Niobium Bearing Structural Steels
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DESIGN AGAINST BRITTLE FRACTURE FOR UNFIRED PRESSURE VESSELS IN EUROPEAN STANDARD EN13445

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Abstract

There have been large uncertainties concerning the risk for brittle failure in welded high strength and duplex stainless steels, since both specific design rules as well as proper materials data have been lacking. This has been of major concern particularly in safety classed components like pressure vessels. To solve this problem, new methods have been developed to allow for an economic and safe design against brittle failure. These are based on principles of fracture mechanics derived in European research during the last 15 years. The new design principles have been implemented in the European pressure vessel code EN 13445, because in the present version of EN-13445 from 2002 (the first published version) there are some severe limitations concerning the use of high strength steels. In fact, steels with yield strength above 460 MPa cannot be used without performing detailed fracture mechanics analysis and duplex stainless are not allowed in gauges above 30 mm, which excludes many modern high strength steels with good toughness properties.

The new method quantifies how the thickness, the strength, impact toughness and heat treatment influence the risk for brittle failure. In the derivation, the influence of the residual stresses has been taken into account as well. Starting from a specified maximum crack size that depends on the component thickness, the minimum safe design temperature has been derived. Together with the charpy toughness to fracture toughness correlations a practical design methodology for end users has been developed. The method has been validated by large scale tests. The presentation will introduce into the European Standardisation activities and provide details how new and modern steels can be introduced into standards by means of combining research results, modern material mechanics methods and existing experience.

Introduction

EN13445 was developed as a unified European Standard for unfired pressure vessels during the 90s of the last century within the frame of the PED 97/23/EC published in the official journal of the European Community in 1997. The new standard was firstly published in 2002 after more than 10 years of hard work by several specialists from all over Europe. However, as a matter of fact, it is obviously clear that such a totally new standard derived by all member countries of CEN cannot be perfect. But it represents two things:

1. a great tender of actual European pressure vessel technology and
2. a compromise on the level of the smallest common acceptance level.

Bearing this in mind and knowing that after publication many national pressure vessel standards, such as AD-Merkblatt (German national standard) or CODAP (French national standard) have not been withdrawn, but have been adapted to the PED (to allow for practical achievement of compliance while staying in the national framework of each country), it is understandable from the practical and also the economical point of view that disadvantages that could result from the application of such a new standard hinder the application by all member states.

However, since 2002 five years have passed and specialists within CENTC54 have started to revise the standard with respect to the problems found during first applications. Only one European country, namely Finland, has started to use the standard consequently since 2002 and could therefore contribute with constructive criticism. In addition, also other specialists from European countries were willing to contribute and make EN13445 more competitive and include latest findings from research e.g. ECOPRESS [1]. On the other hand, since 2000 ASME has started to revise their standard taking also advantage of latest knowledge provided in EN13445 and increasing the pressure on the European standard to survive in the world wide competition. This new revision of ASME is meanwhile available, which shows the differences between the complicated standardisation processes in Europe in comparison to USA.

Concerning revision of EN13445 part 2 “Materials” the new working group started in 2003 under new convenor ship of the author of this paper with the evaluation and definition of new work items which resulted in three amendments as follows:

1. EN13345-2-prA3 dealing with the amendment of table A2.-1
2. EN13445-2-prA4 dealing with the amendment of chapter B4.3, working plate requirements
3. EN13445-2-prA5 dealing with a full revision of Annex B with respect to method 1 and 2 for the steel selection to avoid brittle fracture.

Details will be given following.

Amendment prA3; Revision of Table A2-1 in EN 13445-2 (2002)

When the first draft was published in 2002 the steels for pressure vessels were listed in Table A2-1 in Annex A including a normative restriction of the maximum plate thickness.

This was necessary because at the time of first publication not all materials listed were also part of Harmonised European Material standards and hence did not fulfil automatically the safety requirements of PED. For the revision JWGB decided to work this table over and list all materials with their maximum thickness as given in the individual Harmonised European Material standards and shift the table from the normative Annex B into the informative Annex D. The accepted explanation for this action was that all steels for pressure vessels were meanwhile harmonised and therefore did fulfil the presumption of conformity (CE mark). Bearing this in mind, it was no more necessary to limit the thickness in the Table A2-1 of EN13445-2 because thickness limits as concerns brittle fracture were given now only by the methods 1, 2 or 3 respectively in Annex B of the part 2 of EN13445. Consequently this table was shifted to informative as to allow inexperienced users to get familiar with the variety of European grades and their Designation. Figure 1 shows an overview, where it becomes obvious that thickness is given informative and not as a limit.

•D.2 European standardised steels grouped according to product forms

The references in this table do not include the date of the standard, but they are dated references as given in clause Bibliography.

Table D.2-1 — European standardised steels grouped according to product forms

1	2	3	4	5	6	7	8		9	10
No	Product form	European Standard	Material description	Grade	Material number	Heat treatment g	Thickness mm		Material group to CR ISO 15608	Notes
							min.	max.		
1	plate and strip	EN 10028-2	elevated temperature properties	P235GH	1.0345	N	0	250	1.1	
2	plate and strip	EN 10028-2	elevated temperature properties	P265GH	1.0425	N	0	250	1.1	
3	plate and strip	EN 10028-2	elevated temperature properties	P295GH	1.0481	N	0	250	1.2	
4	plate and strip	EN 10028-2	elevated temperature properties	P355GH	1.0473	N	0	250	1.2	
5	plate and strip	EN 10028-2	elevated temperature properties	16Mo3	1.5415	N, NT	0	250	1.2	e
6	plate and strip	EN 10028-2	elevated temperature properties	18MnMo4-5	1.5414	NT	0	150	1.2	
7	plate and strip	EN 10028-2	elevated temperature properties	18MnMo4-5	1.5414	QT	150	250	1.2	
8	plate and strip	EN 10028-2	elevated temperature properties	20MnMoNi4-5	1.6311	QT	0	250	3.1	
9	plate and strip	EN 10028-2	elevated temperature properties	15NiCuMoNb5-6-4	1.6368	NT	0	100	3.1	

Figure 1. Extract from page 1 of new Table D2-2 as proposed in amendment prA3 to EN13445 -2-.

Amendment prA4; Revision of Clause B4.3 "Working Plate" of EN 13445-2

This amendment has become necessary before the negative experience of Finnish companies which, as mentioned above, applied EN13445 from the beginning on and found that the requirements on working plate as formulated in B4.3 resulted in massive testing and hence economical disadvantages for users fabricating in the frame of EN13445.

The clause B4.3 reads as given in Figure 2. It was discussed intensively and found as a conclusion that the amount of testing is not matter of part 2, where only requirements shall be given for steel grades. It was accepted opinion of all members of JWGB that testing should be defined in EN13445 part 4 *Fabrication*. Following working group D, responsible for part 4, was asked to revise the clause 8 where such test requirements are defined. In parallel TC54 agreed that prA4 shall be included into the revision only in conjunction with prA3 of EN13445-4. The revised chapter B4.3 now reads as given in Figure 3. The prA4 has been accepted meanwhile and is ready for publishing when prA3 is through formal vote.

B4.3 Production test plates

The weld production test plate shall be performed in accordance with EN 13445-4:2002-05, clause 8.
The following requirements are additional to the requirements in EN 13445-4:2002-05, clause 8. In addition to this a weld production test plate is required according to welding procedure specifications for T_{KV} equal to or above – 30 °C, if the material thickness is greater than 12 mm.
For T_{KV} below – 30 °C a weld production test plate [3)] is required if the material thickness is greater than 6 mm.
The impact energy requirements of method 1 or 2 shall be met.

Figure 2. Extract from EN13445-2 Annex B, 2002.

B4.3 Production test plates

The weld production test plate shall be performed in accordance with EN 13445-4:2002-05, clause 8. The impact energy requirements of method 1 or 2 shall be met.

Figure 3. Amendment prA4 to EN13445-2.

Amendment prA5; Revision of Method for Selection of Steel to Avoid Brittle Fracture, EN13445-2

The amendment prA5 was the one with the greatest changes to EN13445-2. It was worked out within Sub Group Low temperature of JWGB in 10 meetings over 2 years and provides the following major changes:

1. Change in philosophy as concerns steels for warm and coldgoing vessels
2. Inclusion of High Strength Steel with Yield Strength up to 690 MPa and Duplex Stainless Steels
3. New method 2
4. New method 1

The impetus for this major changes resulted from the ECOPRESS project. Beside this research results industry from Germany required a more economical and practical handling of this part of the standard.

Change in Philosophy as Concerns Steels for Warm and Coldgoing Vessels

To allow for the use of steels for warmgoing vessels without additional charpy requirements at temperatures lower than room temperature ($T_R = T_{KV}$ for KV = 27 Joule) the user is directed into a new chapter B. 5 defining the requirements to be fulfilled in such a case. The criterion for warm or coldgoing vessel is given by a limit-temperature of 50°C, where application with design temperature at normal operation higher than 50°C are classified as warmgoing and vice versa those with design temperature for normal operation at temperatures below 50°C down to -272 °C are classified as coldgoing. The details are given in Figure 4.

It is important to note that situations which require lower design temperatures down to -10°C such as start up and shut down procedures require special provisions to avoid brittle fracture.

B.5 Materials for use at elevated temperatures

B.5.1 General

B.5 applies for pressure equipment:

- with normal operation temperatures higher than 50 °C and
- temperature at start up, shut down and at possible process upsets is not lower than – 10 °C and
- start up and shut down procedure is under controlled conditions as given in B.5.4 and
- the conditions for pressure test as specified in B.5.5 are fulfilled

If any of these requirements is not satisfied the methods for low temperature materials shall be applied.

B.5.2 Materials

Materials shall have a specified minimum impact energy measured on a standard Charpy-V-notch impact test specimen (see EN 10045-1:1990) as follows:

— ≥ 27 J for ferritic steels;

— ≥ 40 J for steels of material group 8, 9.3 and 10

at a temperature not higher than 20 °C.

B.5.3 Welding procedure qualification and production test plates

Welding procedure qualification shall be performed in accordance with part 4 of this standard.
The weld production test plate shall be performed in accordance with part 4 of this standard.

B.5.4 Start up and shut down procedure

To avoid brittle fracture occurrence during start up and shut down procedures the pressure shall not exceed 50 % of the design pressure at temperatures lower than 20 °C.

B.5.5 Pressure test

Hydrostatic pressure test shall not be carried out at temperatures lower than 10 °C.

Figure 4. New chapter B.5 proposed in prA5 to EN13445-2, status after public inquiry.

Inclusion of High Strength Steel with Yield Strength up to 690 MPa and Duplex Stainless Steels

It was the aim of the ECOPRESS project to demonstrate that High Strength Steels up to 690 MPa yield strength and Duplex Stainless steels up to 550 MPa yield strength can be included into the method 2 of Annex B. In the existing Annex B the nomogram limits the use of C-Mn steels to yield strength of max. 460 MPa and thickness of max. 110 mm (Figure 5).

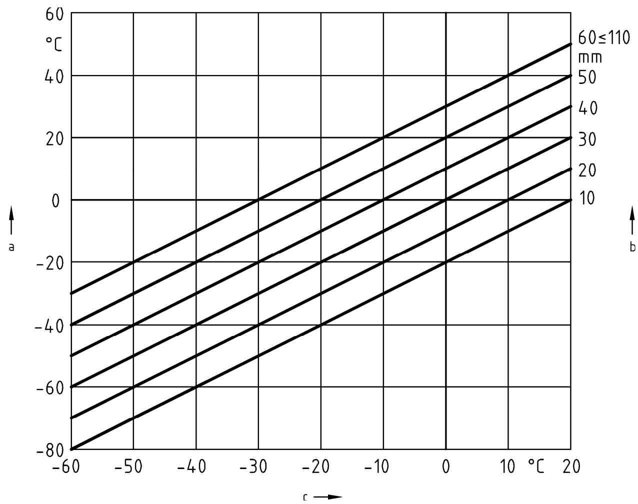


Figure B.4-3 — Design reference temperature and impact test temperature post weld heat treated (PWHT) condition, for 310 N/mm^2 < R_e ≤ 460 N/mm^2 : 27 J

Figure 5. Nomogram from EN13445, 2002, indicating limitations to yield strength and thickness.

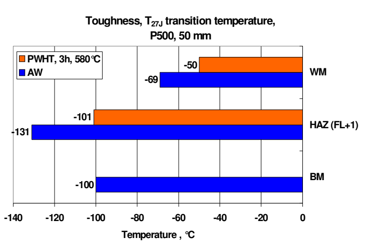


Figure 6a. Toughness of P500.

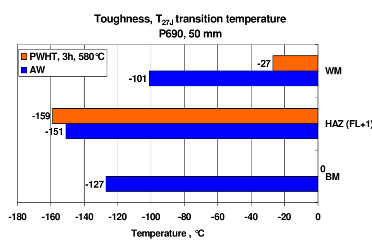


Figure 6b. Toughness of P500.

Within ECOPRESS extensive fracture mechanics and large scale tests have been performed on P500 (Figure 6a) and P690 steels (Figure 6b) in the conditions base metal. As welded and post weld heat treated, showing that these steels provide sufficient toughness at low temperatures. Only extreme post weld heat treating yields considerably lower toughness in the tested steel weldment variant of P690. The reason was identified from the Vanadium content in the plate that is picked up by the weldment especially in the root and which forms carbides during PWHT leading to embrittlement. This can be avoided e-g- in niobium-alloyed steel grades.

A second part of the research was related to the revision of the existing fracture mechanics method used for the derivation of the nomograms published in the first version of EN13445. These nomograms were not directly based on the original calculation model proposed by Sandström [2], but were only derived on the basis of this model in combination with the experience of the member states contributing to the EN13445 part 2, meaning based on compromise and hence being more conservative than the calculated lines were.

The new fracture mechanics based calculation model derived throughout the project comprises the latest findings in structural integrity methods to revise the Sandström model. These were the Wallin–Master Curve Concept in conjunction with an empirical correlation between Fracture toughness transition temperature and Charpy transition temperature T_{27J} and the Failure Assessment Diagram (Two Criteria Approach) which allows the derivation of the crack driving force in a component such as a pressure vessel on an analytical basis. In Figure 7 the combination of this method is schematically demonstrated. More details can be found from literature [3, 4, 5]. The methods were verified with means of large scale tests at low temperatures with welded and post weld heat treated specimen. The result is shown in Figure 8, where the calculated fracture temperature is shown against the actual test temperature. The results scatter around the 1:1 line with a scatter of 20 K, Hence 20 K is included as a safety element into the model. An overview to the tests gives Figure 9.

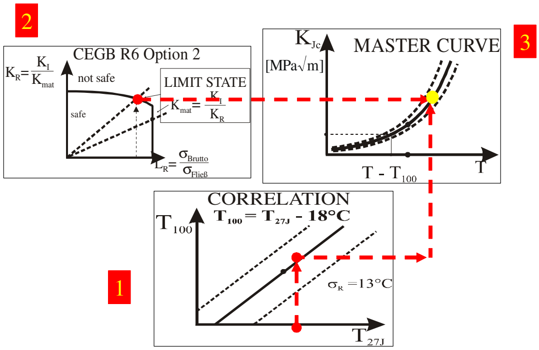


Figure 7. Principal derivation of limit state of fracture with fracture mechanics methods.

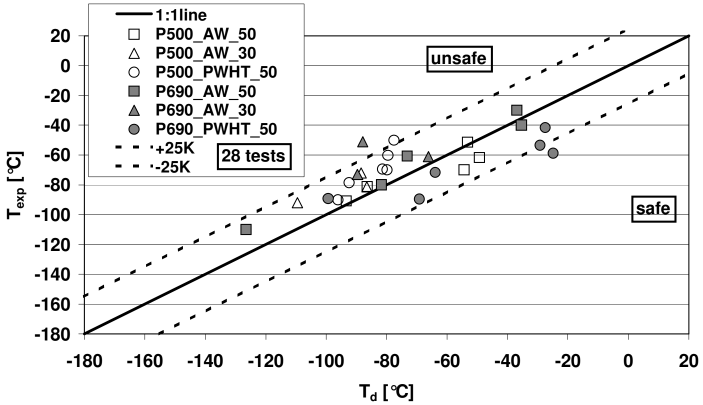
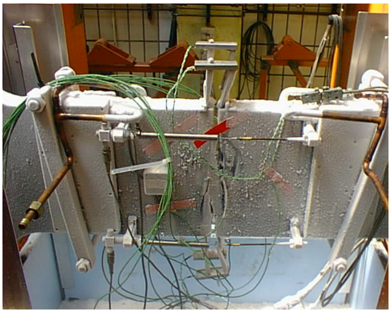
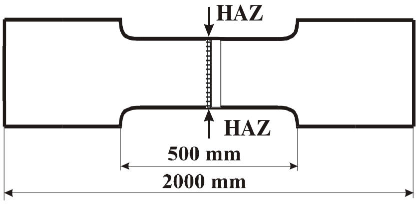


Figure 8. Verification tests within ECOPRESS project.





Steels		P500			P690	
t , mm	30	50	80	30	50	80
BM	no	3	3	no	3	3
AW	3	5	no	3	5	no
PWHT	no	6	no	no	6	no

Figure 9. Wide plate test performed in ECOPRESS project.

Revision of Method 2 in EN13445 part 2, Annex B

On this technological basis a revision of method 2 was proposed to JWGB with the aim to include the high strength steel grades up to 690 MPa yield strength and to a limiting thickness of 80 mm, as this was the largest thickness tested. The details to this new method have been published by the author and Sandström [6].

After long and intensive discussion the following compromise was found for the revision of Annex B, method 2:

- Swedish delegates would not allow including the nomogram for P690 into the revision because of lack of experience with that steel so that limit was set to P500. (This opinion was not shared by other member countries).
- However, also Swedish delegates did not have any problems with including austenitic-ferritic grades up to 50 mm thickness and 550 MPa strength.
- The new calculation model shall be applied for all grades down from 500 MPa to 265 MPa and lower.
- For each strength class reading as follows: ≤265, ≤355, ≤460, ≤500 (always MPa) one nomogram is presented for PWHT and one for AW condition.
- for Austenitic Ferritic steels three diagrams for the lowest 385, one for 465 and one for 550 MPa and lower is introduced.
- For steels with yield strength higher and equal to 460 MPa 40 J is required for KV instead of 27 J as for lower strength grades.

Figures 10 a,b show examples for the high strength P500 in PWHT condition and the austenitic ferritic grade.

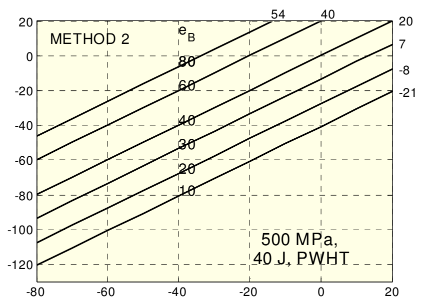


Figure 10a. Nomogram for P500, PWHT.

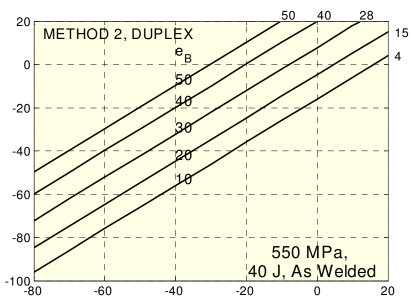


Figure 10b. Nomogram for austenitic ferritic Re ≤ 550 MPa.

Finally, it was found that existing method 1 includes inconsistencies against method 2. Therefore Subgroup Low Temperature worked out a proposal which provides a new format to method 1 and compatibility to method 2 for C, C-Mn grades. To achieve this it was found necessary to create tables which are more easy to use and witch is based on the following facts:

- Listing of all C, C-Mn grades with yield strength ≤355 MPa with EN standard name and designation as also given in Table D2-2.

- Calculation of limiting thickness for PWHT condition on the basis that design temperature T_R is equal to T_{KV} with KV = 27 J (where T_{27J} is given in the technical standards as a qualification parameter of the steel grade).
- Limitation of AW condition to 35 mm thickness.
- Limitation of calculation model to steel with Ni-content lower 1.5 % as no experience or research results are available for the 3 to 5 % Ni-steels.
- Limiting thickness for 3 to 5% Ni and 9% Ni steels in relation to limiting thickness given in EN10028 parts 3 and 4 and T_R is equal to T_{KV} with KV = 27 J.
- Revision of Table with austenitic grades with relation to specific requirements on weldments.
- Total revision of requirements for fasteners with relation to EN10269, starting material to fulfil Essential Safety Requirements.

Figure 11 shows a part of one of the new tables in method 1 with the ferritic steel grades. From this table one can see that the calculation model allows only 76 mm maximum thickness for a P265 GH with T_{27J} = -20°C and 52 mm for P355 NH with same T_{27J} temperature.

Plates and Strips								
No. as per Table D.2-1	European Standard EN	Grade	Material No.	Max. reference thickness e_B AW	PWHT	Design reference temperature T_R (°C)	Material group to CR ISO 15608:2000	Remarks
1	10028-2:2003	P235GH	1.0345	35	90	– 20	1.1	Rounded
2		P265GH	1.0425	35	75			
3		P295GH	1.0481	35	65		1.2	
4		P355GH	1.0473	35	55			
29	10028-3:2003	P275NH	1.0487	35	75	– 20	1.1	
30		P275NL1	1.0488	35	75	– 40		
31		P275NL2	1.1104	35	90	– 50		
32		P355N	1.0562	35	55	– 20	1.2	
33		P355NH	1.0565	35	55	– 20		
34		P355NL1	1.0566	35	55	– 40		
35		P355NL2	1.1106	35	55	– 50		
36								
37								
38								

Figure 11. New steel selection after method 1, limiting thickness calculated with method 2 and for the assumption Design Temperature $T_R = T_{27J}$.

This situation was to the opinion of German industry in contradiction to good experience with this type of conventional steel grades. A limitation to this thickness would result in uneconomical results when applying the standard and consequently the chance for this standard to be applied after revision would be limited. To cover the experience of the industry the following solution was proposed and accepted as an interim solution.

1. The nomograms for P355 PWHT and P265 PWHT are extended by one dashed line for the condition $T_R = T_{KV}$.
2. The required toughness to use this line is lifted from 27 to 40 J for both strength classes.
3. The allowed thickness when above conditions are fulfilled is 75 to 110 mm for ≤265 MPa and 65 to 110 mm for ≤ 355MPa.

Figure 12a,b shows the compromise solution which was accepted by JWGB on there latest meeting on 30 and 31st of May, 2007 in Berlin.

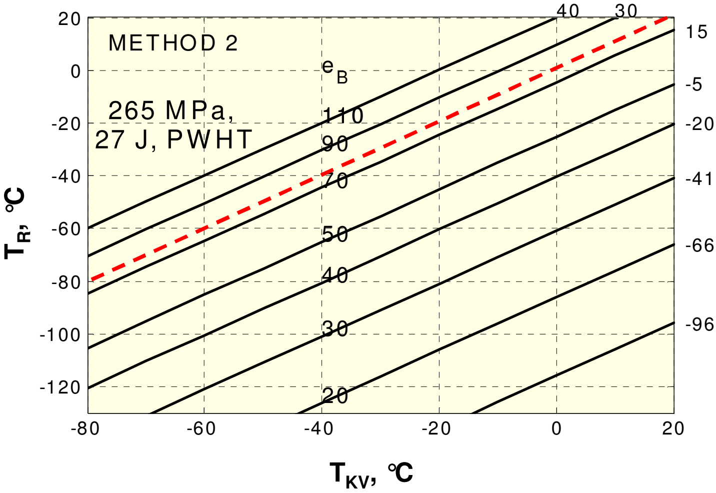


Figure 12a. New nomogram for conventional steel grades with strength level 265 MPa, dashed line allows use of thickness up to 110 mm if T_{KV} = 40 J at T_R.

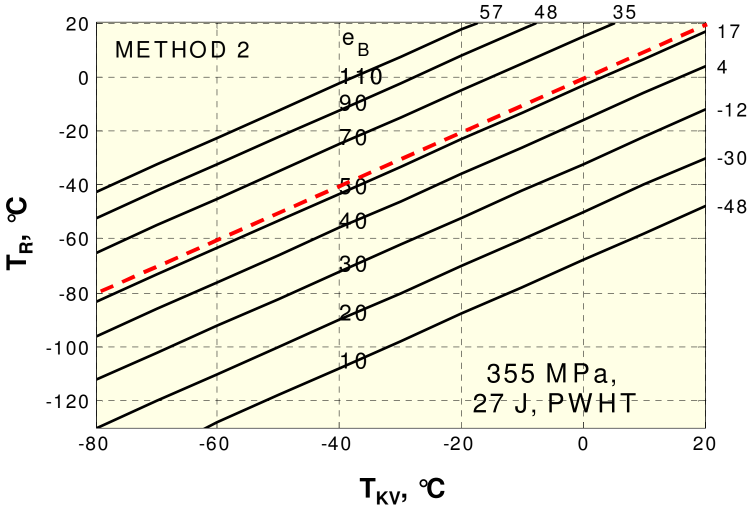


Figure 12b. New nomogram for conventional steel grades with strength level 355 MPa, dashed line allows use of thickness up to 110 mm if T_{KV} = 40 J at T_R.

Conclusions

Within the Joint Working Group JWGB of CENTC 54 and CENTC 267, the first revision of part 2 was worked out during the past 4 years and is finalised now and documented in three amendments EN13445-2- prA3, -prA4 and -prA5. The major changes have been shortly presented underlining the basic idea of this revision to make the EN standard a more practical standard for application and allow European Industries a competitive application in Europe and overseas countries, especially in the competition with ASME.

The main achievements were:

- The new and practical handling of steels from Harmonised European Standard.
- The reduction of test efforts on working plates.
- The full revision of method 2 and method 1 including a new fracture mechanics based calculation model and extending to higher strength and austenitic-ferritic steels.
- The consideration and acceptance of operation experience instead of the calculation model where appropriate.
- The differentiation after materials for warm and coldgoing vessels, where for warmgoing vessels no extra low temperature testing is required anymore.

Throughout the preparation it was found that the countries like Sweden had problems with accepting the use of P690 and application of the calculation model. However, as the latter could be introduced in spite of this opposition it was the compromise not to include the P690, which other countries would have accepted.

Three other points of great interest for European industry could also not be solved:

1. Extension to plate thickness higher than 110 mm
2. Reduction factor for lower pressure is treated rather conservative in the EN standard in comparison to German experience and leads to uneconomical solutions.
3. The calibration of the calculation model to experience for low strength grades could not be achieved due to lack of time and manpower.

These items will be started as new work items of JWGB from summer 2007. An inclusion into next revision is intended. The works shall be carried out by subgroup low temperature. However support of the industry is needed for this work and appreciated, too.

Acknowledgements

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