes:

(1) Plate A was tested at STC and duplicate tests results are given above. All other plates were tested at the University of Gent.

(2) Elongation values for tests done at STC are quoted over a gauge length (l_O) of 100 mm. For other tests this was $5.65\sqrt{S_O}$.

(3) 0.2% proof strength ($R_{P0.2}$) instead of the lower yield strength (Rel) is given for all tests done at the University of Gent.

Table 5
Transition temperatures determined from Charpy test results

Plate Code	Test Position	Longitudinal		Transverse	
		27 J (°C)	50% FATT (°C)	20 J (°C)	50% FATT (°C)
A	End A - Edge	-30	0	-30	0
	End A - ¼ width	-30	-5	-30	-5
	End A - ½ width	-30	-5	-20	-5
	Mid-length - Edge	-35	0	-35	0
	Mid-length - ¼ width	-15	0	-10	0
	Mid-length - ½ width	-15	0	-10	5
	End B - Edge	-30	-5	-25	5
	End B - ¼ width	-25	5	-10	10
	End B - ½ width	-15	10	-35	5
B	Mid-length - Edge	-30	-5	-15	20
	Mid-length - ¼ width	-30	-10	-10	10
C	Mid-length - Edge	-15	10	-10	30
	Mid-length - ¼ width	-10	15	-10	35
D	Mid-length - Edge	-40	-10	-40	20
	Mid-length - ¼ width	-40	-15	-30	5
G	End A - Edge	-35	5	-35	10
	End A - ¼ width	-35	5	-35	5
	Mid-length - ¼ width	-35	-10	-30	-5
	Mid-length - ½ width	-40	-5	-30	-5
H	End A - Edge	-15	-5	-25	5
	End A - ¼ width	-20	-10	-10	0
	Mid-length - ¼ width	-10	-5	-10	0
	Mid-length - ½ width	-10	-5	-20	5
I	End A - Edge	-55	-55	-65	-10
	End A - ¼ width	-55	-55	-55	-20
	Mid-length - ¼ width	-60	-60	-60	-20
	Mid-length - ½ width	-50	-50	-60	-25

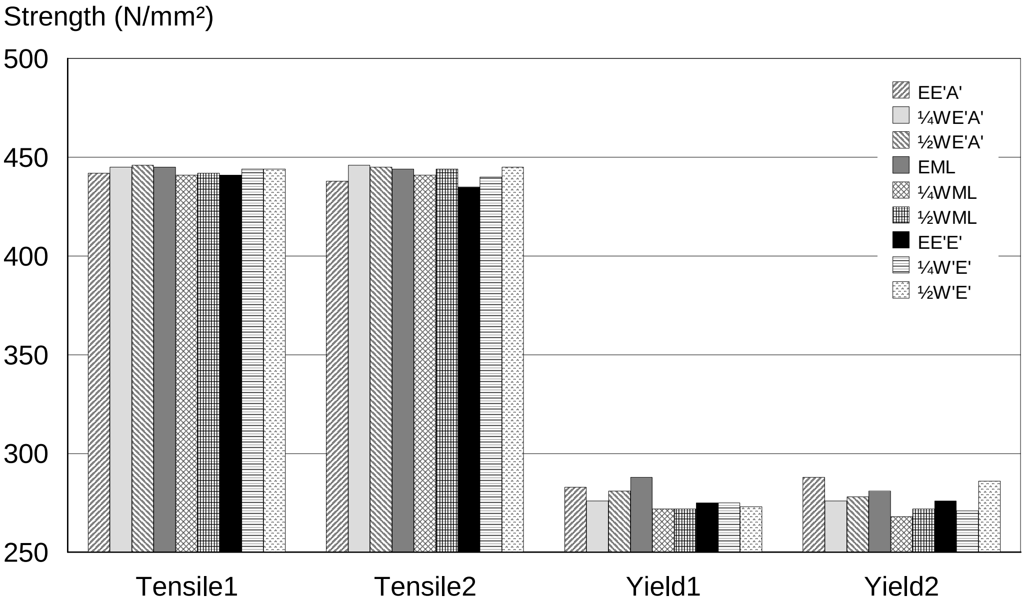

Figure 1
Tensile property variations in Plate A - longitudinal tests

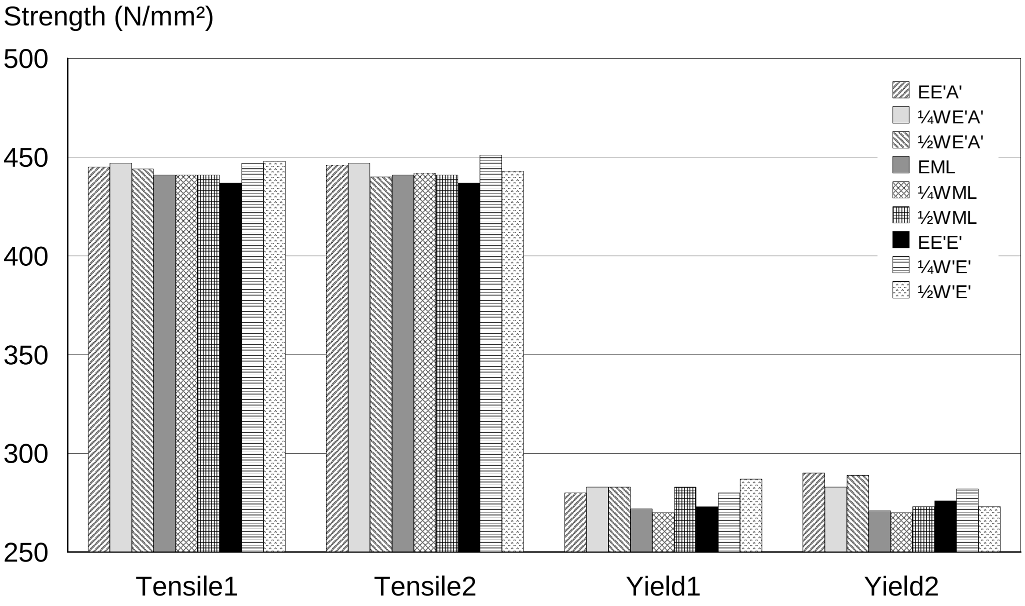

Figure 2
Tensile property variations in Plate A - transverse tests

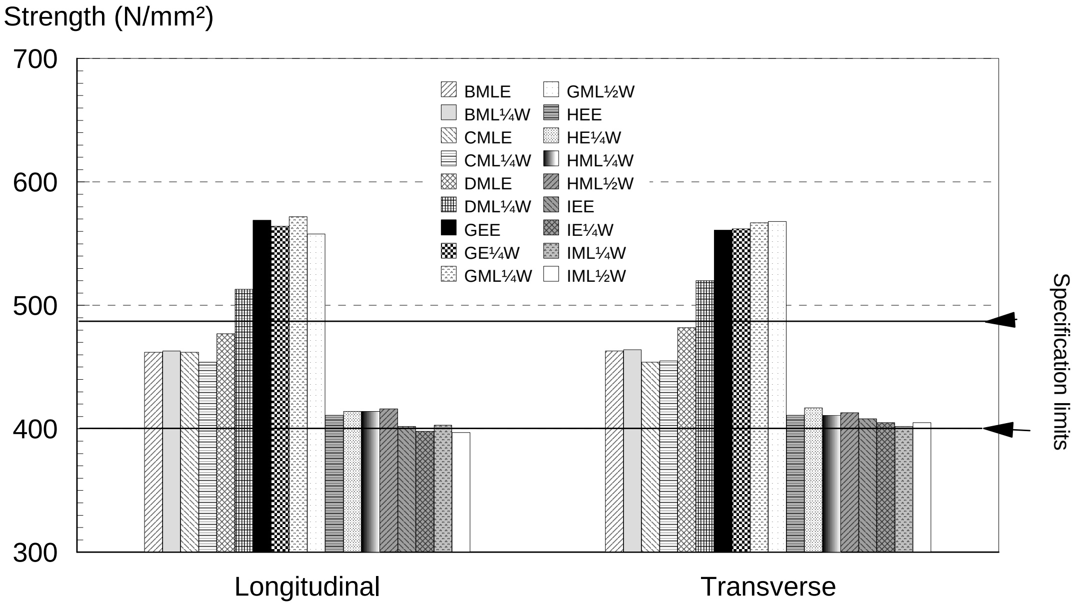

Figure 3
Tensile strengths of Plates B to I all tests

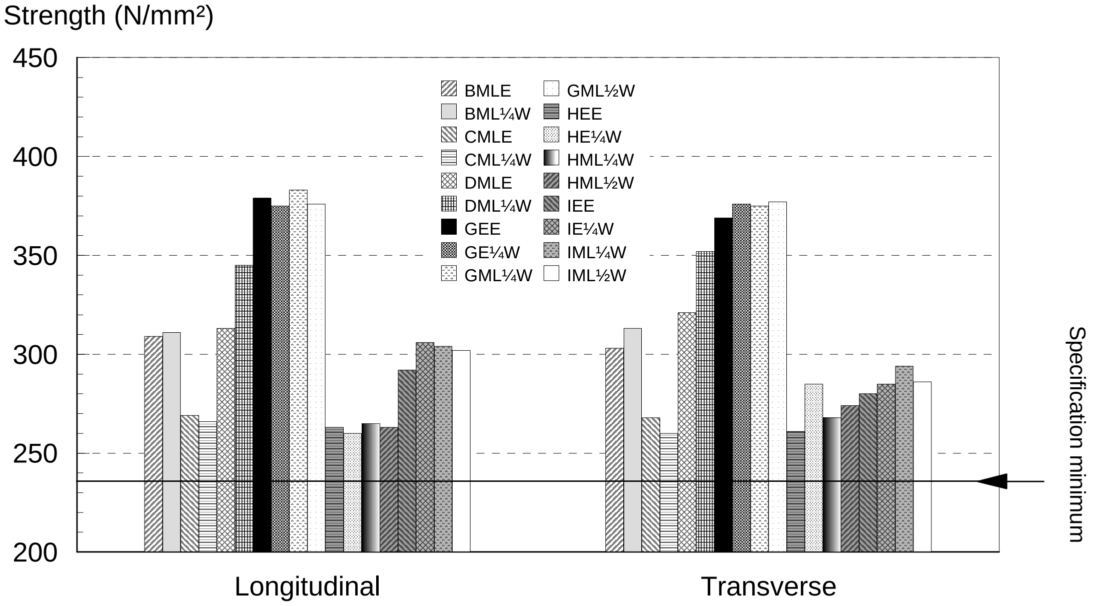

Figure 4
Yield strengths of Plates B to I all tests

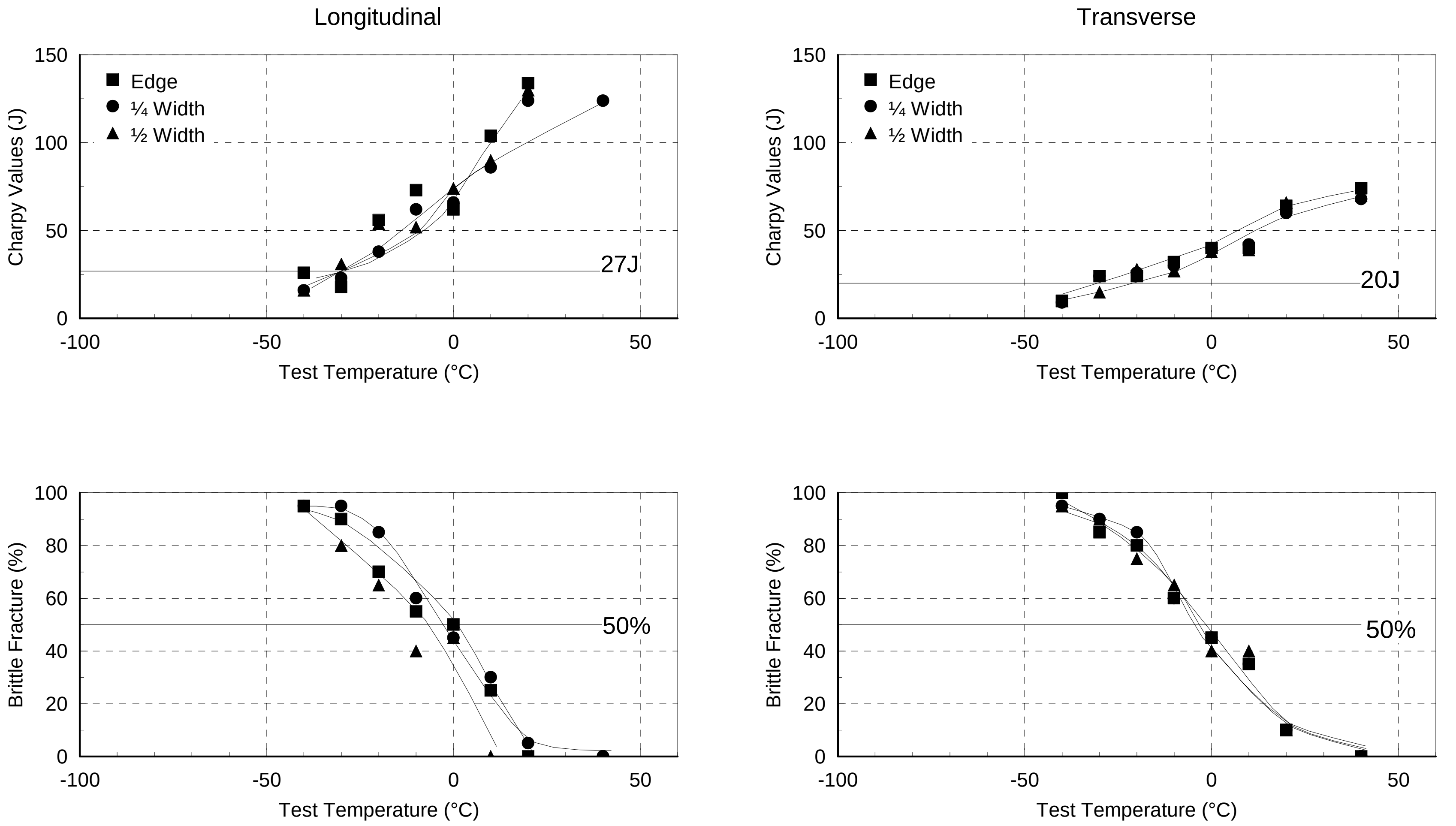

Figure 5
Charpy results for the Plate A End 'A'

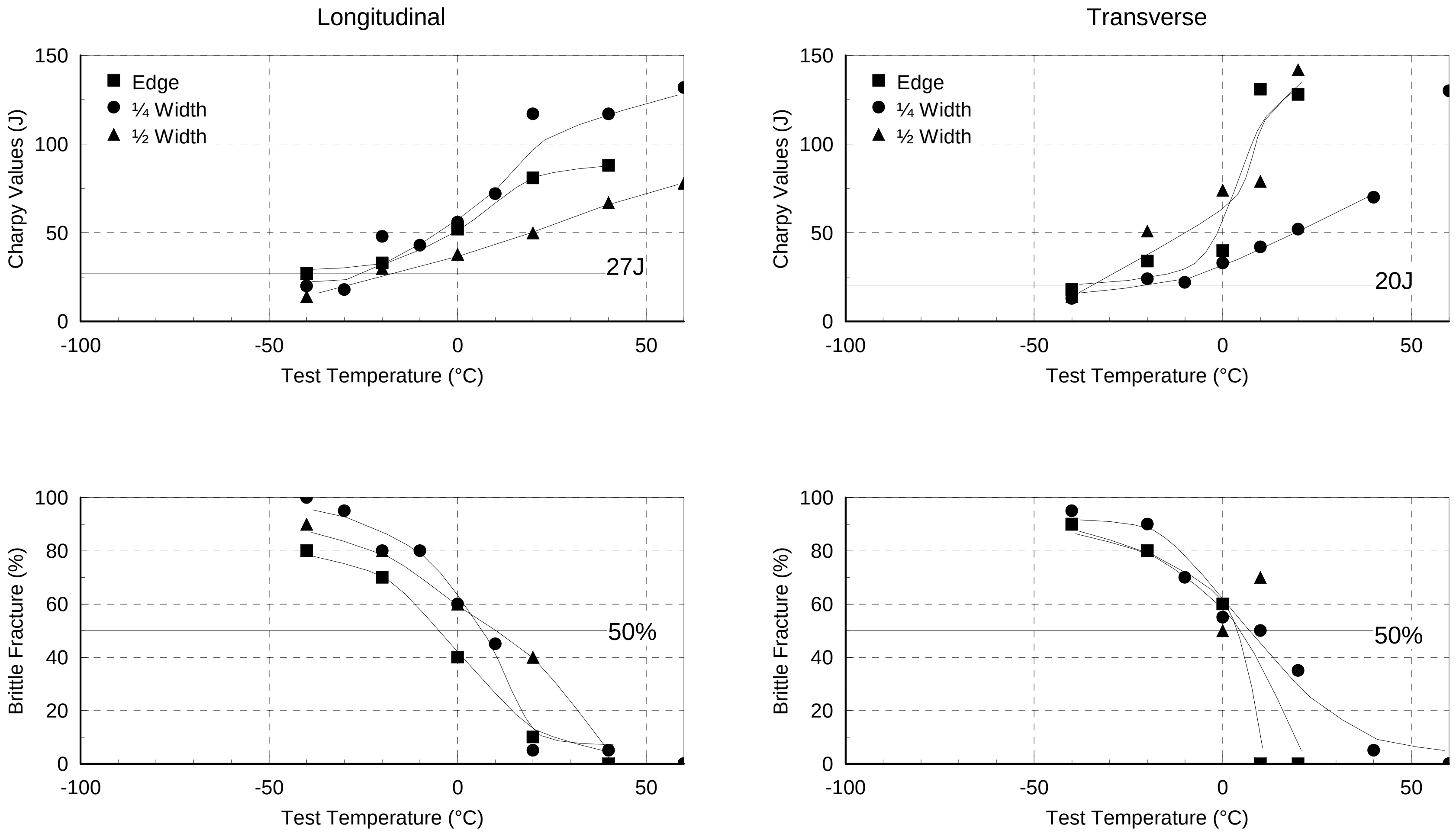

Figure 6
Charpy results for the Plate A End 'B'

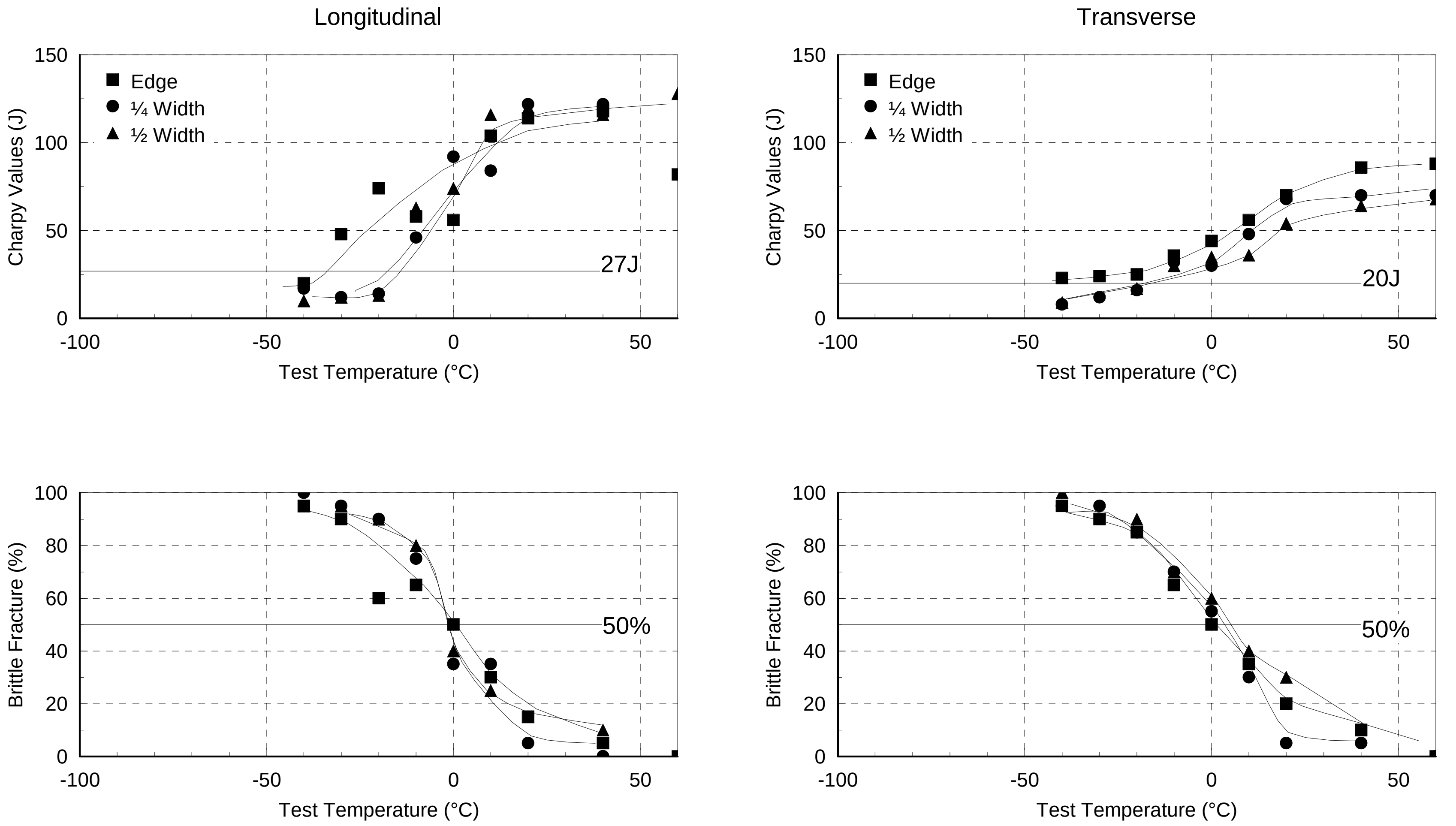

Figure 7
Charpy results for the Plate A Mid-Length

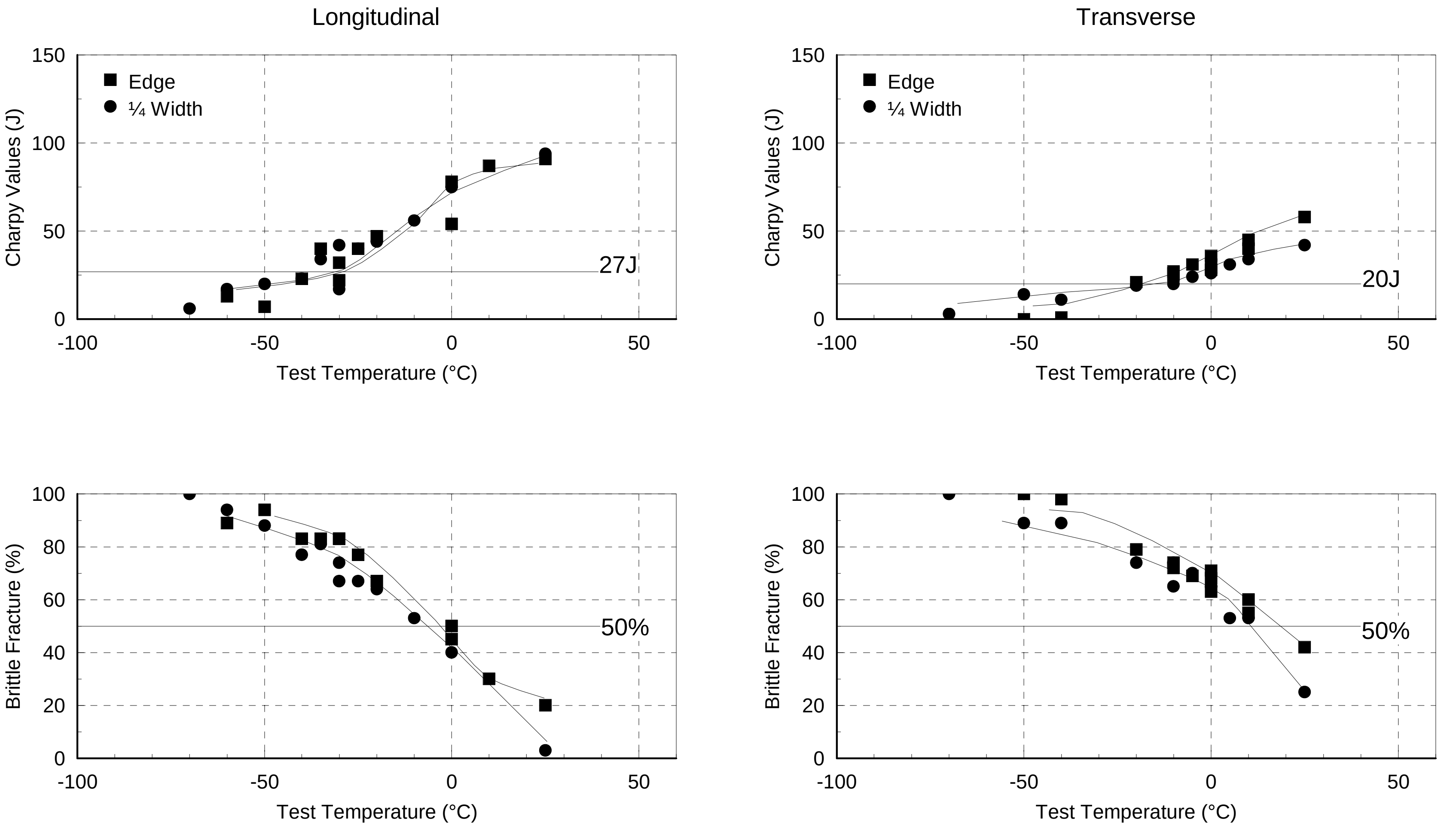

Figure 8
Charpy results for the Plate B Mid-Length

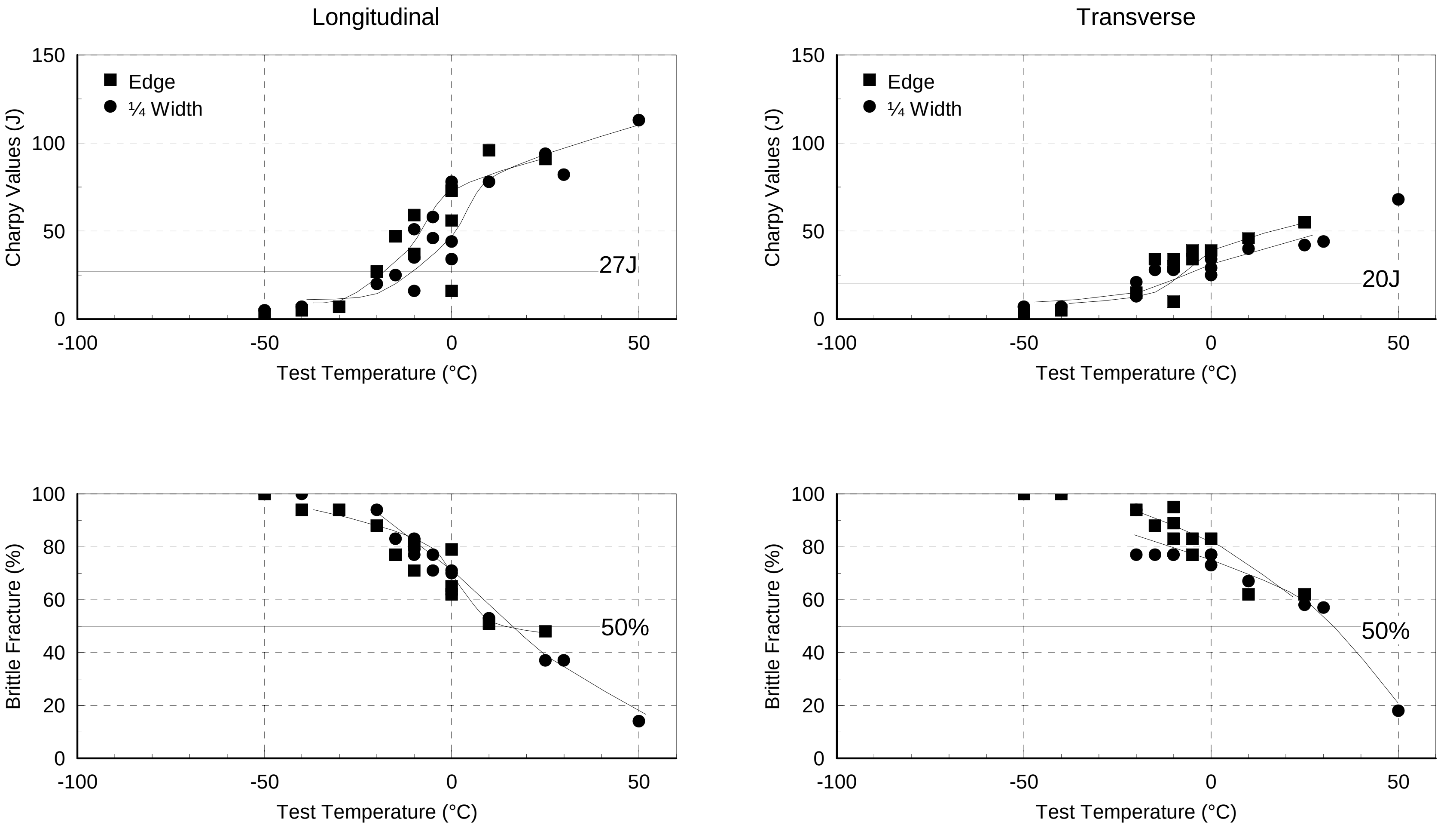

Figure 9
Charpy results for the Plate C Mid-Length

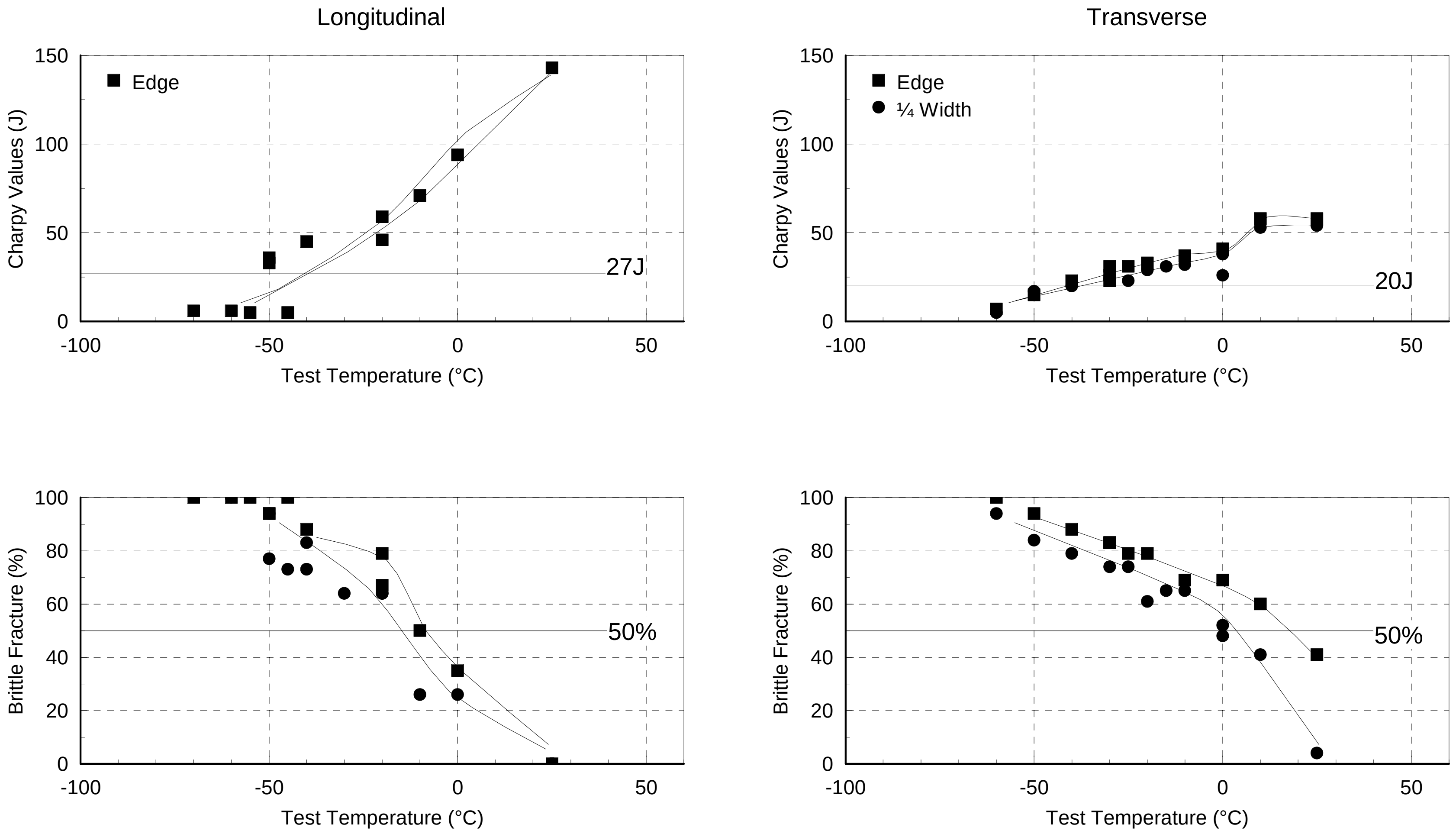

Figure 10
Charpy results for the Plate D Mid-Length

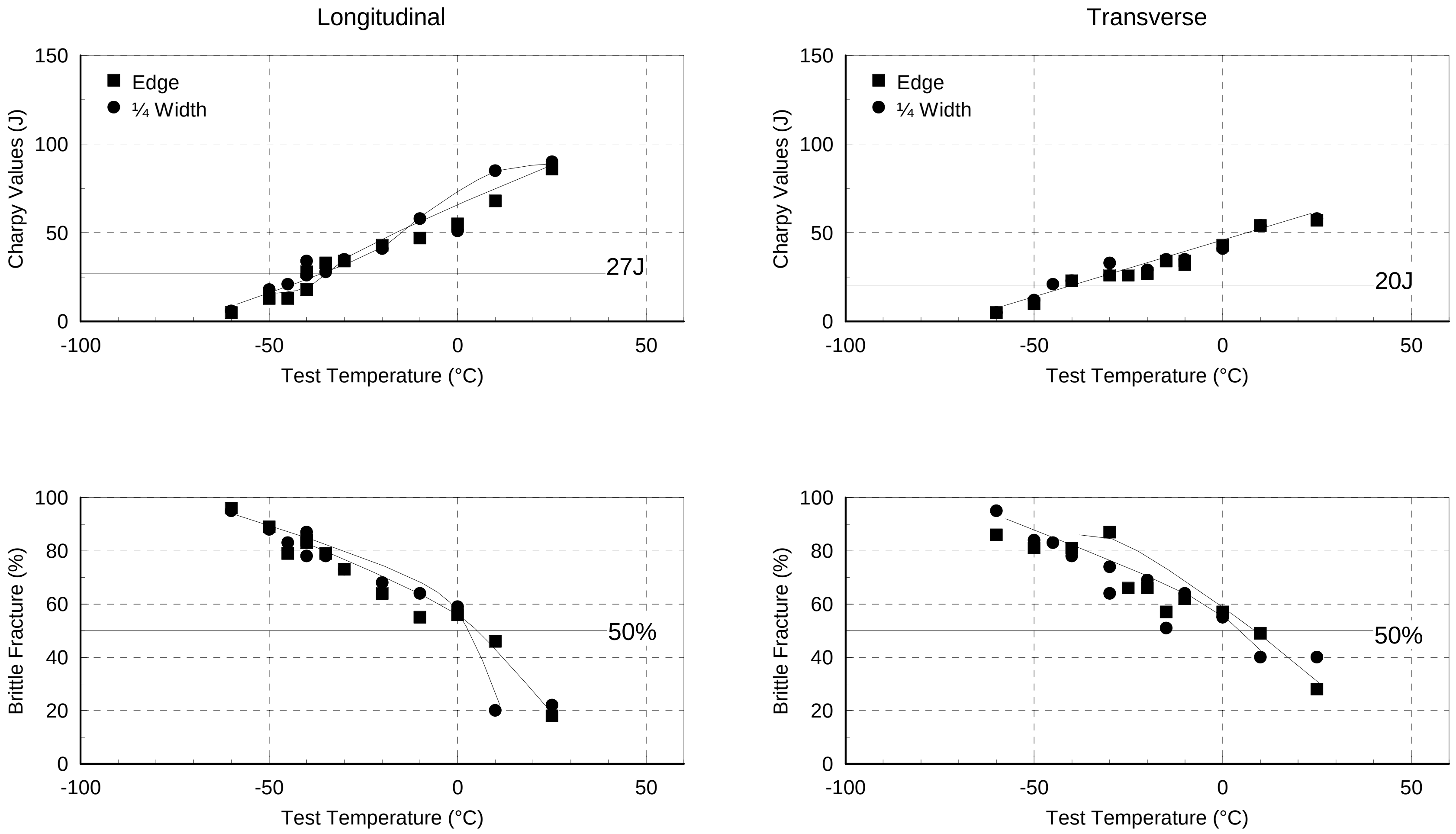

Figure 11
Charpy results for the Plate G End

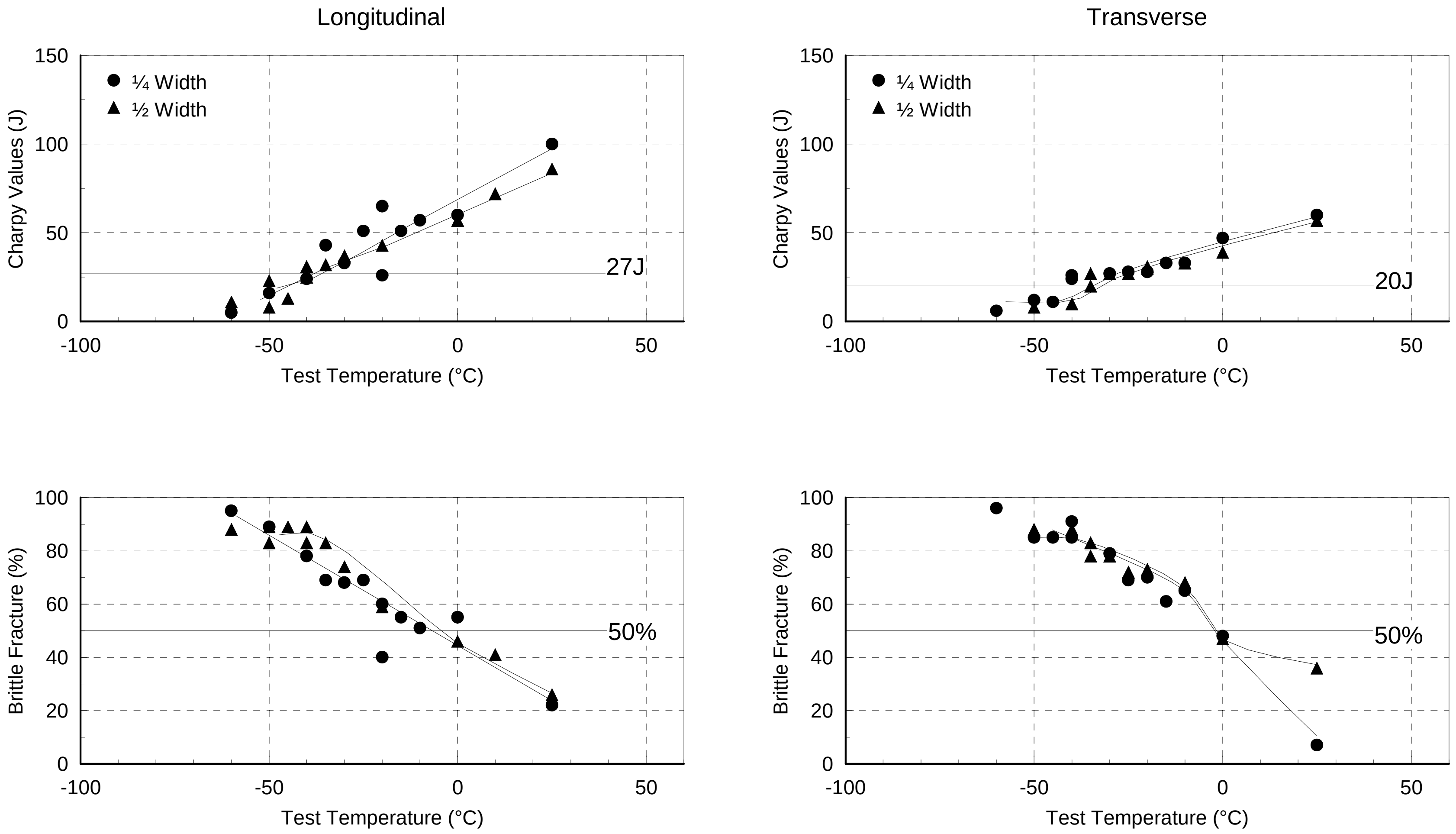

Figure 12
Charpy results for the Plate G Mid-Length

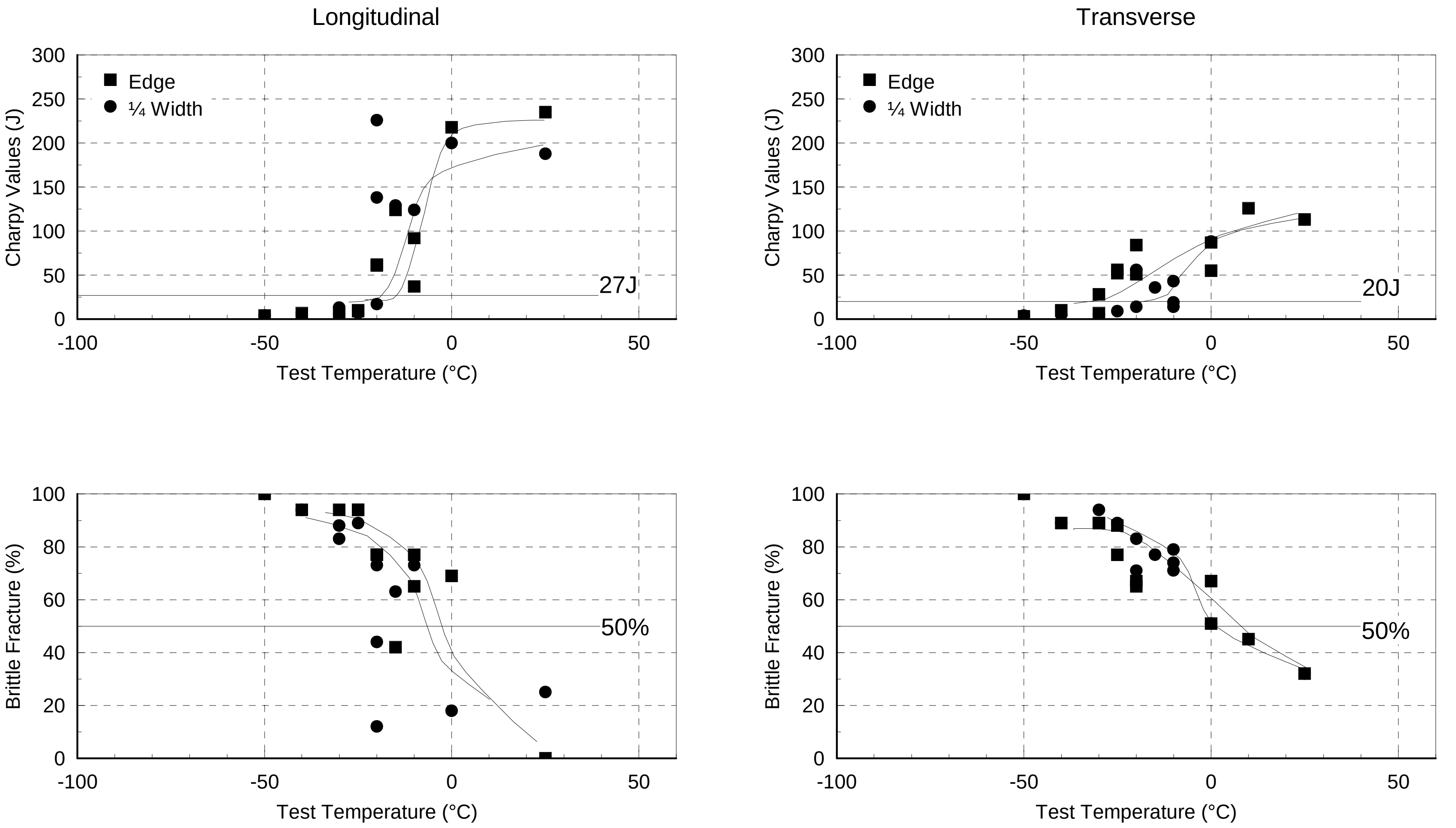

Figure 13
Charpy results for the Plate H End

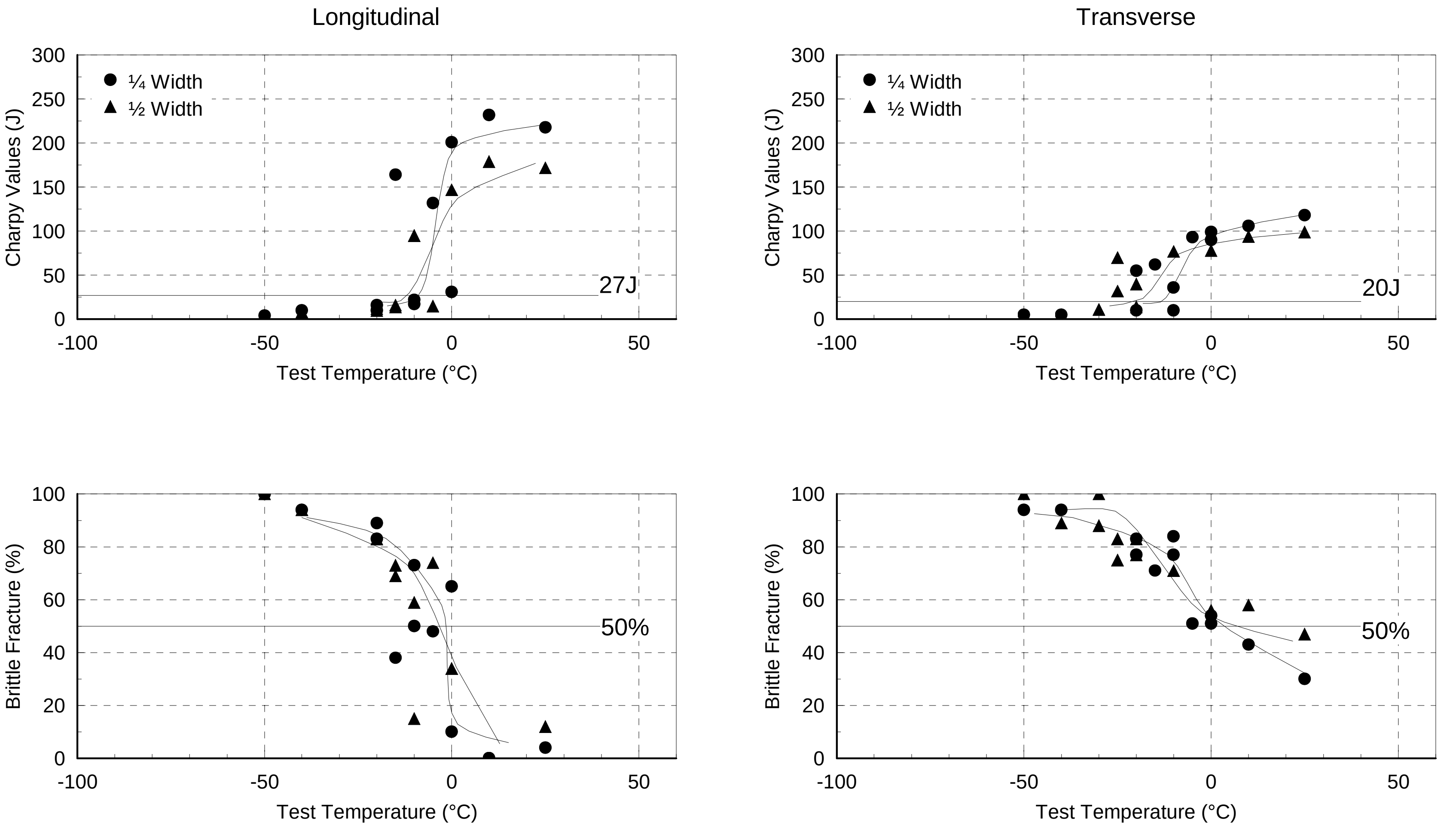

Figure 14
Charpy results for the Plate H Mid-Length

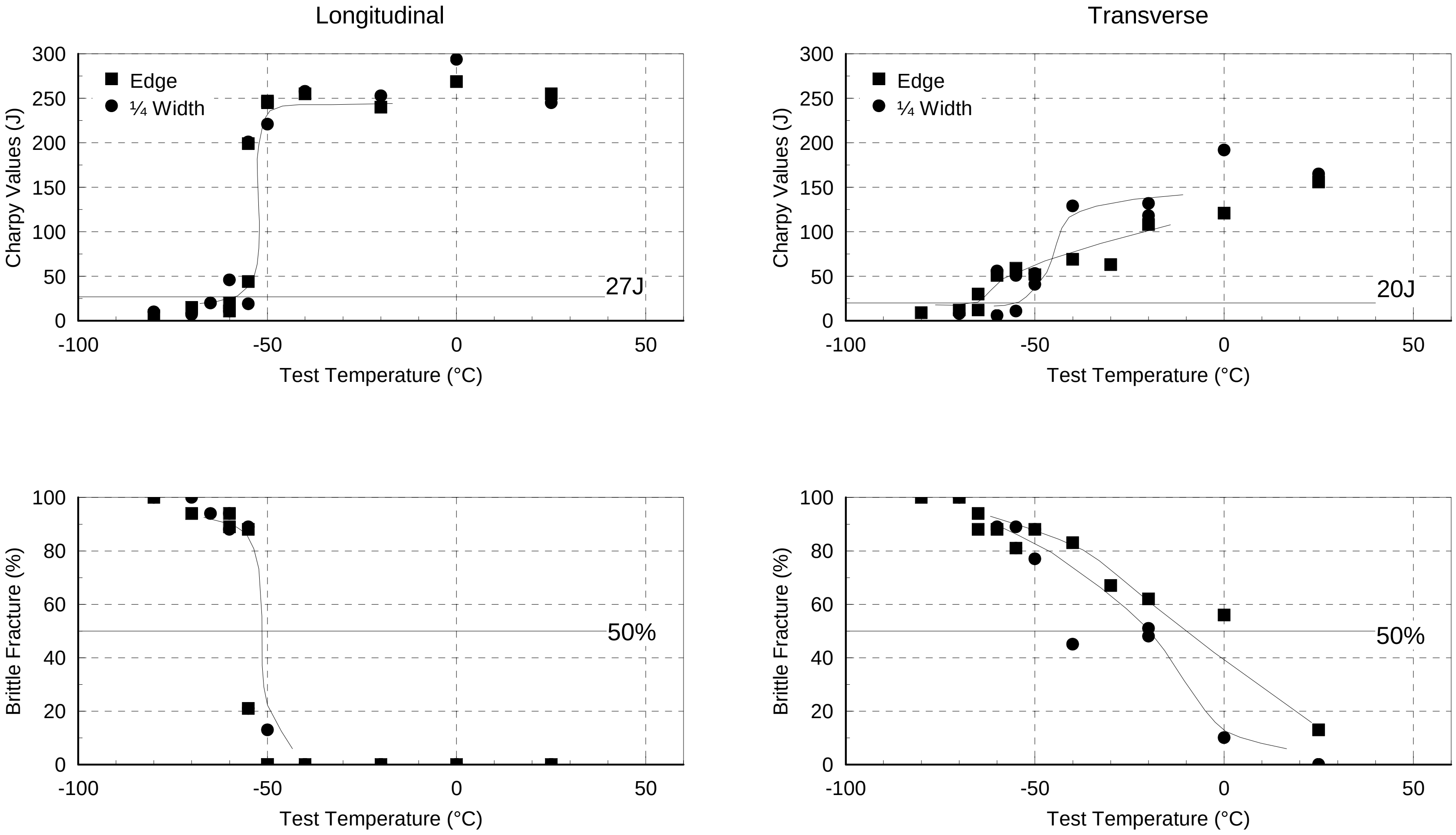

Figure 15
Charpy results for the Plate I End

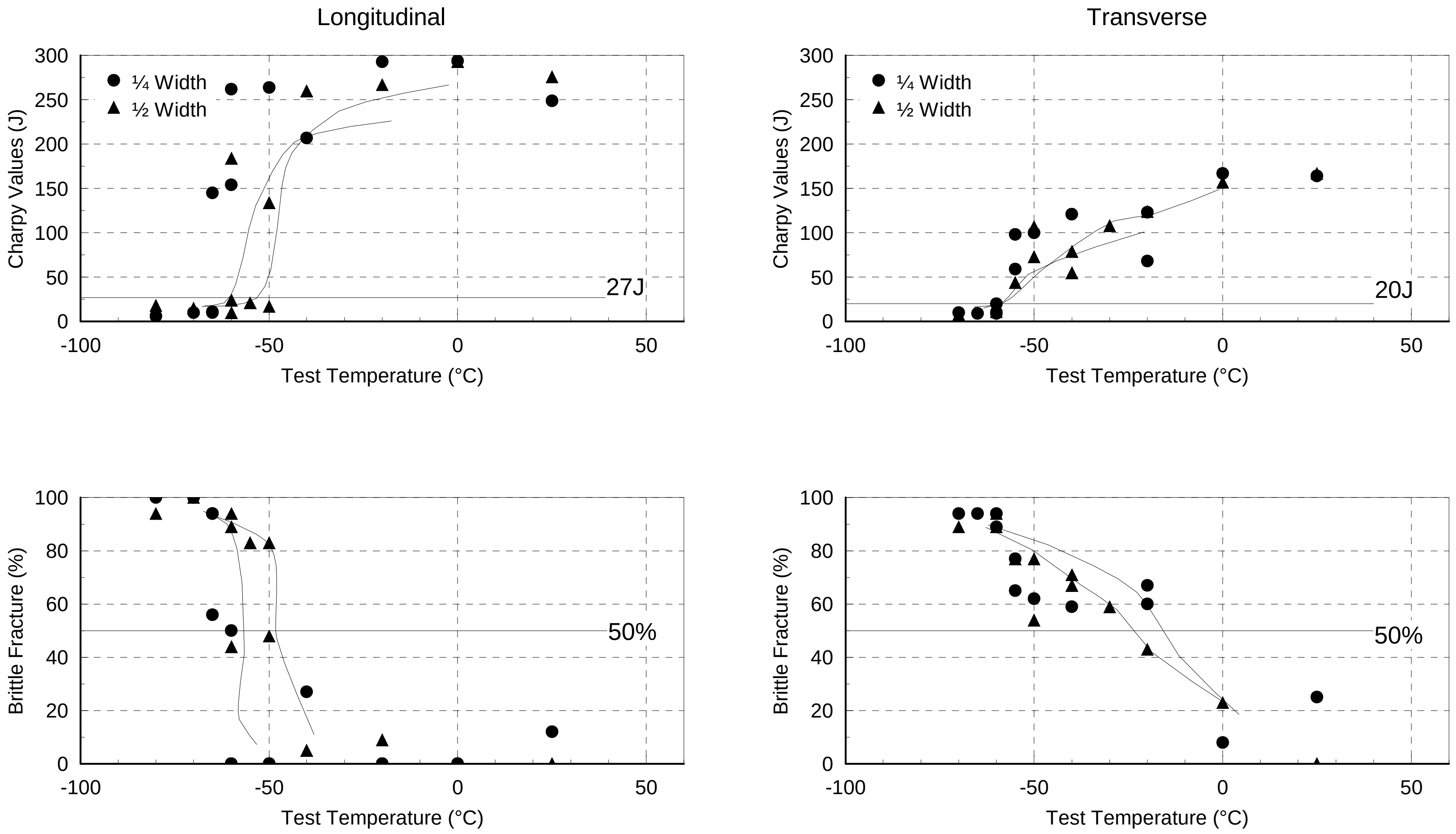

Figure 16
Charpy results for the Plate I Mid-Length

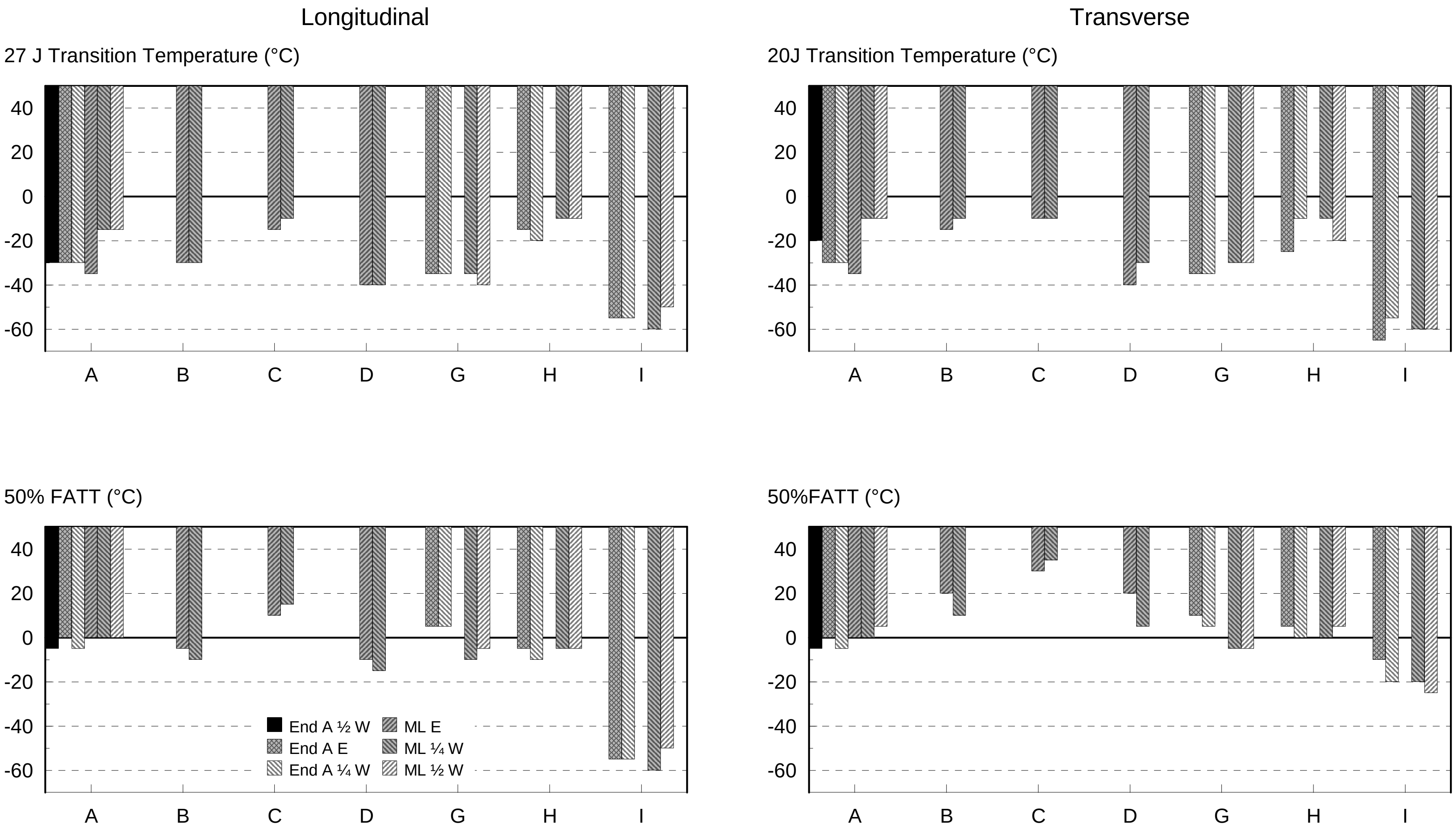

Figure 17
Transition temperatures determined from Charpy results

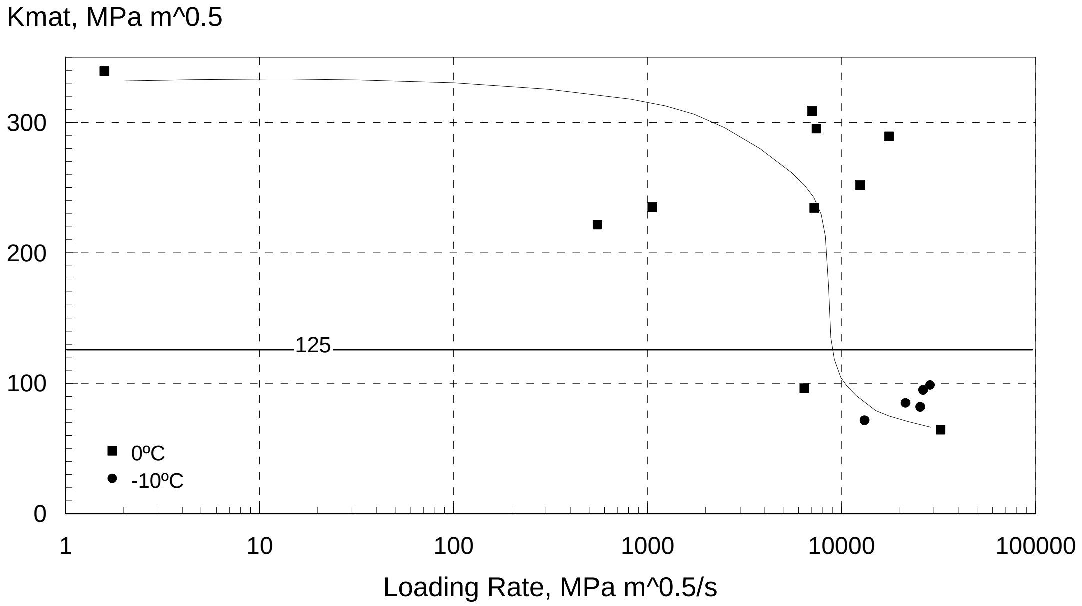

Figure 18
Strain rate sensitivity of K_{mat} - Plate A

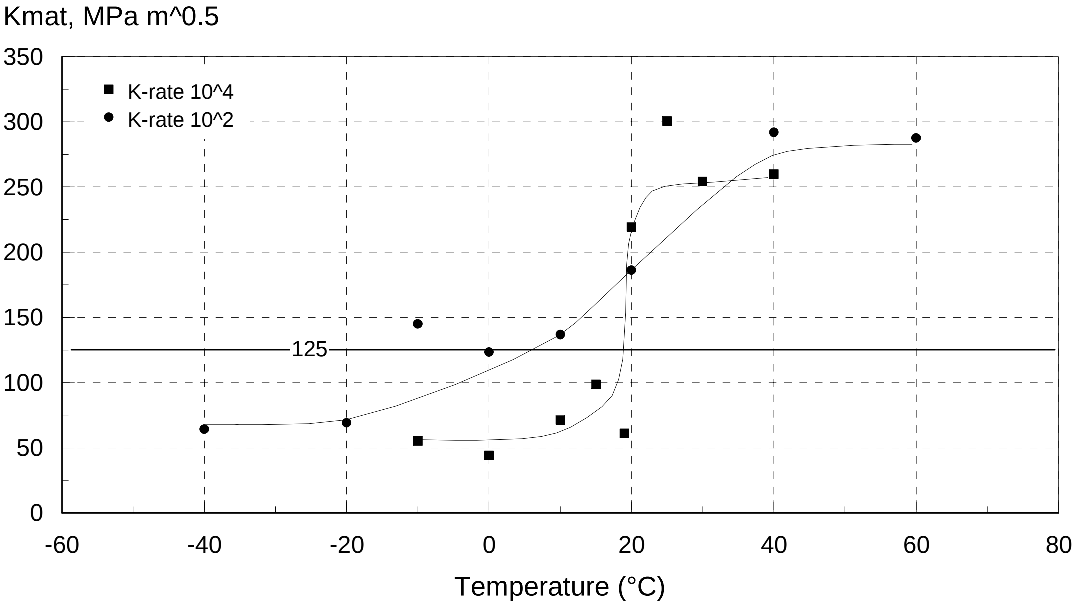

Figure 19
Temperature transition of K_{mat} - Plate C

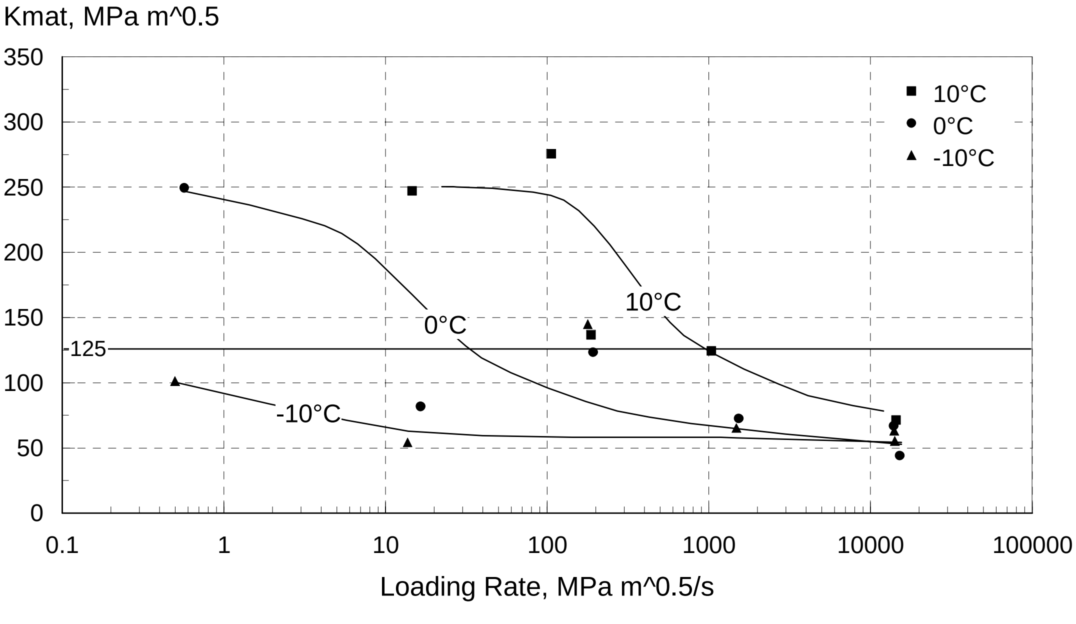

Figure 20
Strain rate sensitivity of K_{mat} - Plate C

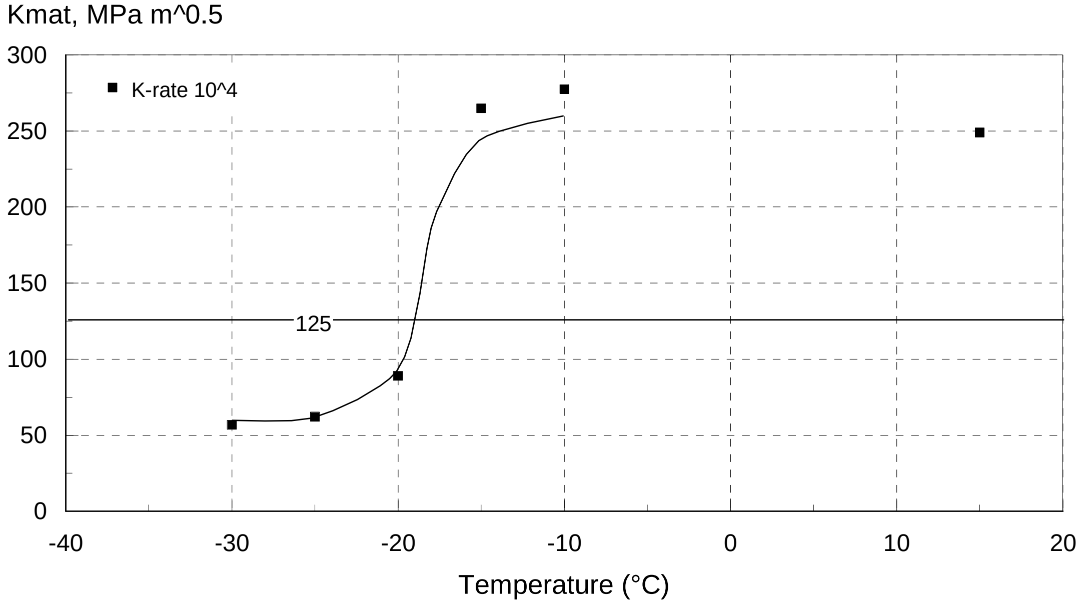

Figure 21
Temperature transition of K_{mat} - Plate G

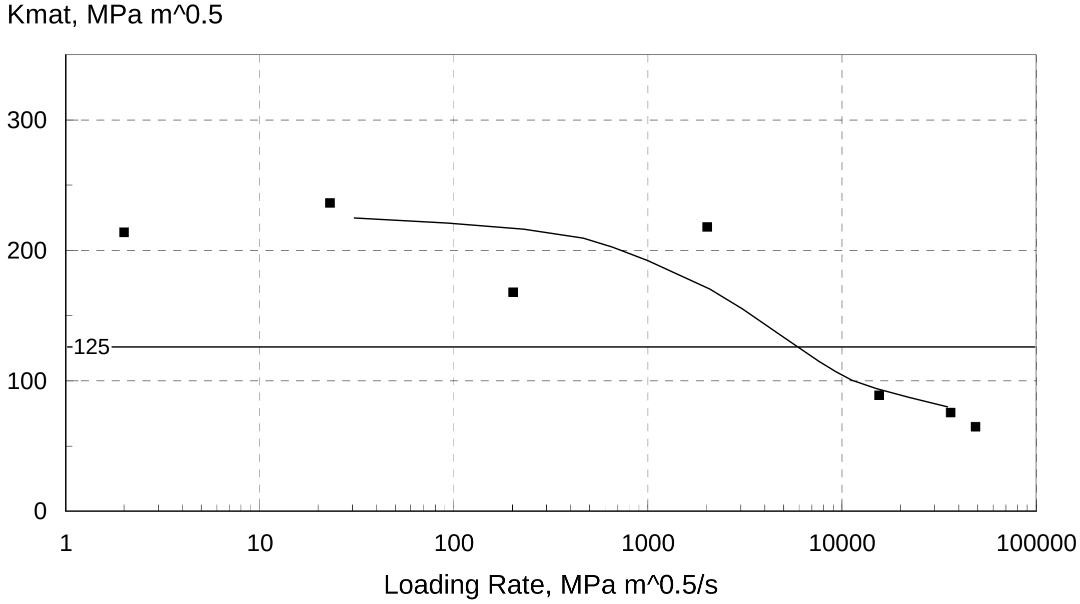

Figure 22
Strain rate sensitivity of K_{mat} - Plate G

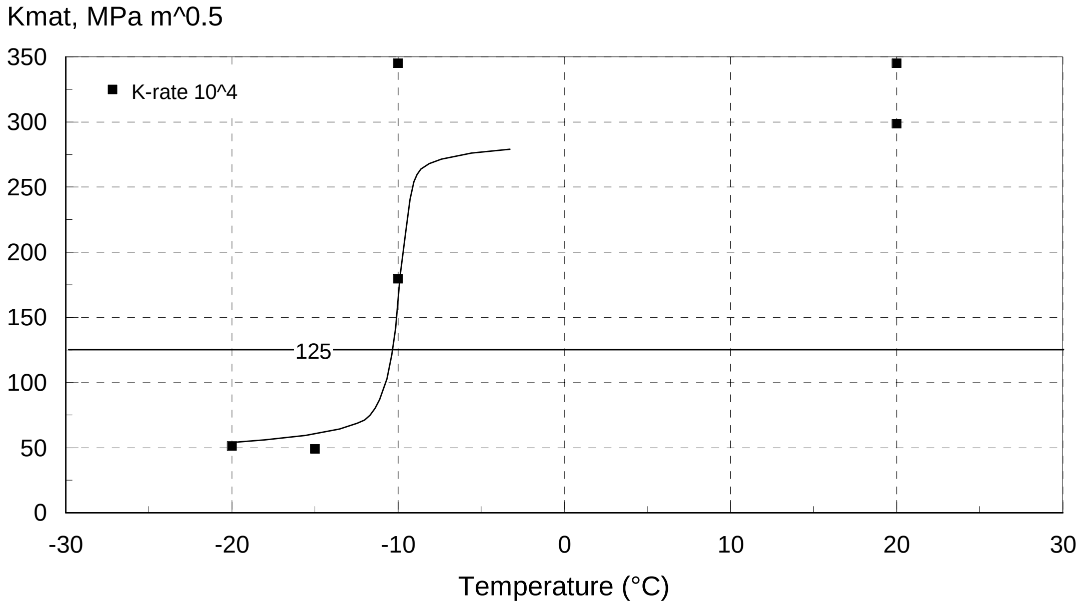

Figure 23
Temperature transition of K_{mat} - Plate H

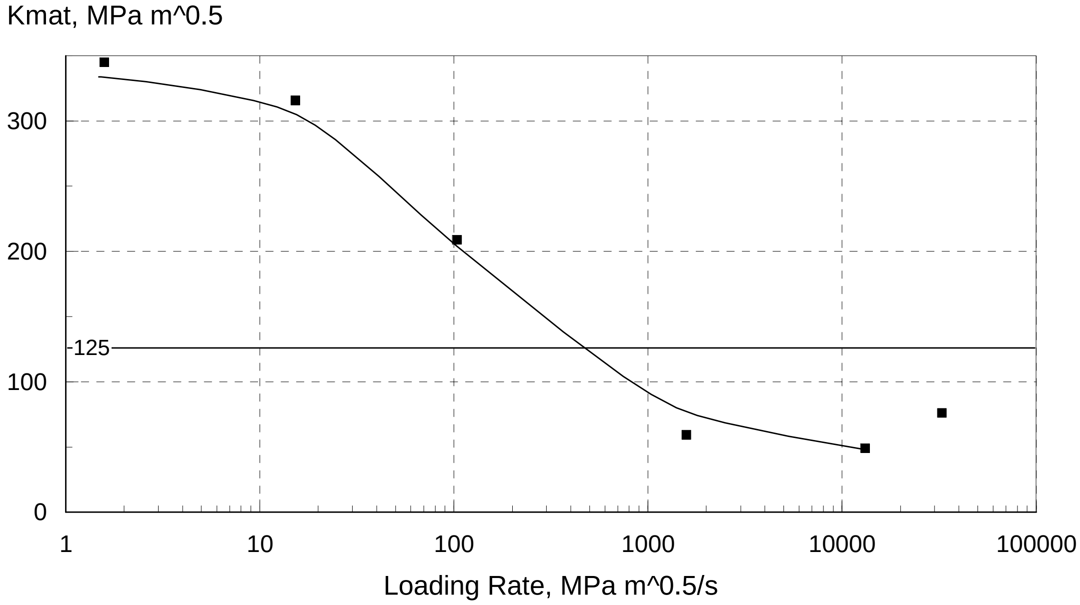

Figure 24
Strain rate sensitivity of K_{mat} - at -15°C - Plate H

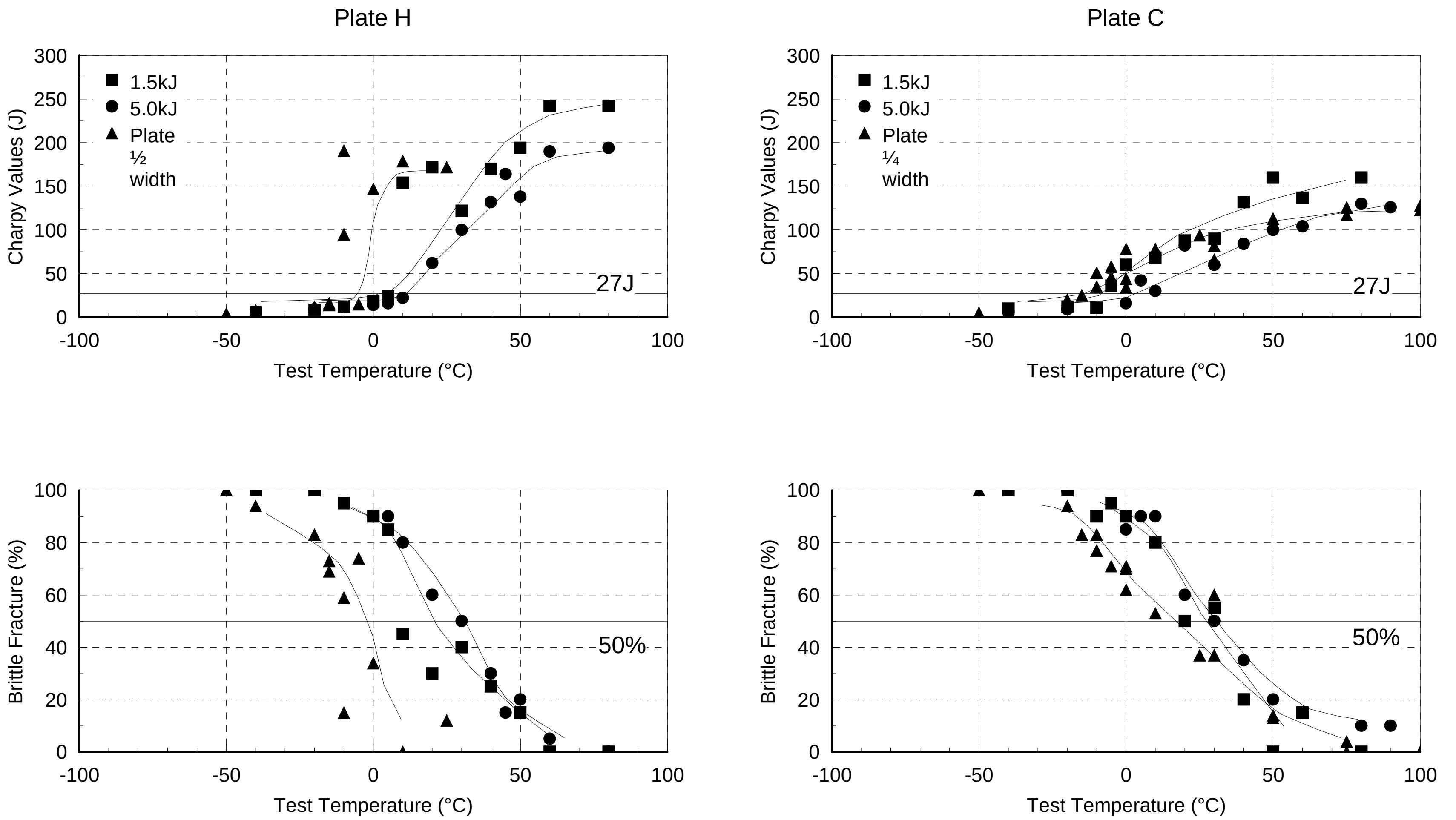

Figure 25
Charpy toughness of plates after thermal simulation

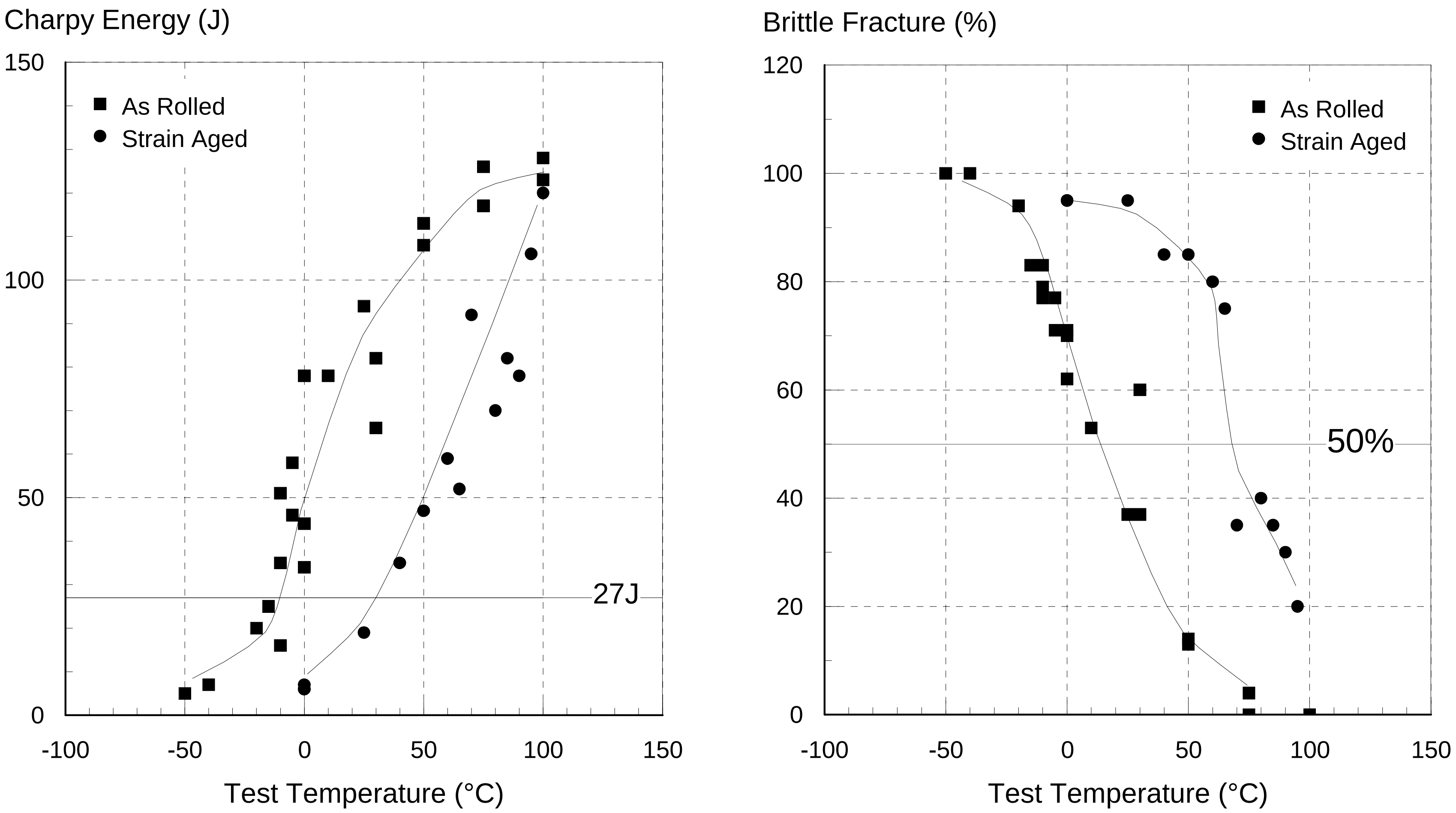

Figure 26
Charpy toughness after strain age treatment