G 2/6

Toughness Requirements for Steels of Components with Low Operating Temperatures

U. Brenner
Rheinisch-Westfälischer TÜV e.V., Leimbachstr. 227, D-5900 Siegen, Germany
H.D. Schulze
Rheinisch-Westfälischer TÜV e.V., Langemarckstr. 20, D-4300 Essen, Germany

In order to exclude the possibility of low-ductility fractures (brittle fractures) in components with safety relevance (e.g. pressurized containments) the materials used have to have an adequate toughness. The toughness requirements for materials are laid down in sets of regulations or in specification. If the guidelines are compared, however it becomes clear that opinions vary considerably concerning minimum toughness to be guaranted and procedure to be evaluated. In this paper the regulations are discussed.

1. Introduction

The structural design of components which are important from a safety point of view is largely laid down in sets of regulations, e.g. for pressure vessels subject to German regulations in the AD-Merkblaetter, compiled by the Arbeitsgemeinschaft Druckbehälter (Pressure Vessel Working Group) (1) For the stress analysis the starting point is a defect-free material structure. Load stress concentration spots resulting from manufacturing- and fabrication-related deficiencies and influences are not taken into account even though the theoretical stress at such locations may exceed the tensile strength during operation. Stress concentrations of this kind may result in fracture if they are not reduced by plastic deformation of the material. There is a danger that the component will fail if the materials used behave in a brittle way instead of a tough fashion.

By toughness is meant accordingly the ability of the material to absorb, by plastic deformation, any energy applied. This property of the material depends on the kind of load which, for its part, includes the multiaxiality of the stress state, the intensity of the stress component and the loading rate.

With ferritic material it is known that the toughness depends to a considerable degree on the temperature. The reduction in toughness from a transition temperature specific to material defect geometry and type of load must be considered when materials are being selected for use in components subject to low temperatures and of importance with regard to safety, e.g. vessels for liquified, low-temperature gases.

The most suitable way of assessing component toughness is to conduct tests on component-like specimens under load conditions specific to the component, but this is only justifiable in exceptional cases because of the effort and expense involved. For the most part toughness is determined in practice using the ISO-V specimen in a notched bar impact test, which is easy to perform. When requirement figures are being fixed there is extensive reliance on experience gained and in some regulations also on the results of wide-plate tensile tests or fracture mechanics analyses.

The concepts of toughness applied in Europe are described below and discussed.

2. Concepts of toughness

Assessment of component toughness

2.1 Values obtained in notched bar impact tests

The toughness requirements for materials for use at low temperatures are laid down in the German pressure vessel regulations, the so-called AD-Merkblätter, in Merkblatt No W 10, issued Nov.'76. In table 1 the most important information from this 'Merkblatt' is given for three grades of different types of steel. The Merkblatt indicates the lowest application temperature to which the materials mentioned may be used for pressure vessels. The lowest application temperature here is related to the load case. Three cases are distinguished: in load cases 2 and 3 there are lower loads or higher safety coefficients as compared to case 1. Toughness should be demonstrated using notched bar impact tests and the type of specimen and its position are laid down according to type and grade of steel. Both DVM and ISO-V specimens, longitudinal and transverse, are used. The minimum notch impact energy for the materials mentioned in Merkblatt AD-W 10 was laid down on the basis of practical experience and by considering cases of damage. Results from wide-plate tests or fracture mechanics analyses to characterize component toughness were not included. Adequate toughness should be demonstrated for the base metal according to AD-W 10 at the test temperature given there, and for the weld metal and heat-affected zone (HAZ) according to AD HP 2/1 and AD-HP 5/2 at the lowest application temperature.

2.2 Results from wide- plate tests and values obtained in notched bar impact tests

In most European regulations on the use of materials at low temperatures, such as the British Standard BS 5500 (2), the standard of the Swiss "Verein Schweizer Maschinenindustrieller" VSM 53165 (3), the French regulation for the manufacture of pressure vessels CODAP 80 (4) and the Dutch pressure vessel regulation M0110 (5) material requirements have been fixed, as in the draft of the corresponding ISO standard, using values obtained in notched bar impact tests and results from wide-plate tests (6). On the basis of welded, as well as welded and stress-relieved wide-plates with artificially induced defects the lowest permissible component temperature could be determined according to grade of steel and wall thickness. The steels investigated were primarely C and C-Mn steels (7). As lowest service temperature one fixed the test temperature in wide-plate tests at which an overall extension of 0,5 % at fracture was achieved.

It was assumed here that components with areas of local stress concentrations up to a stress concentration factor of about 2.5 could not then fail in a brittle way with pressure test load (1.3 times service load), but that the stress concentration are reduced by plastic deformation of the material. Nomograms were drawn up from evaluation of the wide-plate tests and from these it is possible to take the minimum permissible componente temperatures according to material and wall thickness. Figure 1 shows such a nonogram from the ISO draft. It applies to steels of various grades with tensile strength < 450 N/mm² in welded condition. In this standard there are also corresponding graphs for the welded and stres-relieved condition of steel grads with tensile strength > 450 N/mm².If the nomogram includes the material-related test temperature which is also prescribed for demonstration of toughness in the notched bar impact test then the nomogram obtained is that shown in fig. 2. It indicates the connection between the structural design data (lowest service temperature, component wall thickness) and the required transition temperature for a given notch impact energy. Comparison with the other European regualtions and standards mentioned above shows that the greatest range of materials and strength is given in the draft ISO standard and the Dutch standard, which is closely related to it. The Swiss standard limits the C-Mn steels at $R_{p\ 0,2} = 373$ N/mm², the British standard includes no Ni steels or austenites.

2.3 Fracture mechanics and values obtained from notched bar impact tests

In the French standard AFNOR A 36-011 (8) the lowest permissible service temperature for material used at low temperatures is determined with the following relation

$T_s \geq 1.4\ TK_{28} + 25 +$ ß $+ \Delta T_e + \Delta T_v$.

where:

T_{K28} = temperature at which 28 J is reached in the notched bar impact test

ß = temperature difference, according to yield point or fracture toughness

ΔT_e = temperature difference, according to wall thickness

ΔT_v = temperature difference, according to loading rate.

When the lowest component temperatur was fixed it was assumed, in line with the accepted facts of fracture mechanics, that components with through wall and surface defects of a conservatively assumed size cannot fail with a load at the level of the yield point if the material used has an adequately fracture toughness. This crack toughness was compared with a notch impact energy of 28 J. For the purposes of the comparison performed at the French Institute for Welding Reasearch (IRSID) (9) tests on C-Mn, Mo, Mn-Mo, Cr-Mo and Ni alloy steels in a yield point range of 235 to 740 N/mm² were analyzed. From the tests it follows for the temperature difference with a deviation of 25° C that:

ß = 70 ln /(Re-100) : 380/

where:

R_e = yield point.

The temperature difference ΔT_e to take account of component thickness was determined from a number of tests (Pellini, Robertson, Battelle)

According to this, for wall thicknesses ≥ 110 mm it is assumed that the plain strain is already present for which $\Delta T_e = 0$. For wall thicknesses ≤ 110 mm the figure for ΔT_e is taken from the standard and inserted into the above relation as a negative value. The temperature difference ΔT_v to take account of the load rate was deduced on the basis of results from corresponding notched tests (10) as $\Delta T_v = (83 - 0.08\ R_e)\varepsilon^{0.17}$. In the standard nomograms were produced according to the above relation for materials with different yield points and these nomograms show the connection between the lowest service temperature, component wall thickness and test temperature for dynamic, medium and quasi-static load. figure 3 shows nomograms for the three load rates for materials with yield points between 690 and 740 N/mm². With a reduction in the level of load the test temperature can be raised according to the figures given in figure 3. In the standard the materials are distinguished according to their yield points, without taking into account welds and heat treatment.

2.4 Porse diagram

The safety requirements for nuclear facilities are higher than those for conventional facilities. The demonstration that primary circuit components are sufficiently tough even at low service and emergency temperatures is to be performed according to the KTA regulation 3201.2 (11) with reference to the ASME Code (12). According to this toughness are required which are so high that even running cracks cannot propagate. For this purpose component analyses are required on the basis fo fracture mechanics or using the so-called Porse diagram (fig. 4). The Porse diagram was developed from the fracture analysis diagram (FAD) (13). It is differnt from the FAD in that the course of the crack arrest line is shown in simplified form and linearized twice and this line indicates the conditions for crack arrest in relation to defect size, stress, wall thickness and temperature. The design transition temperature (DT-temperature) is obtained from RT_{NDT} + 33K with RT_{NDT} as the greatest of three temperatures T_1 to T_3.

T_1 = NDT
T_2 = T_{cv}(68J) - 33K
T_3 = T_{cv} (0,9 mm lateral extension) -33K

Within the framework of the brittle fracture analysis all service conditions (stress and temperatures) are plotted in the modified Porse-diagram (as in fig. 4) by way of example as a service curve. The brittle fracture safety is characterized in the Porse diagram by the temperature difference between the service curve and the crack arrest line. A component is considered to be brittle fracture-proof if the service curve is located to the right of the crack arrest line without intersecting it.

3. Discussion of the toughness requirements

The Porse diagram is used to demonstrate adequate toughness in nuclear facilities. It assumes the precondition that fast running cracks must not spread in a brittle fashion. For pressure-bearing components in conventional facilities this requirement is not applied; instead of this the toughness of the component must only be so great that brittle fracture do not start. The difference with regard to requirements for noth impact energy for ISO-V specimens is accordingly high (Av = 68J according to Porse and A_v = 20 J to 27 J for conventional components).

The French standard (8) is based on fracture mechanics analyses which are intended to help prevent unstable crack growth. In the analyses the basic factors favouring brittle fracture, such as stress intensity, component wall thickness, temperature and loading rate, are taken into account. What is a disadvantage is that the nomograms included in the standard have only been produced for plates with defects which do not properly characterize real components, e.g. vessel nozzles. Other weak spots in the standard are the evaluations of the influence of rate and wall thickness. To date the influence of the rate has only been quantified using notched bar impact tests (10).

There is as yet no check using fracture mechanics test. The influence of the wall thickness is, according to the French standard, related to the material. This contradicts greneral experience and is presumably based on results obtained for only one grade of steel.

In most European standards (2 to 5) and in the draft ISO standard (6) the toughness requirements have been fixed in the form of nomograms with the aid of results from wide-plate tests and notched bar impact tests. From the nomograms given in the regulations it is possible to determine the lowest component temperature according to the wall thickness. The influence of the load rate is not taken into account in the nomograms, since they are only applied with results from wide-plate tests under quasi static load. A further disadvantage of these standards is that a lowering of the maximum permissible load level is either not considered at all or only insufficiently in the assessment of toughness. In fig. 5 there is a comparison of the standards quoted and drawn up on the basis of wide-plate tests for two wall thickness (strength $\leqq$ 450 N/mm^2, welded condition). Considerable differences result and these are caused partly by deviations in the grades of steel and strength classes, and partly by different toughness requirements and safety coefficients. In addition some standards start from yield points and some from tensile strength. Comparison of the individual curves shows that the wall thicknesses are weighted differently in the different standards. The same is true for the stress-relieved condition.

Where the above mentioned standards agree is that for small wall thickness (e.g. 10 mm) use is possible at temperatures below the test temperatures for the ISO-V specimens.

This can only apply if no drop in toughness occurs between the test temperature and application temperature or if the influence of any drop in toughness in the notched bar impact test between the test temperature and service is no greater than the effect arising due to the different load rates (dynamically loaded ISO-V specimen at static service). From this it follows that the diagrams can strictly speaking only apply for the groups of steels indicated and for quasi-statically loaded components.

One basic disadvantage in all the above mentioned standards which should be emphasized is that, regardless of the direction of load, in relation to the main direction of deformation of the plates, ISO-V specimens are generally tested as longitudinal specimens. This does not take into account that transverse values are basically worse than longitudinal values and that in addition their level depends on the conditions of deformation.

The AD-Merkblatt W 10, issued in November 1976 differs in a number of important ways from the above mentioned standards. Thus, according to the steel, both DVM and ISO-V specimens, taken as longitudinal or transverse specimens, are tested. Furthermore neither the influence of wall thickness, nor stress relief, nor loading rate is given weight. Nevertheless an increase in the safety coefficient is taken into account in the design.

References

/ 1 / AD-Merkblaetter, published by Vereinigung der Technischen Überwachungs-Vereine e.V., Essen

/ 2 / British Standard BS 5500: 1976 Appendix D

/ 3 / Standard of Verein Schweizerischer Maschinenindustrieller VSM 53165 (1974)

/ 4 / Code des appareils â pression, CODAP 80, Annexe MA 2.

/ 5 / Regels voor toestollen on der druck: M0110/75 - 12, Rules, 5th consignment.

/ 6 / ISO/TC 11/SC 2/ WG 15 (NL-3) 5, Entwurf September 1971.

/ 7 / WOODLEY, C. C., F:M. BURDEKIN and A.A. WELLS, British Welding Journal, 1964, Vol. 03, p.123-136

/ 8 / Afnor 1980: A 36-010, Mai 1980

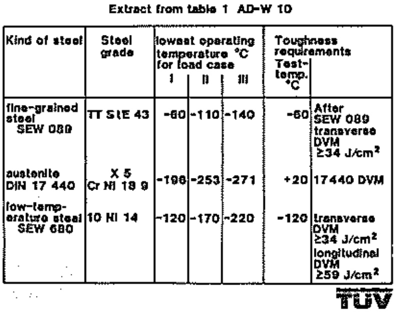
/ 9 / SANZ; G.: risque de rupture fragile, published by Afnor, 1981

/10 / BARSON, J.M., and T. ROLFE. ASTM, STP 466 (1970), p. 281-302

/11 / KTA-Regel 3201.2 published by Vereinigung der Technischen Überwachungs-Vereine e.V., Essen

/12 / ASME-Code, Section III, Division 1, Subsection NB 2300.

/13 / PELLINI, W.S.: WRC, Supplement to the Welding J., März 1971, p .91-109 and p. 147-157



Extract from table 1 AD-W 10

Kind of steel	Steel grade	lowest operating temperature °C for load case I	II	III	Toughness requirements Test-temp. °C	
fine-grained steel SEW 089	TT StE 43	-60	-110	-140	-60	After SEW 089 transverse DVM ≥34 J/cm²
austenite DIN 17 440	X 5 Cr Ni 18 9	-196	-253	-271	+20	17440 DVM
low-temperature steel SEW 680	10 Ni 14	-120	-170	-220	-120	transverse DVM ≥34 J/cm² longitudinal DVM ≥59 J/cm²

Table 1: Extract from table 1, AD-W 10, German rule for pressure vessels

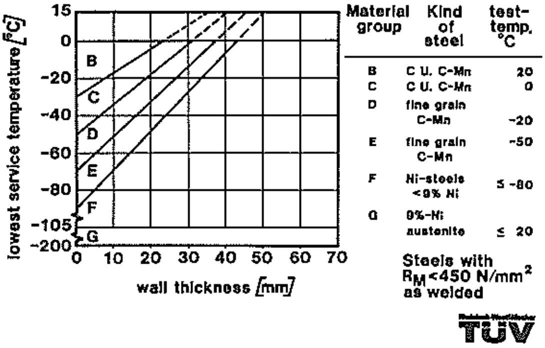


Figure 1: Relation between lowest service temperature, component wall thickness and material group, ISO-draft /6/

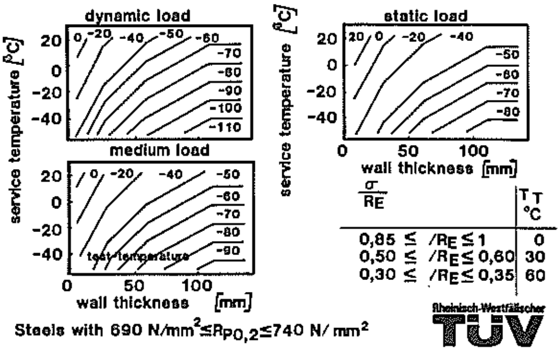


Figure 2: Relation between design parameters: lowest service temperatur, component wall thickness and necessary transition temperature of the allowable material group (ISO-draft /6/)

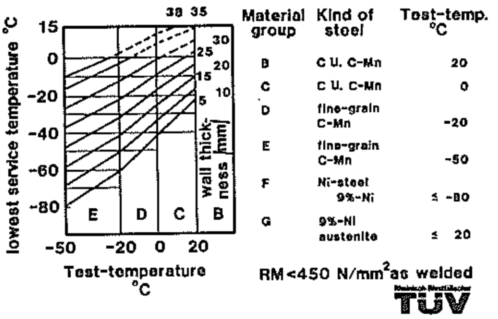


Figure 3: Relation between lowest service temperature, component wall thickness, loading rate, stress and test temperature for steels with 690 N/mm² ≤ $R_{p0,2}$ ≤ 740 N/mm² /8/

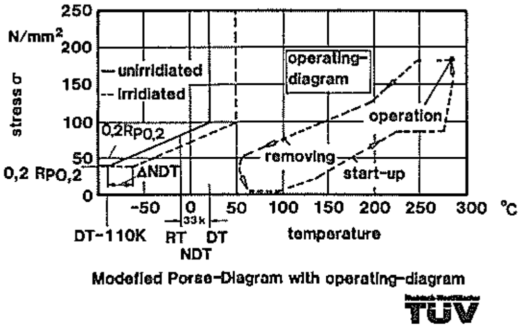


Figure 4: The porse-diagram with service-diagram /11/

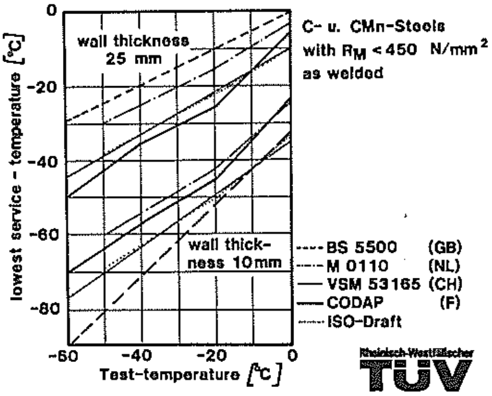


Figure 5: Comparison of rules based on wide-plate test