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BS5500 Appendix D: An Assessment Based on Wide Plate Brittle Fracture Test Data

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ABSTRACT

This paper summarises an internationally funded assessment of the low temperature fracture toughness requirements of the British Standards Institution Document BS5500:1976, 'Specification for unfired fusion welded pressure vessels'. The assessment was based on an analysis of wide plate brittle fracture tests, supporting chemical compositions and small-scale mechanical test data from worldwide sources, all these data having been collated in a programme of work involving The Welding Institute (UK), Gent University Research Centre of Welding (Belgium) and Delft University of Technology Metallurgical Department (Netherlands).

The assessment showed that the BS5500 requirements are generally safe. However, attention is drawn to the relatively few wide plate test data that are available for section thicknesses less than 25 mm.

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NOMENCLATURE

e_f	fracture strain
e_Y	yield strain at +20 °C
σ_{Nf}	net section fracture stress
σ_Y	yield strength at +20 °C
σ_U	tensile strength at +20 °C
T	temperature
E	Young's modulus
C_v	Charpy V-notch energy
B	section thickness
MDT	minimum design temperature
MRT	materials reference temperature
HAZ	heat affected zone
sub-HAZ	sub-critical HAZ
WM	weld metal
fus. BOU	fusion boundary
AW	as-welded
PWHT	post weld heat treated
WPT	wide plate test specimens
MMA	manual metal arc
SA	submerged arc
MIG	metal inert gas
CO	CO_2 shielded arc
FCW	flux cored wire CO_2
ES	electroslag
EG	electrogas

INTRODUCTION

The selection of steels for a high resistance to brittle fracture initiation is commonly based on empirical correlations between Charpy V-notch impact test energies and service experience and/or large scale tests. In the case of such pressure vessel standards as BS1515, its successor BS5500, and the draft 'Requirements for the prevention of brittle fracture' prepared by ISO/TC11/SC2/WG15, the empirical correlations were obtained from the results of approximately 60 notched and welded Wells wide plate tension tests.[1] These tests were carried out in the early 1960s.

Since that time large numbers of wide plate tests, of various designs, have been carried out in laboratories around the world. For example, it was known that, by the late 1970s, the published literature contained more than 1000 wide plate test results for steels.

Following a suggestion by Gasunie and Shell, therefore, it was decided that all the accessible wide plate test data should be assembled and used for assessments of design standards. This decision led to the formation of an international sponsor group, and eventually to the collation of 1182 wide plate tests (WPTs) results and supporting data.[2]

This paper summarises an analysis[3] of the collated WPT data that was carried out to assess the low temperature requirements of the British Standards Institution document for pressure vessels BS 5500, Appendix D.

CLASSIFICATION OF MATERIALS

The WPT data were divided into eight categories determined by the parent metal chemical compositions. These are summarised in Table 1, which also indicates the numbers of WPTs in each category. It will be observed that 910 out of the total of 1182 WPTs involved carbon and carbon–manganese steels, i.e. Categories 1–3.

ANALYSIS OF DATA

This concerned correlations between the results of WPTs and Charpy V-notch impact tests which formed the basis of Figs. 1 and 2. From the viewpoint of this paper the main difference between the low temperature requirements of BS1515 and BS5500 concerns the fracture toughness requirements for weld metals. It is important to note, therefore, that the following sections of this report consider the requirements for weld region fracture toughness in relation to BS5500, Appendix D, Issue 3, May 1979, Section D.3.3.5.

Unfortunately, not all the WPT data collected were in a form that permitted direct correlation with BS5500, Appendix D. The criterion for the selection of materials in Appendix D was that they should be able to withstand deformations of 4 × yield point strain in the presence of a 10 mm long through-thickness notch. Unfortunately many of the WPT results gathered gave only the stress, not the strain of fracture.

TABLE 1
Classification of Base Metals

Distinguishing elements	*Categories*							
	1 (*583 tests*)	*2* (*296 tests*)	*3* (*31 tests*)	*4* (*3 tests*)	*5* (*105 tests*)	*6* (*16 tests*)	*7* (*45 tests*)	*8* (*103 tests*)
	Carbon and carbon-manganese steels			*High carbon steels, not in Cats. 1–3*	*Micro-alloyed steels, not in Cats. 1–4*	*Cr–Mo steels, not in Cats. 1–5*	*Ni steels not in Cats. 1–6*	*Other steels, not in Cats. 1–7*
	Coarse grained	*Fine grained*	*Fine grained but not in Cats. 1 and 2*					
C	<0·23%	<0·23%	<0·23%	≥0·23%	<0·23%	—	—	—
Cr	<0·4%	<0·4%	<0·4%	<0·4%	<1·0%	<3·0%	<0·4%	—
Ni	<0·4%	<0·4%	<0·4%	<0·4%	<1·5%	<0·4%	<11·0%	—
Mo	<0·2%	<0·2%	<0·2%	<0·2%	<0·5%	<1·3%	<0·2%	—
Nb	<0·02%	—	Mo <0·2% and/or ≥0·02%	—	—	—	—	—
V	<0·05%	—	Mo <0·2% and/or ≥0·05%	—	—	—	—	—
Ti	<0·02%	—	Mo <0·2% and/or ≥0·01%	—	—	—	—	—
Al	<0·01%	≥0·01%	—	—	—	—	—	—

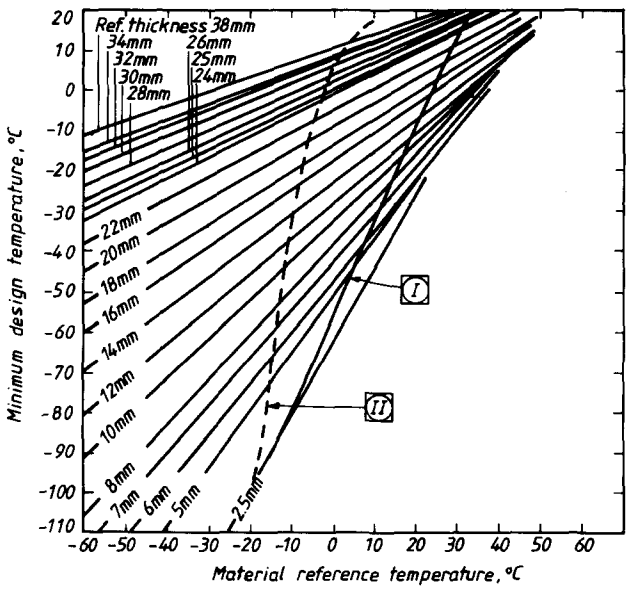


Fig. 1. Minimum design temperatures for as-welded components. (After BS1515, Appendix C and BS5500, Appendix D.)

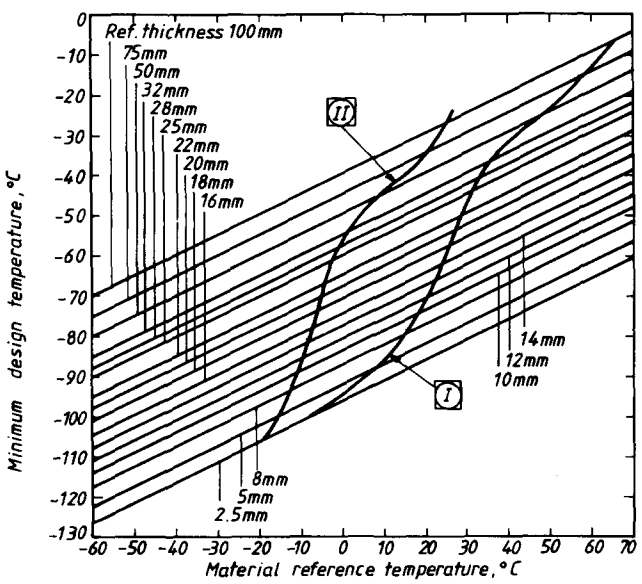


Fig. 2. Minimum design temperatures for post weld heat-treated components. (After BS1515, Appendix C and BS5500, Appendix D.)

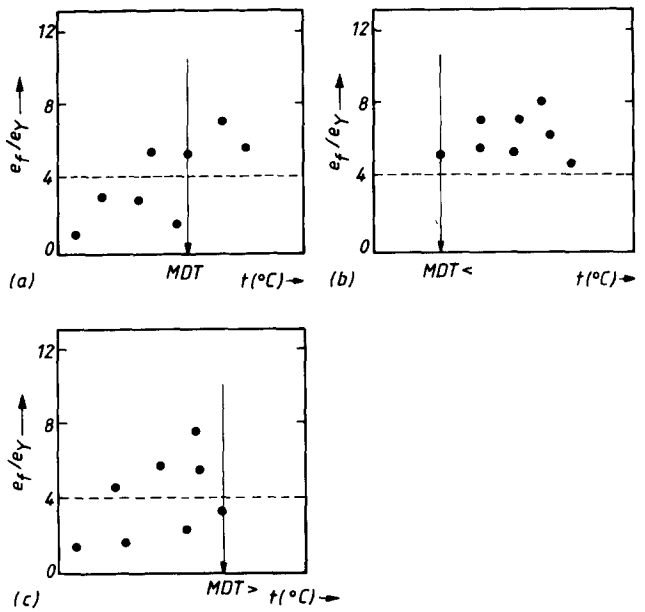


Fig. 3. Procedures for determining MDT from graphs of normalised fracture strain versus temperature. (a) and (b) The MDT was taken as the lowest temperature above which all values of $e_f/e_Y > 4{\cdot}0$. However, in test series where all $e_f/e_Y \geq 4{\cdot}0$ the MDT was defined as being less than the lowest test temperature. (c) Where fracture at the highest temperatures occurred with $e_f/e_Y < 4{\cdot}0$, the MDT was defined as being greater than the highest test temperature.

Therefore, to make use of both types of data, graphs were obtained of normalised fracture strain (e_f/e_Y) or normalised net section fracture stress (σ_{Nf}/σ_Y) versus temperature (T). The fracture strains and stresses were normalised by the relevant room temperature ($\simeq 20\,°C$) yield strength values, i.e. σ_Y/E and σ_Y respectively. However, in approximately 20 % of the tests analysed, yield strength values had not been measured and therefore the minimum specified yield strengths were used instead.

The e_f/e_Y and/or σ_{Nf}/σ_Y versus T graphs were used to determine the BS1515, and BS5500 minimum design temperatures (MDT), which corresponded to fracture strains of $4e_Y$. In many instances, however, it was difficult to determine the MDT. For example, in some series of WPTs only the fracture stresses were available, and values of $\sigma_{Nf}/\sigma_Y > 1{\cdot}0$ were clearly disguising values of $e_f/e_Y \gg 1{\cdot}0$. In other instances the computed values of e_f/e_Y were up to 100, which was considerably higher than the value of 4 associated with the MDT. Also, it was considered inevitable

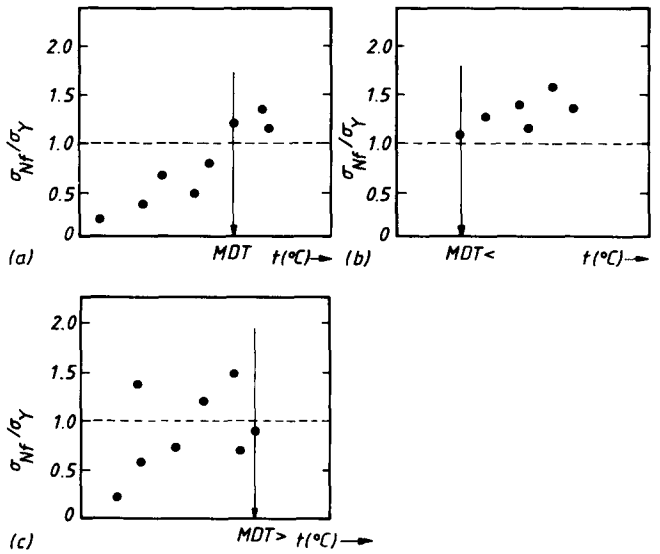


Fig. 4. Procedures for determining MDT from graphs of normalised stress versus temperature. (a) and (b) Where only fracture stresses were given, the MDT was defined as the lowest temperature above which all values of $\sigma_{Nf}/\sigma_Y > 1{\cdot}0$. However, in test series where all $\sigma_{Nf}/\sigma_Y \geq 1{\cdot}0$, the MDT was defined as being less than the lowest test temperature. (c) Where only fracture stresses were given and fracture at the highest temperatures occurred with $\sigma_{Nf}/\sigma_Y < 1{\cdot}0$, the MDT was defined as being greater than the highest test temperature.

that the high values of e_f/e_Y would be accompanied by ductile crack growth at the notch tips. To overcome these difficulties all values of $e_f/e_Y > 12{\cdot}0$ were plotted as being equal to 12·0 and the MDT values were defined with reference to Figs. 3 and 4 as follows:

1. The MDT was taken as the lowest temperature above which all values of $e_f/e_Y > 4{\cdot}0$. However, in test series where all $e_f/e_Y > 4{\cdot}0$, the MDT was defined as being less than the lowest test temperature; see Figs. 3a and 3b.
2. Where fracture at the highest temperature occurred with $e_f/e_Y < 4{\cdot}0$ the MDT was defined as being greater than the highest temperature; see Fig. 3c.
3. Where only fracture stresses were given, the MDT was defined as the lowest temperature above which all values of $\sigma_{Nf}/\sigma_Y > 1{\cdot}0$. However, in test series where all $\sigma_{Nf}/\sigma_Y > 1{\cdot}0$, the MDT was defined as being less than the lowest test temperature; see Figs. 4a and 4b.

4. Where only fracture stresses were given, and fracture at the highest temperatures occurred with $\sigma_{Nf}/\sigma_Y < 1{\cdot}0$, the MDT was defined as being greater than the highest test temperature; see Fig. 3c.

In some instances the MDTs appeared to be influenced by notch size. When this occurred the MDT was tabulated as being both greater and less than a specific value.

Graphs of Charpy V-notch impact energy (C_v) versus temperature were obtained for the plain plate materials corresponding to those series of wide plate tests for which the data were available. In most instances the Charpy results were for longitudinal specimens (extracted with their lengths parallel to the rolling direction and the line of the notch tip perpendicular to the plate surfaces). However, in some instances only transverse Charpy results were available or the orientation was unspecified. These cases were considered separately.

The C_v versus T graphs for the plain plate materials were used to determine the BS1515 and BS5500 materials reference temperatures (MRT). These are the temperatures that correspond to 27 and 40 J energy absorption in steels having actual tensile strengths $<450\ N/mm^2$ and $\geq 450\ N/mm^2$ respectively. Where actual tensile strengths were not available the minimum specified values were used. The MRTs were generally interpolated from the C_v versus T curves. In some instances it was necessary to extrapolate the data, in which case the MRT values were recorded as being greater than or less than a particular value. Sometimes the C_v data were given as the temperature corresponding to a single value of energy absorption, e.g. the 3·5 kg m temperatures. When this occurred, and the Charpy energy was between 20 and 47 J, the given temperature was converted to the MRT assuming a change in Charpy energy of 1·5 J/°C, as specified in BS1515 and BS5500.

The experimental MDT and MRT for each steel category in the as-welded (AW), post weld heat treated (PWHT), and plain material conditions were compared with the curves for the relevant thicknesses and conditions from the standards, i.e. the appropriate curves from Figs. 1 and 2. In doing this it was appropriate to compare the plain material data with the standard curves for one quarter of the section thicknesses for the PWHT condition (Fig. 2) as described later. Figure 5 is one example from a total of 35 such comparisons for different section thicknesses and conditions. It may be noted that, in order to obtain more information from the wide plate test data, the MRT scales and standard curves were extrapolated from $-60\,°C$ (in Figs. 1 and 2) to $-100\,°C$.

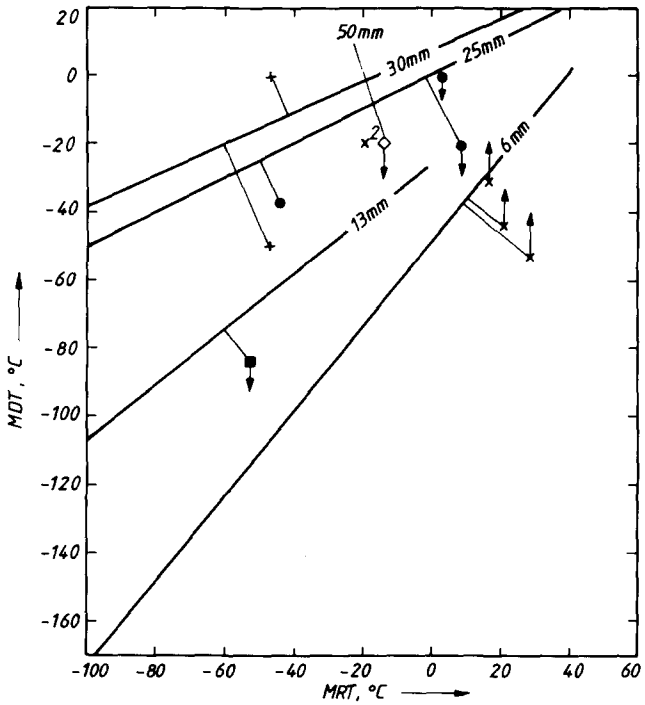


Fig. 5. Comparison of MDT and MRT for Category 1 steel as-welded wide plate tests. The symbols ×, ■, ●, + and ◇ refer to five specimen section thicknesses from 6 mm to 50 mm, filled symbols indicating MRT based on longitudinal Charpy properties and open symbols on transverse Charpy properties. Two coincident points are indicated by $\times^2$.

Correlations such as those in Fig. 5 were used to define the theoretical MDTs (based on the standard curves) corresponding to specific experimental MRTs and MDTs. Hence, the experimental MDTs were expected to be lower than the theoretical MDTs in order to demonstrate the safety of Figs. 1 and 2. However, it should be borne in mind when considering the following results that *according to BS1515 and BS5500, Figs. 1 and 2 are strictly relevant to the carbon and carbon–manganese steels in Categories 1 to 3 only.*

RESULTS FOR AS-WELDED WIDE PLATES

An examination of the results for all eight categories of steel showed 13 instances where, at first sight, the experimental MDTs were higher than

TABLE 2
Summary of As-welded WPT Data Indicating Experimental MDTs Greater than Theoretical MDTs

Steel category	*Type of WPT specimen, see Fig. 6*	*Plate numbers*	*Welding process*	*Plate thickness (mm)*	*Notch location*	*MRT (°C)*	*Experimental MDT (°C)*	*Theoretical MDT (°C)*	*Comments*
1	(a)	90–104	MMA	25	Sub. HAZ/WM	−10	−1	−6	No WM fracture toughness
1	(a)	110–123	MMA	25	Sub. HAZ/WM	−40	−15	−20	data available.
1	(b)	527, 528	ES	30	Fus. BOU/WM	−47	0	−14	Fus. BOU and WM fracture toughness did not meet full requirements of BS5500.
2	(c)	832–839	EG	20	WM	−64	$\leqslant -30$	−48	Net section yield at
2	(c)	840–845	EG	20	WM	−64	$\leqslant -30$	−48	temperatures > -30 °C. Also, WM fracture toughness did not meet full optimal requirements of BS5500.
4	(d)	782, 783	MMA	25	WM	−72	> -35	−36	No WM fracture toughness data available.
5	(c)	187–190	MMA	30	Fus. BOU	−66	−5	−22	No fus. BOU or WM
5	(c)	463, 464	MMA	30	Fus. BOU	−42	> -20	−22	fracture toughness data
5	(c)	470–472	SA	30	Fus. BOU	−66	> -20	−22	available.
5	(c)	479–481	SA	30	Fus. BOU	−61	> -20	−25	
5	(c)	191–193	MMA	30	Fus. BOU	−61	−20	−25	
5	(c)	461, 462	MMA	30	Fus. BOU	−61	> -20	−25	
5	(c)	467–469	SA	30	WM	−66	> -20	−22	No WM fracture toughness data available.

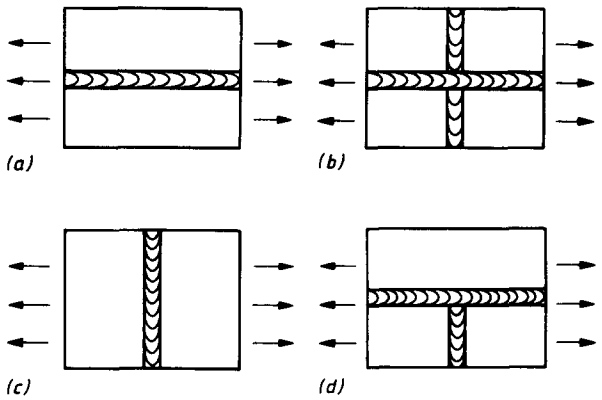


Fig. 6. Different types of wide plate tests considered in the text.

the theoretical values, i.e. instances suggesting that the standards might be unsafe. Detailed considerations of the individual results showing that this is not necessarily so are given below and summarised in Table 2.

Category 1 steel—AW plates Nos. 90–104 and 110–123 (Table 2)

These plates were of the classical single weld Wells WPT form (similar to Fig. 6a) and contained double chevron notches cut into the plate edges before welding. In these test specimens the notch tips are generally referred to as being located in the sub-critical heat affected zone (HAZ). However, in single weld specimens each chevron notch also has one tip located in weld metal. It is possible, therefore, that fracture initiation in the present Wells WPTs may have been controlled by fracture initiation in weld metal. Unfortunately, no weld metal fracture data were available for these test results.

Category 1 steel—AW plates Nos. 527–528 (Table 2)

In this case the procedure for determining the MDT may have exaggerated the difference between the experimental and theoretical values, since WPT specimens 527 and 528 give values of e_f/e_Y of 0·5 and > 12 at −20 and 0 °C, respectively. Therefore, further tests between −20 and 0 °C may have defined a lower experimental MDT.

Other details of interest are the fact that these were cross-welded WPT specimens (Fig. 6b). The WPT specimen which fractured, No. 527, contained a through-thickness notch having one tip in the fusion

boundary region of the crossing weld and one tip in the edge of the longitudinal weld. Also, the brittle fracture in this specimen propagated along the fusion boundary region of the crossing weld. The original reference to these tests[2] indicated that the electroslag fusion boundary region and centre of weld metal gave C_v energies of approximately 20 and 40 J, respectively, at the WPT temperature of $-20\,°C$. These C_v values would not meet the full requirements of BS5500. For instance, unless otherwise agreed between the purchaser and the manufacturer, the HAZs of welds made using heat inputs >5 kJ/mm are required to meet the minimum requirements of the parent material, which in this case amounted to 40 J at the MRT ($-47\,°C$). Similarly, the present weld metal gave only 7 J at the MRT, whereas at this temperature BS5500 would require a minimum average value of 30 J in the weld metal for plates having yield strengths $\leq 300\ N/mm^2$, and a value of 40 J for plates having yield strengths $>300\ N/mm^2$. The present plate material had a room temperature yield strength of $302\ N/mm^2$.

Finally, it is also relevant to point out that both BS1515 and its replacement BS5500 state that automatic welding processes other than the submerged arc process (e.g. the electroslag process) should not be used unless the manufacturer has clearly disclosed his intention to do so, and the purchaser has agreed to the proposed procedure.

Category 2 steel—AW plates Nos. 832–839 and 840–845 (Table 2)

These wide plates contained through-thickness notches in the centre of the weld metals. Except for differences in crack size, the plates had similar overall dimensions and transverse weld forms (see Fig. 6c); but had been welded using different welding wires. Consequently the weld metals in plates Nos. 832–839 overmatched the parent material yield strength by a factor of 1·14, whereas the weld metals in plates Nos. 840–845 undermatched the parent material yield strength by a factor of 0·89.

Since all the tests had been carried out at $-30\,°C$, the MDTs in Table 2 were tabulated as being greater than or less than this temperature, depending on crack size. Unfortunately, for the present test results, the definition of the MDT as the temperature corresponding to $4e_Y$ has led to an anomalous interpretation of some of the test results. This was due to the fact that the $4e_Y$ strain criterion was intended for situations where fracture occurs under conditions of gross section yield, not situations where sufficiently large ratios of crack size to plate width result in full yield

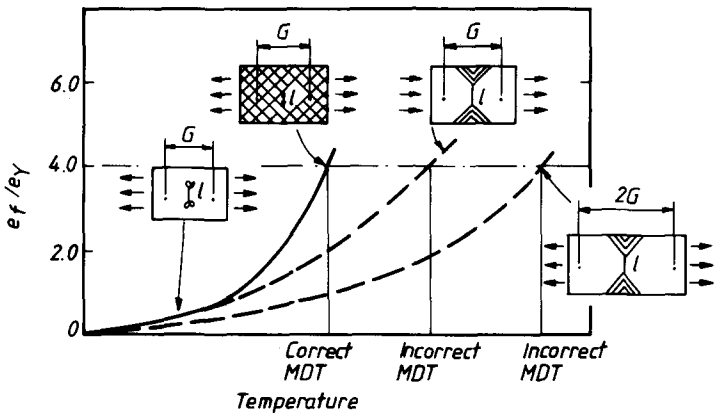


Fig. 7. Influence of deformation mode and gauge length on the MDT.

of the net sections only. The yielding behaviour is important, since once net section yielding occurs the apparent overall strain measured across the notch is inversely proportional to the gauge length. For example, reducing the gauge length used in the present tests from 200 to 100 mm would have had the effect of doubling the apparent overall strains. Therefore when net section yielding only occurs, the overall strain measurements are not simply related to the MDT, as illustrated in Fig. 7.

For the present tests, gross section yielding was confined to the overmatching yield strength plates Nos. 832–834 and the undermatching yield strength plate No. 840, which had ratios of notch length to plate width of $\leq 0{\cdot}18$ and $0{\cdot}091$, respectively. In all these tests the values of e_f/e_Y were > 12, which indicates that the correct MDTs were $< -30\,°C$.

The above discussion exemplifies a difficulty in interpreting the overall strains which applies to some of the later test results. However, from the viewpoint of BS5500, further discussion of the present electrogas welded wide plates is not justified, since, quite apart from any objection to using electrogas process in the as-welded condition, the present weld metals failed to meet the Charpy V-notch impact energy requirement of 40 J at the MRT, i.e. $-64\,°C$.

Category 4 steel—AW plates Nos. 782 and 783 (Table 2)

These wide plates contained sawn notches in manual metal arc (MMA) welds in the 'T weld' configuration shown in Fig. 6d. The plates contained surface notches 48 mm long × 6 mm deep and 96 mm long × 6 mm deep,

respectively. Unfortunately the original reference to these tests (confidential) did not contain the relevant weld metal fracture toughness data.

Category 5 steel—AW plates Nos. 187–190, 463–464, 470–472, 479–481, 191–193 and 461–462 (Table 2)

These examples concerned 300 mm wide × 30 mm thick plates having single central MMA and SA welds aligned at 90° to the loading direction (Fig. 6c). The plates contained central surface fatigue cracks ranging from 50 to 65 mm in length and 10 to 17 mm in depth, which were located in weld fusion boundary regions after welding. Fracture propagation generally followed these regions, but in some instances there was a definite tendency for fracture propagation in weld metal. For this reason it was unfortunate that no weld fusion boundary nor weld metal fracture toughness data were available for any of the following series of wide plate test specimens.

Plates Nos. 187–190 gave an experimental MDT of −5 °C, which was 17 °C above the theoretical value. These plates contained MMA welds in which the yield strengths undermatched those of the base metal.

Plates Nos. 463–464 contained an overmatching yield strength MMA weld metal. The results for these plates suggest an experimental MDT > −20 °C, which is >2 °C higher than the theoretical value.

The submerged arc welded plates, Nos. 470–472, contained an undermatching yield strength weld metal and resulted in an estimated MDT of > −20 °C, which, as in the previous series of tests, is >2 °C higher than the theoretical MDT.

At this point it is worth noting that the three series of wide plates referred to above were prepared from the same base metal. Also, the next three series of wide plates were prepared from a similar base material, but one of slightly lower strength.

Plates Nos. 479–481 were welded using an undermatching yield strength submerged arc weld. The experimental MDT was estimated as being > −20 °C. The theoretical MDT was −25 °C.

Plates Nos. 191–193 contained overmatching yield strength MMA welds. For these plates the experimental and theoretical MDTs were −20 and −25 °C, respectively.

Plates Nos. 461–462: for both of these MMA welded plates the experimental MDTs were estimated as > −20 °C, as compared to −25 °C for the theoretical values. However, plate 461 contained an overmatching

yield strength weld metal which was deposited in the flat position, whereas plate 462 contained an undermatching yield strength weld metal that was deposited in the vertical position.

Category 5 steel—AW plates Nos. 467–469 (Table 2)

These submerged arc welded plates were virtually identical to plates Nos. 470–472 (mentioned above), except that the notches were positioned in the centre of the weld metal instead of in the weld fusion boundary. It seems significant, therefore, that both series of wide plates gave an experimental MDT $> -20\,°C$. This similarity in fracture behaviour could be due to the weld metal controlling the fracture behaviour in both series of wide plate tests. In fact, the possibility cannot be ruled out that all the higher than theoretical MDT values discussed so far were due to fracture initiation in weld metal. Unfortunately, the C_v properties for the weld metals and HAZs were rarely available.

RESULTS FOR PWHT WIDE PLATES

There were 12 instances where the results for the PWHT plates gave experimental MDTs that were higher and therefore on the potentially unsafe side of the theoretical values. These instances are summarised in Table 3 and are further discussed below.

Category 2 steel—PWHT plates Nos. 766, 768–769 and 771 (Table 3)

These plates contained crossing (Fig. 6b) electroslag and MMA welds. The electroslag welds were made first and then double chevron notches were cut into the electroslag weld HAZ before making the crossing MMA welds. These welds were aligned parallel to the loading direction, as shown in Fig. 6b. The wide plate test specimens were therefore similar to the classical Wells WPT specimens, except that the double chevron notches had one tip in the HAZ of the transverse electroslag welds, instead of one tip being located in the sub-critical HAZ of the longitudinal weld in plate material. Plates Nos. 766, 768 and 769 were in the stress relieved condition. These resulted in an experimental MDT of $> -26\,°C$, which was $>28\,°C$ above the theoretical value for 40 mm thick plates (Table 3). Assuming agreement between purchaser and manufacturer,

TABLE 3
Summary of PWHT WPT Data Indicating Experimental MDTs Greater than Theoretical MDTs

Steel category	*Type of WPT specimen, see Fig. 6*	*Plate numbers*	*Welding process*	*Plate thickness (mm)*	*Notch location*	*MRT (°C)*	*Experimental MDT (°C)*	*Theoretical MDT (°C)*	*Comments*
2	(b)	766, 768, 769	ES/MMA	40	Fus. BOU-ES, WM-MMA	−3	> −26	−54	No directly relevant Fus. BOU and WM C_v data available.
2	(b)	771	ES/MMA	40	Fus. BOU-ES, WM-MMA	−3	> −42	−54	
2	(b)	762, 770, 772	ES/MMA	40	WM-ES	−3	> −35	−54	WM C_v properties would not meet requirements of BS5500, Appendix D.
5	(c)	175–177	MMA	30	Fus. BOU	−66	> −20	−89	No WM or Fus. BOU fracture toughness data available.
5	(c)	184–186	MMA	30	Fus. BOU	−66	> −20	−89	
5	(c)	460	MMA	30	Fus. BOU	−66	> −35	−89	
5	(c)	476–478	SA	30	Fus. BOU	−66	> −20	−90	
5	(c)	482–484	SA	30	Fus. BOU	−71	> −20	−91	
5	(c)	517–519	SA	100	Fus. BOU	−29	>0	−54	No WM or Fus. BOU fracture toughness data available.
5	(c)	473–475	SA	30	WM	66	> −20	−90	No WM fracture toughness data available.
5	(b)	486	MMA	63	WM	< −10	> −10	−53	WM C_v did not meet requirements of BS5500.
8	(c)	754–758	MMA	25–28	HAZ	<< 0	−40	−60	Notches greater than 10 mm long.

these welds would be acceptable, according to BS5500, provided that the HAZ had at least the same Charpy properties as the base metal. Unfortunately, no HAZ fracture toughness data were available. In addition to the HAZ requirements, BS5500 would require the weld metals in this instance to have a minimum average Charpy energy of 30 J at the theoretical MDT +20 °C (= −34 °C). No Charpy energy values were available for the MMA welds, but a value of 30 J at 0 °C was reported for the electroslag weld metal, from which it is reasonable to conclude that the electroslag weld would have had an unacceptably low Charpy energy at −34 °C.

Plate No. 771 was identical to those above, except that it was normalised instead of stress relieved. Although this difference in PWHT appeared to have no significant effect on the weld metal C_v, it cannot be assumed that the same would be true for the HAZ. The experimental MDT for this plate was > −42 °C, which is >12 °C higher than the relevant theoretical value (Table 3).

Category 2 steel—PWHT plates Nos. 762, 770 and 772 (Table 3)

These plates were part of the same test series described above, and the only differences concerned the fact that these plates were in the normalised condition and contained notches in the centre of the crossing electroslag welds. The experimental MDT (> −35 °C) was >19 °C higher than the theoretical MDT. Also, the normalised electroslag weld metal C_v energy of 29 J at 0 °C is clearly inferior to the value of 30 J at −34 °C (= MDT +20 °C), which is the requirement for a 40 mm thick PWHT weld metal according to BS5500, Appendix D.

Category 5 steel—PWHT plates Nos. 175–177, 184–186, 460, 476–478 and 482–484 (Table 3)

These plates gave five examples of high experimental MDTs. All involved 300 mm wide × 30 mm thick plates containing single welds orientated at 90° to the loading direction (Fig. 6c). All the wide plates contained central surface fatigue cracks ranging from 50 to 65 mm in length and 10 to 17 mm in depth, which were positioned in the weld fusion boundaries. It will be recognised, therefore, that these WPT specimens were similar and complementary to some of the as-welded specimens that were referred to earlier, i.e. plates Nos. 187–190, Table 2.

The results were also similar to those obtained for the as-welded specimens. For example, the experimental MDTs were of the same order of magnitude, and the fractures tended to propagate into the weld metal. However, as in the case of the as-welded wide plates, no weld metal Charpy properties were available for the PWHT WPT specimens.

Category 5 steel—PWHT plates Nos. 517–519 (Table 3)

Although of similar design to those immediately above, the wide plates involved much larger dimensions, being 800 mm wide × 100 mm thick. Also, surface notches 80 mm long × 20 mm deep were positioned in the weld fusion boundaries. These plates gave an experimental MDT > 0 °C, which was 54 °C higher than the theoretical MDT. In these plates the fractures propagated out of the fusion boundary and into the weld metal. Once again, no weld metal Charpy properties were available.

Category 5 steel—PWHT plates Nos. 473–475 (Table 3)

These plates were similar to plates Nos. 476–478, except that the present plates had surface notches in the centre of the weld metal instead of in the weld fusion boundary. Nevertheless, for both series of wide plates the experimental MDTs were > -20 °C. It will be recalled that the same pattern of behaviour was observed in relation to the similar series of as-welded wide plates, Nos. 467–469 and 470–472, which contained notches in weld metals and weld fusion boundaries, respectively. In all these instances, no weld metal nor fusion boundary fracture toughness data were available.

The cross-welded (see Fig. 6b) 63 mm thick plate No. 486 fractured from a double chevron notch in the weld metal where the two MMA welds crossed. This test indicated an experimental MDT > -10 °C, which was >43 °C higher than the theoretical value. This might be expected as the fracture occurred in a weld metal which had a C_v energy that was significantly lower than that required by BS5500, Appendix D. In this instance the standard would require a C_v energy of 40 J at a temperature not exceeding the MRT (less than -10 °C for the 63 mm thick material), whereas the present weld metal gave only 24 J at -10 °C.

Category 8 steel—PWHT plates Nos. 754–758 (Table 3)

The 25 to 28 mm thick plates contained single MMA welds at 90° to the

loading direction (Fig. 6c) and central through-thickness notches. The notches were 30 mm long and were sited in an undefined region of the weld HAZ. These plates gave an experimental MDT of $-40\,°C$, which was at least 20 °C higher than the theoretical value. It may be noted that the fractures in these plates tended to propagate in the HAZ and base metal. The weld HAZ gave mean Charpy V-notch impact energy absorptions of 63 J at $-40\,°C$ and <94 J at the estimated MRT of $<0\,°C$. It may be noted that the present experimental MDT would be unsafe according to BS5500 except for the fact that this standard does not apply to notches >10 mm long, nor to Category 8 steels.

RESULTS FOR PLAIN MATERIAL WIDE PLATE TESTS

BS5500, Appendix D, Issue 3, May 1979, Section D.2.2.3.6 states that unwelded items (i.e. plain materials) should be taken as stress relieved and the reference thickness (B) should be taken as *one-quarter* of the thickness of the item. This requirement is a somewhat arbitrary one, and it is understood that it was adopted to prevent the use of exceptionally brittle materials, even though no brittle fractures of pressure vessels were known to have started in plain material. Regardless of whether this is correct, the fact remains that the plain plate requirements exist, and they could encourage the application of the same requirements in other applications. Thus, it was seen as encumbent on the present investigations to demonstrate the adequacy of the plain plate materials to achieve the specified pre-fracture strain of $4e_Y$ at the theoretical one-quarter thickness MDT.

There were 10 instances where the experimental MDTs appeared to be higher than the theoretical MDTs implied by the 'quarter thickness' or $B/4$ curves. These instances are summarised in Table 4 and discussed in more detail below.

Category 1 steel—plain material plates Nos. 550–555, 558–561 and 564 (Table 4)

All these test plates were 14 mm thick and 111 to 1000 mm wide and contained central through-thickness notches ranging in length from 32·1 to 500 mm. All the plates were tested at $-30\,°C$ and gave pre-fracture strains of $<4e_Y$ ($=0{\cdot}51\,\%$). Therefore it appeared initially that the

TABLE 4
Summary of Plain Material WPT Data Indicating Experimental MDTs Greater than Theoretical MDTs

Steel category	*Plate numbers*	*Plate thickness B (mm)*	*Notch type*[a]	*MRT (°C)*	*Experimental MDT (°C)*	*Theoretical MDT*[b] *(°C)*	*Comments*
1	550–555	14	CTN	+22	> −30	−85	Notch length/plate thickness >2·0 and notch length/plate width >0·03 generally resulted in failure accompanied by net section yielding (see Fig. 7); therefore tabulated experimental MDT was too high.
1	558–561 564	14	CTN	+22	> −30	−85	
2	744–753	30	CTN	−21	> −20	−99	Notch length/plate thickness = 1·0 and notch length/plate width = 0·081, which generally resulted in failures being accompanied by net section yielding. Consequently the tabulated experimental MDT was too high.
5	723–783	30	CTN	−86	−20	−132	
5	852–856	30	CTN	−86	≲ +20	−132	The upper limits of tabulated experimental MDTs were based on different notch lengths and net section yielding and were generally too high.
5	857–863	30	CTN	−86	≲ −40	−132	
5	864–867	30	CTN	−86	≲ −55	−132	
8	713–722	31	CTN	+6	> +20	−86	The experimental MDT was only relevant to a 30 mm long notch.
8	734–743	30	CTN	−30	+20	−104	The experimental MDT was based on net section yielding and was therefore too high.
8	793–824	31	CTN	< −50	> +20	−115	The tabulated experimental MDT was based on a notch length of 4 mm.

[a] CTN refers to central through-thickness notch
[b] Based on $B/4$

experimental MDT was $> -30\,°C$, which was approximately 55 °C higher than the theoretical MDT of $-85\,°C$ as given by the relevant $B/4$ curve in Fig. 2.

A more detailed examination of the results showed that the overall strains to fracture were a function of the relative notch sizes. In fact all the wide plates referred to above had notches with lengths greater than twice the plate thickness and greater than $0{\cdot}03\times$ the plate widths, which generally resulted in net section yielding. Hence, as illustrated in Fig. 7, the experimental MDTs were overestimated in these instances. This observation was confirmed by other wide plate tests in the same series that contained smaller notches and failed by gross section yielding at larger overall strains, thus indicating experimental MDTs less than the testing temperature of $-30\,°C$. Clearly, an experimental MDT equal to the theoretical value of $-85\,°C$ would involve notch lengths that were less than the plate thickness.

Category 2 steel—plain material plates Nos. 744–753 (Table 4)

These plates were 30 mm thick and 370 mm wide and contained 30 mm long through-thickness sawn notches. The experimental MDT for these plates was tabulated as $> -20\,°C$. This was the highest test temperature used for these wide plate tests, and it coincided with an overall strain of $0{\cdot}29\,\%$, which was significantly less than the $4e_Y$ MDT strain criterion (in this instance $0{\cdot}71\,\%$). However, a more detailed examination of the results showed that the majority of the specimens fractured after net section yielding. In fact, fractures occurred by net section yielding at temperatures down to at least $-80\,°C$. Therefore, had the plates contained notches less than 30 mm long or had the plates been wider than 370 mm, gross section yielding may have occurred with concomitantly larger overall strains at temperatures down to at least $-80\,°C$, which represents a more realistic experimental MDT and one that is much closer to the relevant theoretical value of $-99\,°C$.

Category 5 steel—plain material plates Nos. 723–733 and 852–867 (Table 4)

Plates Nos. 723–733 were 30 mm thick and 370 mm wide and contained 30 mm long through-thickness notches. The steel had a yield strength of 717 N/mm^2 at approximately 20 °C, and therefore a $4e_Y$ strain of $1{\cdot}39\,\%$.

Apart from the different steel and higher yield strength, therefore, these wide plates were identical to those described above, i.e. plates Nos. 744–753. As in the latter tests, plates Nos. 723–733 showed a large difference between the tabulated experimental value of MDT (−20 °C, Table 4) and the lowest temperature for net section yielding, which in these plates was also down to at least −80 °C. Furthermore, it was observed that the wide plate tested at the next lower temperature, −97 °C, fractured with an overall strain of 0·41 % under conditions of contained yielding. It seems probable, therefore, that notches <30 mm long and possibly wider test plates would result in gross section yielding and an experimental MDT at a temperature < −100 °C, which is approaching the theoretical MDT of −132 °C for these plates.

Plates Nos. 852–867 were manufactured from a steel having a yield strength of 692 N/mm^2 at approximately 20 °C, which corresponds to a $4e_Y$ strain of 1·34 %. These plates were 30 mm thick and 110 mm wide and contained central through-thickness sawn notches ranging in length from approximately 6 to 30 mm. This range of notch lengths was used for series of tests at each of three temperatures, e.g. plates Nos. 852–856, 857–863 and 864–867 were tested at 20, −40 and −55 °C, respectively. The test results showed that notches less than approximately 7 mm long were associated with pre-fracture gross section yielding and overall strains > 2 % down to the temperature of −55 °C. In other words, plates having notches <7 mm long gave acceptable experimental MDTs < −55 °C. However, even at this temperature, full net section yielding was occurring with notches up to 30 mm long. The question remains, therefore, whether gross section yielding could be maintained in wider specimens or specimens containing notches shorter than 7 mm at temperatures down to the theoretical MDT of −132 °C.

Category 8 steel—plain material plates Nos. 713–722 and 734–743 (Table 4)

In common with many of the previously discussed WPT specimens, all these plates were approximately 30 mm thick and 370 mm wide and contained 30 mm long through-thickness sawn notches.

The steel used for plates Nos. 713–722 had a yield strength of 1074 N/mm^2 at approximately 20 °C, which corresponds to a $4e_Y$ strain of 2·1 %. Although these tests were carried out over a wide range of temperatures (20 to −150 °C), all the specimens fractured in a brittle

manner under contained yielding conditions. The highest overall strain, 0·38 %, occurred at +20 °C. Thus, the experimental MDT for a 30 mm long notch was obviously > +20 °C. This temperature is 106 °C higher than the theoretical MDT of −86 °C. On the other hand, if it is assumed that the critical fracture stresses are inversely proportional to the square root of the notch toughness, then assuming a conservatively adjusted yield strength for −90 °C of 1200 N/mm^2, the test result for plate 719 at this temperature can be used to show that the critical notch length for gross section yielding would be approximately 8 mm. In other words, the theoretical MDT of −86 °C would not be expected to be safe for the present 30 mm thick materials for notch lengths greater than approximately 8 mm.

The steel for plates Nos. 734–743 had a yield strength of 489 N/mm^2 at approximately 20 °C, which corresponded to a $4e_Y$ strain of 0·95 %. Wide plates were tested at temperatures ranging from 20 to −150 °C. The initial consideration of the test results led to an estimated experimental MDT of +20 °C. However, a more detailed examination of the results shows that full net section yielding occurred at all temperatures down to at least 100 °C. For notches having lengths <30 mm, or plates >370 mm wide, therefore, gross section yielding and higher overall strains may be obtained at temperatures < −100 °C, which compares well with the theoretical MDT, this being −104 °C.

Category 8 steel—plain material plates Nos. 793–824 (Table 4)

These plates were approximately 30 mm thick and 106 mm wide and contained through-thickness sawn notches ranging in length from 4 to 60 mm. The plate material had a yield strength of 994 N/mm^2 at approximately +20 °C, which corresponds to a $4e_Y$ strain of 1·9 %. The tests were carried out at temperatures of +20, 0 and −20 °C.

As shown in Table 4, the experimental MDT for these plates was tabulated as being > +20 °C, which is at least 135 °C higher than the theoretical MDT. In fact, the aforementioned experimental MDT was only relevant to a 4 mm long notch. Consequently experimental MDTs < +20 °C in the present WPT specimens would require notch lengths of <4 mm.

The dependence of the MDTs on notch size will be discussed again in a later section of this paper.

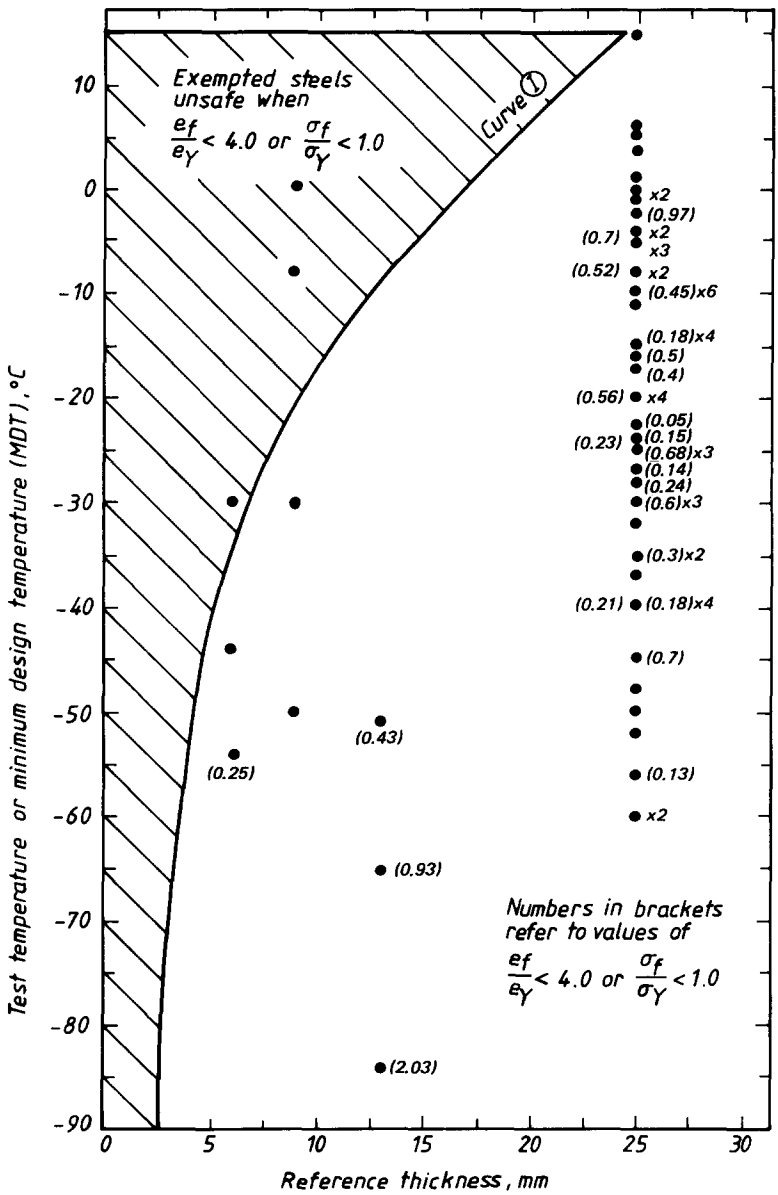


Fig. 8. BS5500, Appendix D, Section D.3.2, exemption of wrought steels (σ_U 450 N/mm^2) from C_v tests. As-welded condition (see curve I, Fig. 1).

EXEMPTIONS FOR WROUGHT STEELS FROM IMPACT TESTS

BS5500, Appendix D, Issue 3, May 1979, Section D.3.2 states that impact testing may be waived, or steels without guaranteed impact properties may be used, except where the purchaser specifies otherwise, in the case of carbon and carbon–manganese steels (Categories 1–3, Table 1) having a specified minimum tensile strength $<450\ N/mm^2$ as follows:

(a) for all points representing combinations of thickness B and MDT lying to the right of Curves 1 in Figs. 1 and 2;
(b) in the case of normalised steels where the specified minimum manganese content divided by the specified maximum carbon content is $\geq 4{\cdot}0$, all points representing combinations of B and MDT lying to the right of Curves II in Figs. 1 and 2.

For the present analysis Curves I and II in Figs. 1 and 2 were redrawn to give graphs of testing temperature and MDT versus thickness, B, as illustrated in Figs. 8–11. Hence, all points above the curves represent combinations of MDT and B for which C_v testing may not be required.

In order to assess these relationships, combinations of testing temperature and B from relevant WPTs in steel Categories 1–3 were plotted in Figs. 8–11. The numbers in brackets beside each point in the figures are the values of e_f/e_Y that were <4, and the values of $\sigma_f/\sigma_Y < 1{\cdot}0$. For reasons discussed later these values were based on WPT specimens having crack lengths $<ca.$ 10 mm long and $<ca.$ $0{\cdot}01 \times$ the plate widths. To appear safe, therefore, no values of $e_f/e_Y < 4$, nor values of $\sigma_f/\sigma_Y < 1$, should occur above the curves in Figs. 8–11.

Note that there were relatively few data that could be used to assess Curves I and II in Figs. 1 and 2 (Figs. 8–11). This was especially true for sections of $<ca.$ 25 mm thickness, for which Curves I and II indicate a significant decrease in the MDTs for which impact testing may be waived. Furthermore, as shown in Figs. 8–11, there were a number of instances where the results for the thinner sections gave values of e_f/e_Y that were $<4{\cdot}0$ for combinations of testing temperature and thickness above Curves I and II. These instances are described in more detail below.

Apparently unsafe C_v exemptions for PWHT plates

As shown in Figs. 10 and 11 there were no suitable WPT results that could

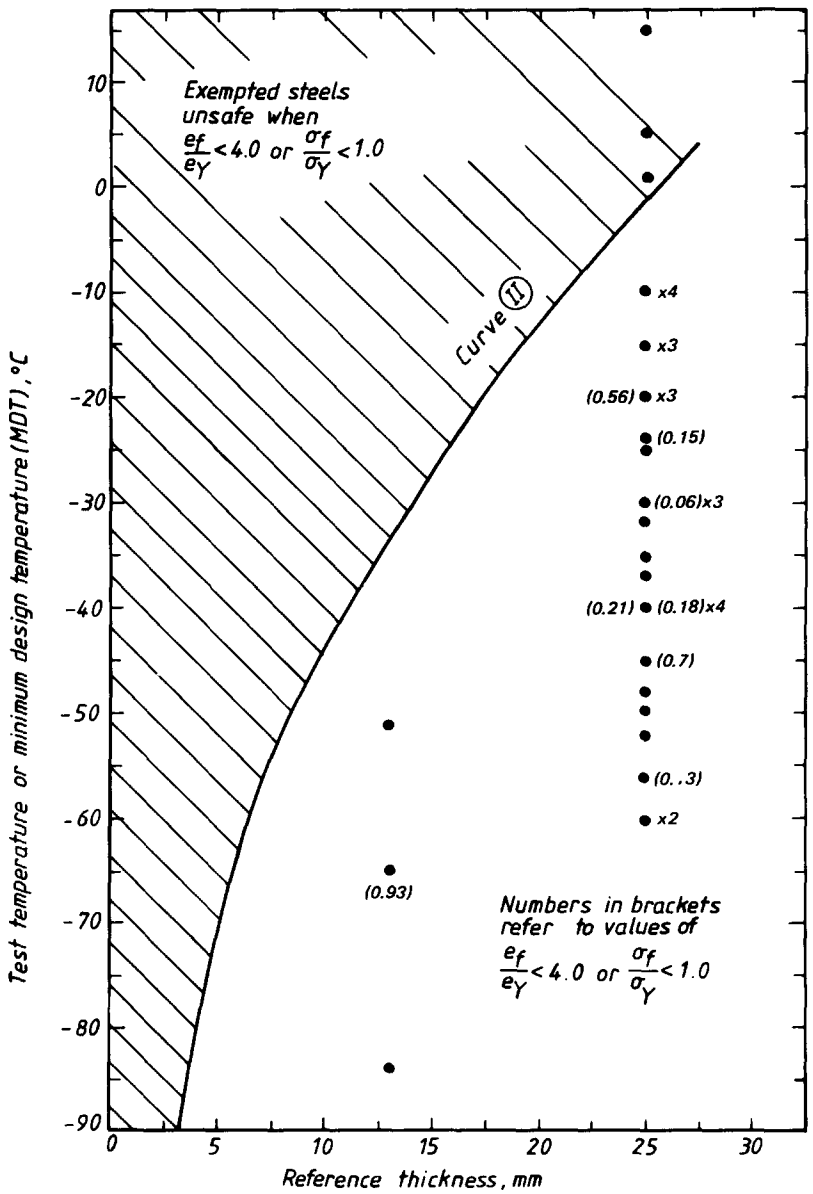


Fig. 9. BS5500, Appendix D, Section D.3.2, exemptions of normalised wrought steels ($\sigma_U < 450\,N/mm^2$, $Mn/C \geq 4$) from C_v tests. As-welded condition (see curve II, Fig. 1).

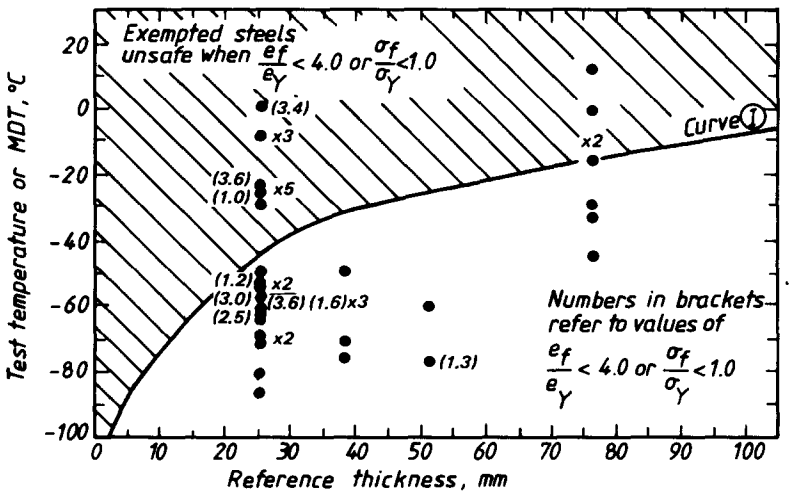


Fig. 10. BS5500, Appendix D, Section D.3.2, exemptions of wrought steels ($\sigma_U < 450\ N/mm^2$) from C_v tests. PWHT condition (see curve I, Fig. 2).

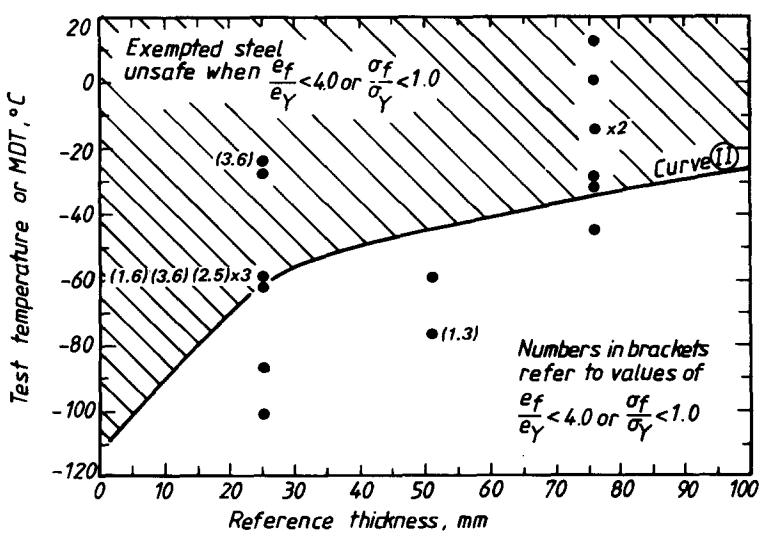


Fig. 11. BS5500, Appendix D, Section D.3.2, exemption of normalised wrought steels ($\sigma_U < 450\ N/mm^2$, $Mn/C \geq 4$) from C_v tests. PWHT condition (see curve II, Fig. 2).

be used to assess Curves I and II for section thicknesses <25 mm. At this thickness, however, Figs. 10 and 11 both show instances where the WPT results gave values of $e_f/e_Y < 4{\cdot}0$ at temperatures above Curves I and II. In Fig. 10, these instances involved WPT specimens 211 ($e_f/e_Y = 3{\cdot}4$), 212 ($e_f/e_Y = 1{\cdot}0$) and 223 ($e_f/e_Y = 3{\cdot}6$).

Referring to Fig. 11 (for normalised plate having ratios of manganese–carbon >4·0), it may be noted that the test result for the above mentioned WPT specimen, No. 223, was also well above Curve II. Three other WPT specimens gave values of $e_f/e_Y < 4{\cdot}0$, but at temperatures only marginally (2 °C) above Curve II. These involved WPT specimens 221 ($e_f/e_Y = 2{\cdot}5$), 222 ($e_f/e_Y = 3{\cdot}6$) and 224 ($e_f/e_Y = 1{\cdot}6$).

Significantly, all the above apparently unsafe results in Figs. 10 and 11 involved PWHT temperatures in the range 450–550 °C, which are lower than the temperatures required by BS5500. Furthermore, all these tests were part of a single investigation of PWHTs.[5] This showed that the ductility in WPTs was enhanced by a PWHT involving a temperature of 650 °C, which meets the requirements of BS5500.

GENERAL DISCUSSION

BS1515 and BS5500 are strictly relevant to steels in Categories 1–3 only, and these steels comprised the majority of the present WPT results. For instance, the total of 1182 WPTs examined comprised 910 from steel Categories 1–3, three from steel Category 4, 105 from steel Category 5, 16 from steel Category 6, 45 from steel Category 7 and 103 from steel Category 8.

All the WPT results for which adequate supporting information was available were used for comparison with the theoretical MDTs as defined in Figs. 1 and 2. This showed that there were a number of cases in which, at first sight, the wide plate test results appeared to indicate that the design rules in BS5500, Appendix D were unsafe. However, a more searching examination of these results showed that the materials tested did not meet the requirements of the British Standard. This was generally because the impact properties of the weld metals and HAZs were either below the requirements of the standard or were unknown.

An important aspect of the above observations is that the low temperature requirements of both BS5500 and the superseded BS1515 were based on tests in which the maximum through-thickness crack

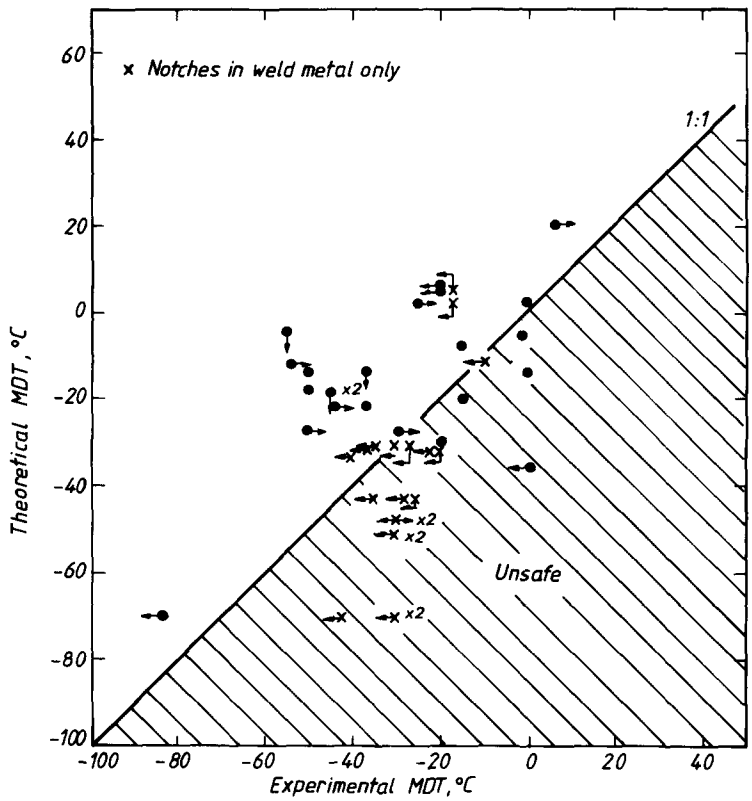


Fig. 12. Comparison of theoretical and experimental MDTs for as-welded wide plates in steel Categories 1 to 3. Arrows indicate the direction that point should be moved to meet the minimum requirements of BS5500 Appendix D, i.e. $e_f/e_Y = 4{\cdot}0$.

lengths were generally < 10 mm in length and $< 0{\cdot}01 \times$ the plate widths. Consequently the occurrence of yield magnitude stresses in the early WPTs usually involved gross section yielding, which is generally the most relevant deformation mode for an overloaded structure. The geometrical aspects are important, since, especially in the plain material WPTs, the experimental MDTs were found to be dependent on crack length. For example, the smaller the crack length, the lower the MDT. However, for steels in Categories 1–3, through-thickness crack lengths < 10 mm generally gave experimental MDTs that were less than the theoretical values. There were also instances for steels in Categories 1–3 where larger crack sizes and net section yielding led to overestimates of the initial experimental MDTs, but values which were nevertheless lower and

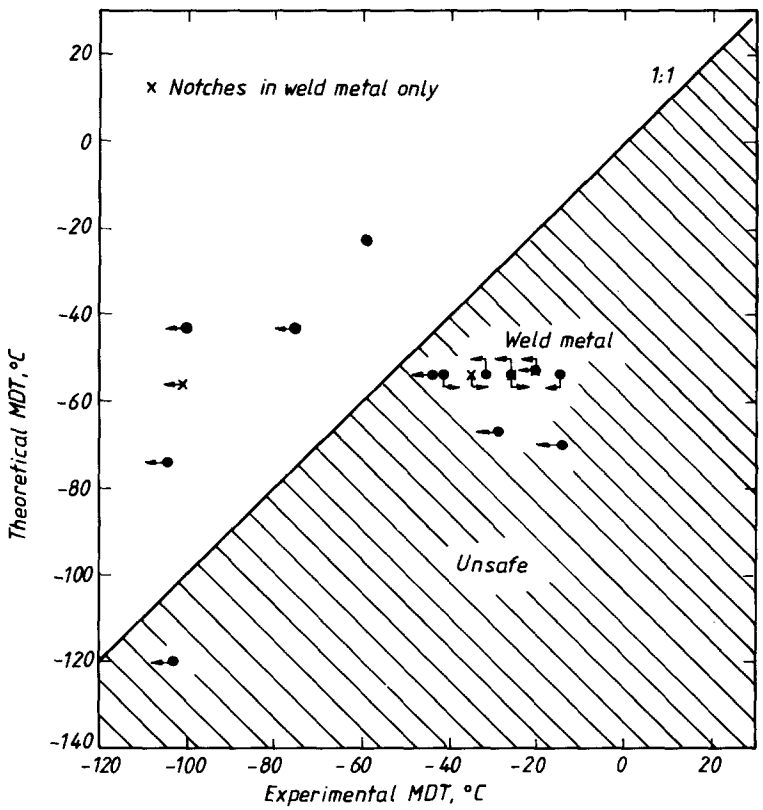


Fig. 13. Comparison of theoretical and experimental MDTs for PWHT plates in steel Categories 1 to 3. Arrows indicate the direction that point should be moved to meet the minimum requirements of BS5500 Appendix D, i.e. $e_f/e_Y = 4{\cdot}0$.

therefore safe compared to the theoretical values. It was not possible within the present analyses to come to any obvious conclusions regarding the acceptable dimensions of surface and buried notches.

Figures 12–14 summarise the comparisons of theoretical and initial experimental MDTs for steel Categories 1–3 for the as-welded, PWHT and plain material conditions, respectively. In these figures each experimental point generally represents a series of WPT results for which supporting longitudinal Charpy V-notch impact test and tensile test data were available. As regards the MDTs for as-welded plates (Fig. 12), it may be noted that no data were included for plates >38 mm thick, since this is the maximum thickness for the definition of theoretical MDTs according to Fig. 1. In general it may be observed that many of the WPT series were

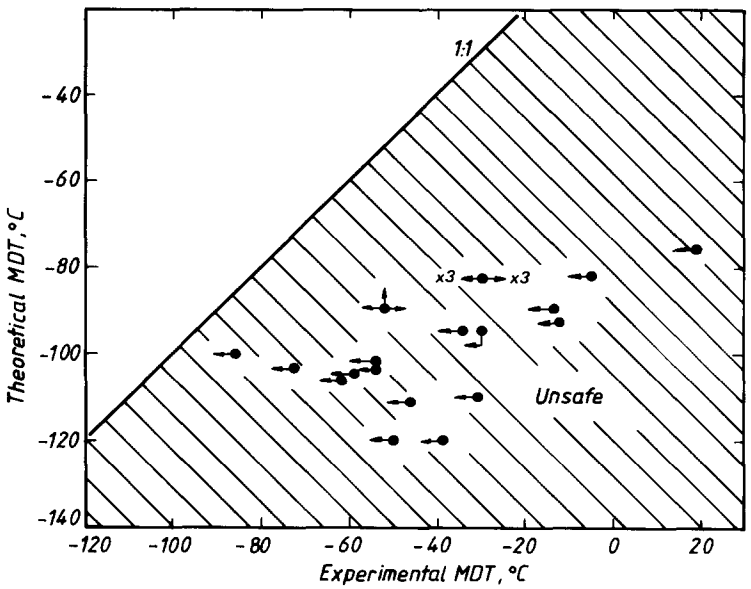


Fig. 14. Comparison of theoretical (quarter thickness) and experimental MDTs for plain plates in steel Categories 1 to 3. Arrows indicate the direction that point should be moved to meet the minimum requirements of BS5500 Appendix D, i.e. $e_t/e_Y = 4{\cdot}0$.

tested over temperature ranges that were remote from the theoretical MDTs. Consequently for these the experimental MDTs had to be estimated as being greater than or less than some limiting test temperature.

Finally, the general paucity of WPT data for section thicknesses < 13 mm is of concern in relation to the present comparisons of theoretical and experimental MDTs. For example, in steel Categories 1–3 only approximately 15% of the comparisons involved thicknesses < 13 mm.

CONCLUSIONS

1. All the as-welded, post weld heat treated and plain material wide plate test series that were known to meet the full requirements of BS5500 gave experimental minimum design temperatures that were lower than the theoretical ones. Thus, the requirements of the standard were shown to be safe, and in many instances excessively so. It is felt important to mention, however, that there were relatively few results assessed for section thicknesses < 13 mm.

2. Although BS5500, Appendix D, is restricted to steels in Categories 1–3 (Table 1), steels in Categories 4–8 meeting the mechanical test requirements of this standard also gave safe minimum design temperatures for the as-welded and post weld heat treated conditions. The same was generally true for the plain materials, the one exception being a Category 8 steel.

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