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Methods for Selecting Brittle-Crack-Resistant Structural Materials Based on Polish and International Standards – Part 1

Abstract: The article describes the phenomenon of the brittle cracking of steel as a component of structural elements of pressure equipment and construction products. The study presents several methods of analysis used by specialists responsible for the design, fabrication and testing of the aforesaid products. The article also indicates numerous international regulations and standards which can be successfully used in many technical solutions. The methods discussed in the study were compared to enable the selection of appropriate material assessment methods ensuring the safe operation of structures.

Key words: brittle cracking, materials, pressure equipment, construction products

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1. Introduction

The selection of materials for welded structures constitutes an important task at the design stage. For this reason, related activities should be performed very carefully to ensure the safe and long-term operation of structures. Applicable standards, regulations and studies contain data in various forms. Regrettably, solutions most frequently adopted by practitioners come from previously prepared tables containing material parameters. The process of selection can be optimised to take full advantage of material properties. The study indicates available solutions. An important criterion for selecting structural materials is their weldability. Mistakes at this stage could lead to the formation of imperfections (e.g. cracks) [1]. For this reason, it is necessary to thoroughly analyse the above-named issue.

2. Materials used in welded structures

Welded structures are widely used in building engineering, mechanical engineering, fabrication of pressure equipment, transport and many other industries. The use of welding processes provides welded structures with the following properties [2]:

- monolithicity, i.e. geometric continuity with the possibility of ensuring the full tightness of the structure,
- lightness, i.e. effective weight reduction compared to castings or forgings while maintaining functional properties such as strength, rigidity and resistance to various effects,
- universality, i.e. the possibility of using nearly any metallurgical products, castings, forgings and other forms of joined materials,
- "technologicality", i.e. the linking of a given structure to a specific manufacturing process affecting the properties of the structure,
- specificity, i.e. in terms of welded structures, the negative effect of stresses, strains and displacements triggered by welding processes.

Welded structures should pose no threat to their users or persons having long or short-term contact with such structures [1]. Welded structures, including construction products or pressure equipment, must primarily satisfy safety criteria. In many countries, including those of the European Union, this indicator takes the form of a legal act.

3. Legal requirements for pressure equipment

There are many legal acts which are in force both in Poland and other EU countries. These acts are usually national acts and community acts applicable in all EU states. In Poland, the aforesaid acts are laws and regulations, whereas in terms of the European Union – EU regulations and directives. Launching pressure equipment on the Community market necessitates the assessment of compliance with the requirements of Directive 2014/68/EU (PED) [11], implemented in the Polish legal area as a regulation of the Minister of Development on requirements for pressure equipment and pressure units (Journal of Laws from 2016, item 1036) [10, 12].

The preamble to the Pressure Equipment Directive (30) states that the fabrication of pressure equipment requires the use of safe materials. It has been assumed that structural materials intended for the construction of pressure equipment are included in the standards harmonised with the aforesaid act. The list of current harmonised standards is available at the website of the European Commission. In cases where harmonised standards are not available, special documents referred to as European Approvals for Materials are developed. These documents are issued by a notified body, designated specifically for this type of task. Despite its original assumptions, the method is rarely used in practice. Significantly more often, parameters of structural materials are determined by the manufacturer of pressure equipment, by developing a one-time material approval also known as Particular Material Appraisal (PMA).

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Requirements for structural materials must be based on the principles of sufficient strength, rigidity and stability. Materials used in the fabrication of pressure equipment must be suitable for specified operating conditions within the specified service life of equipment (unless they are intended to be replaced). The final principle also applies to welding consumables. As the above-named requirements for materials (specified in relevant legal acts) must be applied by manufacturers, the application of such requirements is obligatory for design engineers, technologists and personnel responsible for tests and quality control. The characteristics of materials used in the fabrication of pressure equipment are selected by a design engineer or a team of pressure equipment design engineers. The parameters of structural materials are determined on the basis of previously adopted functional dependences or analysis performed using, e.g. the finite element method (FEM) or fracture mechanics relationships.

3.1. Technical requirements for materials used in pressure equipment

Technical requirements for materials intended for pressure equipment are specified in the Pressure Equipment Directive (PED) [11]. The selection of materials for the fabrication of pressure equipment must be based on the expected service life of the equipment and its application. Welding consumables are also covered by the same requirements. The manufacturer of pressure equipment must confirm the use of material characterised by required technical specifications. Each material used in the production of pressure equipment should be provided with an inspection document issued by the manufacturer.

The fabrication of pressure equipment involves the use of various welding processes. Pressure equipment manufactured using welding processes includes, among other things, the following devices/units:

- various types of chemical devices – absorbers, adsorbers, cyclones, distillers, filters, mills, reactors and mixers,
- equipment used in heat power engineering – water-tube boilers, fire-tube boilers and heat exchangers,
- gas and liquid media transmission networks – oil and gas pipelines,
- tanks used in water systems – hydrophores, accumulators and pipelines,
- cooling devices – pumps, heat exchangers and operating medium tanks,
- transport equipment – tank cars, cylinders and pressure containers.

3.2. Standards harmonised with the Pressure Equipment Directive

The term of "harmonised standard" refers to a standard published by a competent institution and harmonised within the meaning of Article 2 point 1 (c) of Regulation (EU) no. 1025/2012. In other words, it is a European standard adopted on the basis of a motion for the application of EU harmonisation legislation and submitted by the Commission.

Therefore, the term of "European standard" refers to a standard adopted by a European standardisation organization, e.g. CEN (Comité Europeéen de Normalisation), CENELC (Comité Européen de Normalisation Electrotechnique), ETSI (European Telecommunications Standards Institute) or another standards organization which has been granted such a status.

In many legal requirements of the European Union, harmonised standards have a special status. For example, the preamble (28) to the Pressure Equipment Directive [11] states that, in order to facilitate the assessment of compliance with its requirements, it is necessary to provide for a presumption of the analogy of pressure equipment or units to harmonised standards. Such a presumption should primarily apply to the design, fabrication and testing of pressure equipment or units.

The application of harmonised standards remains the most common practice used by manufacturers of pressure equipment and units, intended to be located in the European Union and many other countries, such as Norway, Serbia, and Switzerland. The foregoing is predominantly related to design teams' experience, yet it tends to be very conservative. The above-presented approach leads to the selection of such parts of standards which contain conservative provisions and requirements, in spite of the fact that there are other possibilities, also contained in harmonised standards. By applying alternative requirements from the stage of designing pressure devices through production to final testing, it is possible to provide users with products which are entirely safe and satisfy related legal criteria. This publication presents an example of a standard harmonised with the Pressure Equipment Directive [11], frequently constituting the basis for works performed by manufacturers of unfired pressure vessels.

3.3. Exemplary standard harmonised by the Pressure Equipment Directive

Pressure vessels constitute an important part of pressure equipment and are used in building engineering, chemical, energy, machinery, mining and many other industries. In addition, the vessels are also used by individual users in apartments and houses as components of central heating boilers, LPG-powered cars, and running water systems and connections, i.e. hydrophores. Table 1 presents parts of the PN-EN 13445 standard: Unfired pressure vessels. This series of standards is often referred to in other standards harmonised with the Pressure Equipment Directive. Such standards use provisions contained in the directive, regarding, among others, materials, construction, fabrication or final tests.

Table 1. Parts of the PN-EN 13445 standard: Unfired pressure vessels [5]

Part	Name	Contents
1	General	General information concerning terms, definitions, parameters, symbols and units used throughout the series.
2	Materials	Requirements for materials used in the fabrication of pressure equipment, including their selection for operation at low temperatures.
3	Design	Information concerning the design of pressure vessels by formula (DBF), analysis (DBA) and experiment (DBE).
4	Fabrication	Vessel fabrication conditions. Tests during fabrication.
5	Inspection and testing	Inspection and testing of pressure vessels for conformity with the requirements of regulations and reference standards.

3.4. Requirements specified in the PN-EN 13445 standard

The brittle cracking of materials is a common phenomenon taking place, among other things, during plastic working or after welding. The brittle cracking of welded structures is defined as the destruction (failure) of welded structures along the welded joint, without any visible additional load. The crack propagation rate can reach several hundred m/s [4]. The formation of cracks takes place during the operation of metallic products, primarily those made of ferritic steels. The conditions for brittle cracking are the following [2]:

- loss of plastic properties of the material, which becomes brittle as a result of its lowered temperature,
- areas in a given structure referred to as stress concentrators, resulting from welding imperfections or other defects as well as design errors,
- internal stresses present near notches, particularly tensile stresses perpendicular to the area of the imperfection (gap) forming the notch,
- thickness of elements; thicker elements tend to undergo brittle cracking more often.

In the past, brittle cracking has been responsible for damage to numerous steel structures including bridges, flyovers, pressure vessels, airplanes, ships, etc. The counter-measures, affecting the design, fabrication and operation have significantly contributed to increased operational safety. Presently, the above-mentioned countermeasures are described and their use in practice is obligatory.

Requirements for preventing the brittle cracking of various steel grades at low temperatures are provided in normative Annex B to the PN-EN 13445-2 standard [6]. The Annex distinguishes between pressure equipment whose design temperature during normal operation exceeds 50 °C and equipment operating at a temperature equal to or lower than 50 °C. In terms of pressure equipment operating at a design temperature equal to or less than 50 °C, the aforesaid Annex provides three alternative methods for establishing criteria aimed at preventing brittle cracking. The methods also apply to test conditions, including pressure tests. In accordance with the requirements, materials can be delivered as sheets, strips, pipes, pipe fittings, forgings, flanges, connectors and joined elements.

The determination of requirements for materials used in the fabrication of pressure equipment entails the use of parameters related to the temperature of metal and impact tests, i.e. impact energy and thickness. For standard-related purposes, several definitions used in calculations are specified, i.e.:

- **Minimum metal temperature** T_M is the minimum temperature of metal for any of the states presented below:
  - operation under normal conditions and nominal parameters,
  - start-up and shut-down procedures,
  - disruption of standard processes, e.g. the discharge of fluid with a boiling point below 0 °C under atmospheric pressure,
  - pressure and leakproof tests.
- **Temperature correction** T_S is connected with the determination of reference temperature T_R (see below), dependent on tensile membrane stress at specified temperature T_M, determined in accordance with Annex C to the PN-EN 13445-3:2014 standard. The value of correction is contained in Table B.2-12 of the PN-EN 13445-2 standard [6].
- **Design reference temperature** T_R jest is used to identify toughness-related requirements; it is the sum of T_M and T_S.
- **Impact test temperature** T_{KV} is a temperature at which the required value of impact energy should be obtained.
- **Impact energy** is energy absorbed KV by a material specimen with the V-notch V, in accordance with the PN-EN ISO 148-1:2010 standard.
- **Reference thickness** e_B is the thickness of a component of an element which should be used to relate reference temperature T_R of that part to required impact test temperature T_{KV}. In relation to unwelded parts, reference thickness e_B is equal to the nominal wall thickness. In terms of welded elements, the reference thickness is specified in Annex B to the PN-EN 13445-2 standard [6].

The selection of material for pressure equipment aimed to prevent brittle cracking can be based on three independent methods, i.e. operating experience, a hybrid method related to fracture mechanics and operating experience and the analysis of fracture mechanics. Based on available input data, each of the above-named methods enables the assessment of the brittle crack resistance of materials used in the fabrication of pressure equipment. It is necessary to use only one (any) of them. Despite the freedom to choose the method, selected solutions tend to be rather conservative.

It is necessary to take into account all combinations of minimum metal temperature T_M and temperature corrections T_S (which are applied). In addition, the lowest possible design reference temperature T_R must be used to determine the temperature of impact energy.

Procedures based on operating experience or operating experience and fracture mechanics included in sections 3.4.1 and 3.4.3 are used to identify the required value of impact energy for materials used in pressure equipment and aimed at preventing brittle cracking. The procedure based solely on fracture mechanics is included in Section 4 of this study, discussing FITNET procedures [6].

3.4.1 Method based on operating experience

The method based on operating experience assumes that the reference design temperature is equal to the impact test temperature at which the value of impact energy amounts to 27 J:

$$T_{KV} = T_R = T_{27J} \tag{1}$$

The above-named condition, specified in standards harmonised with the Pressure Equipment Directive (PED), e.g. PN-EN 13445-2 [6] and PN-EN 13480-2 [7], also applies to the properties of materials after the fabrication process. The procedure allows the selection of materials directly from the standard harmonised with the PED, assuming that the expected strength will be achieved after the manufacturing processes. Table B.2-2 of the PN-EN 13445-2 standard [6] contains data enabling the identification of design reference temperature T_R for sheets and strips in relation to steel grades and their reference thickness e_B after welding (AW) or after welding and post-weld heat treatment (PWHT). Some data contained in the standard are provided in Table 2.

3.4.2. Method based on operating experience – example

The EN 13445-2:2015 standard enables the estimation of required fracture test temperature directly on the basis of harmonised standards containing data concerning materials intended for pressure equipment. Assuming that

Table 2. Parameters used to determine the temperature of impact energy for selected steel grades [6]

Sheets and strips						
Standard no.	**Grade**	**Material no.**	**Maximum reference thickness e_B**		**Design reference temperature T_R [°C]**	**Material group**
			AW	**PWHT**		
EN 10028-4: 2017	P355NH	1.0565	35	70	-20	1.2
	P355NL1	1.0566	35	70	-40	1.2
	P355NL2	1.1106	35	70	-50	1.2

Table 3. Parameters used to determine the temperature of impact energy for nickel steels [6]

Sheets and strips						
Standard no.	**Grade**	**Material no.**	**Maximum reference thickness e_B**		**Design reference temperature T_R [°C]**	**Material group**
			AW	**PWHT**		
EN 10028-4: 2017	11MnNi5-3	1.6212	35	80	-60	9.1
	13MnNi6-3	1.6217	35	70	-60	9.1
	15NiMn6	1.6228	35	70	-80	9.1

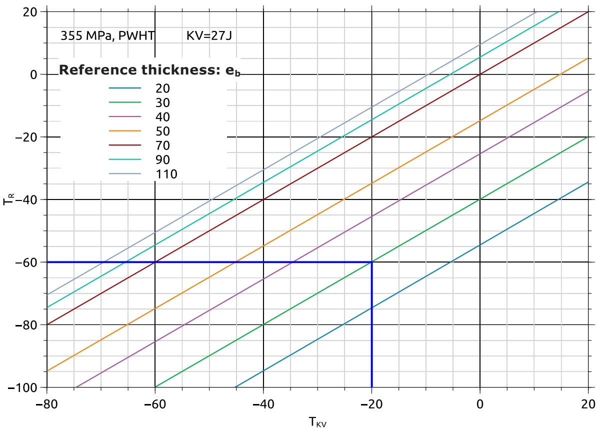

Fig. 1. Diagram enabling the determination of impact test temperature for materials having a yield point of up to 355 MPa after welding and heat treatment (own elaboration based on [6]

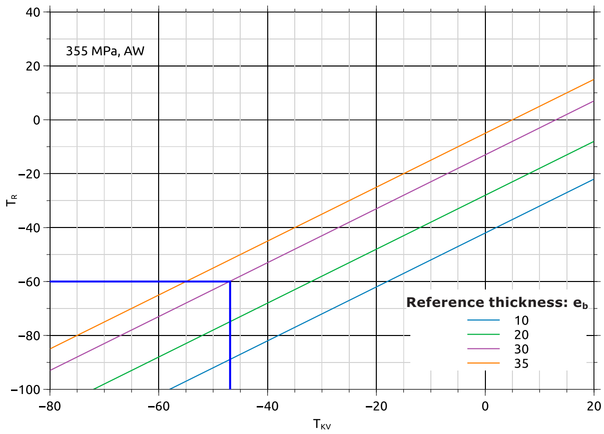

Fig. 2. Diagram enabling the determination of impact test temperature for materials having a yield point of up to 355 MPa after welding (own elaboration based on [6]

$T_{KV} = T_R = T_{27J}$, it is necessary to read out the appropriate value of reference temperature T_R. Presented below is an exemplary part of Table B.2-2 [6].

Taking into account the data from Table B.2-2, the required fracture test temperature for nickel alloy steel 13MnNi6-3 (1.6217) could be determined as equal to T_{KV} = -60 °C. In accordance with the conditions provided before, the value of impact energy should be equal to or greater than 27 J. These requirements apply to materials having a reference thickness of up to 35 mm after welding or up to 70 mm after welding and post-weld heat treatment. The above-named values are indicated in Table 3 (in grey).

3.4.3. Method based on fracture mechanics and operating experience

This method adopts a more flexible approach than that referred to in paragraph 3.4.1. The method is used for carbon, carbon-manganese, fine-grained, alloy steels and steels containing nickel up to 1.5 % having a specified minimum yield point of ≤500 MPa as well as for ferritic-austenitic steels having a specified minimum yield point of ≤550 MPa. The method can be applied to the above-named materials within a wider range of thicknesses and temperatures than the previous one as reference temperature T_R does not have to be equal to the impact test temperature T_{27J}. In addition, in cases of ferric steels having a maximum yield point of 355 MPa after heat treatment, operating experience takes into account greater material thicknesses.

3.4.4. Method based on fracture mechanics and operating experience – example

In accordance with the EN 10028-4 standard, the minimum yield point of steel 13MnNi6-3 (1.6217) amounts to 355 MPa. Therefore, the temperature impact energy for the steel having a thickness of 30 mm was determined (in accordance with the method based on fracture mechanics and operating experience) using the diagrams presented in Fig. B.2-3 (in relation to the steel after welding and heat treatment) and Fig. B2-4 (in relation to the steel after welding) [6]. Figure 1 presents the method for determining the fracture test temperature for steel 13MnNi6-3 having a thickness of 30 mm. The diagram reveals that reference temperature T_R amounting to -60 °C requires fracture test temperature T_{KV} amounting to -20 °C. Therefore, in relation to the steel subjected to post-weld heat treatment (PWHT), the temperature is 40 °C higher than that determined using the method based solely on the harmonised standard (i.e. based on operating experience). Figure 2 presents data for determining the fracture test temperature without post-weld heat treatment (AW). In relation to the material having reference thickness e_B amounting to 30 mm, the fracture test temperature amounts to -47 °C, i.e. is 13 °C higher than that used in the first method. In the above-presented example, the values refer to longitudinal or circumferential joints of the pressure vessel shell. In terms of other types of joints present in pressure vessels, it is necessary to take into account reference thicknesses provided in Table B.4.1 of the PN-EN 13445-2 standard [6].

4. FITNET procedures

The systematisation of knowledge concerned with assessing the strength of structural elements containing defects was initiated at the request of the European Commission in 2006. The cooperation of scientific and research units from the European Union (based on the SINTAP procedures [9]), starting from 2003 and 2004, led to the development of a document called FITNET Report [8] or (in full) "European Fitness-for-service Network". This document, commonly known as "FITNET Procedures", recommended by the European Union, includes guidelines for assessing the strength, service life and operational safety of structural elements containing defects. Apart from many theoretical foundations, the document contains information useful in solving practical problems [3].

In the most general description, the FITNET procedure [8] can be divided into four main modules, related to fracture mechanics, fatigue, creep and corrosion. The document contains a significant amount of condensed theoretical information, sometimes requiring the extension of knowledge by referring to professional publications (which is illustrated with numerous practical examples in the appendix of "Case Studies") [8]. The most frequently applied elements of FITNET procedures include submodules enabling the following activities [8]:

- determination of mechanical parameters in the static tensile test, based on previously known values of the yield point,
- estimation of crack resistance K_{mat} using data obtained in impact strength tests, standard tests used to assess the critical value of stress intensity factor K_{IC} (simple statistical analysis for specimens having the same thickness and tested under the same ambient conditions) or using the MML analysis for experimental data obtained at the same or different ambient temperature, using specimens having different geometric dimensions,
- assessment of replacement defects (replacement defect) for a set of defects in a structural element,
- determination of loads of the first type (primary loads), commonly referred to as "primary stresses" and loads of the second type, referred to (in the procedures) as "secondary stresses",
- estimation of ultimate loads and theoretical values of stress intensity factor K_I,
- analysis of sensitivity, based on failure assessment diagrams (FAD) crack driving force (CDF),
- assessment of fatigue strength and fatigue crack growth on the basis of Paris' law or Forman-Mett's law,
- assessment of creep strength along with the assessment of crack length growth under creep conditions,
- assessment of corrosion resistance.

The FITNET procedures [8] can be used when designing new elements (components), during the fabrication of these elements (as support in ensuring appropriate quality), during the operation of structural elements and, in the event of failure, to assess and calculate the failure of a structural element. The general diagram of the FITNET procedures is presented below in Fig. 3 [8].

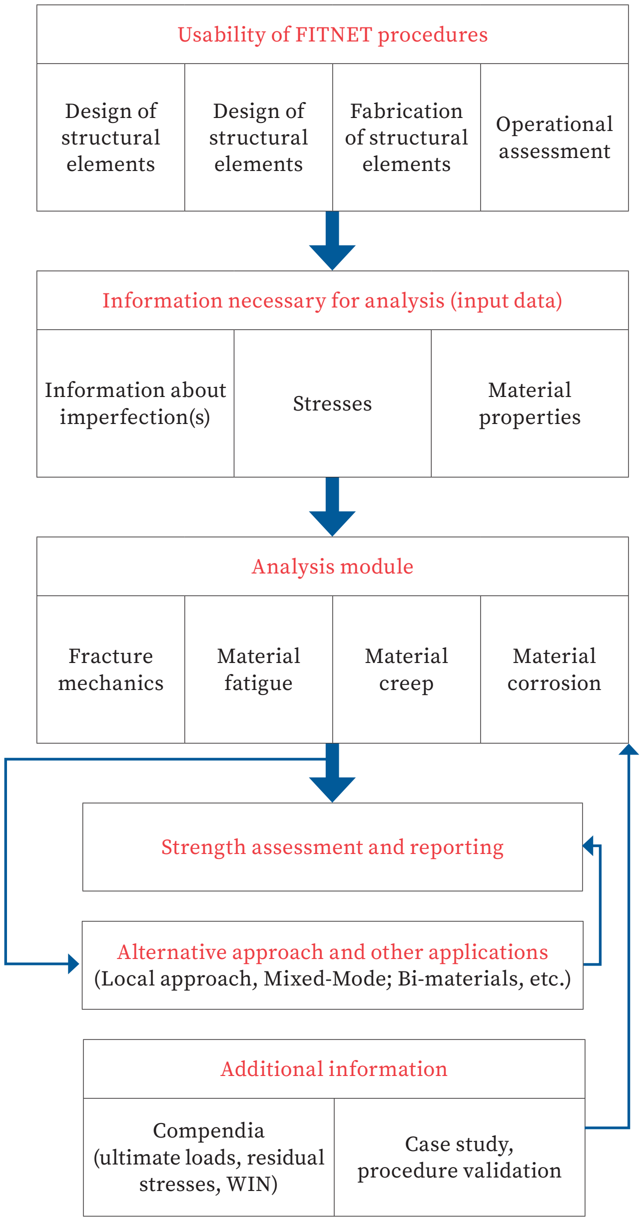

Fig. 3. General schematic diagram of FITNET procedures (own elaboration based on [8])

5. Summary

The brief presentation of several options enabling the assessment of various structural elements in terms of brittle cracking indicates numerous solutions usable at the design stage as well as during fabrication and operation. It is essential to properly assess brittle crack resistance in each of the above-presented possibilities as well as to estimate the temperature in relation to which impact energy amounts to 27 J. The aforesaid value results from many years of operating experience concerning pressure equipment. This is necessary both in terms of the application of harmonised standards and SINTAP/FITNET procedures. Because of the limited volume of the article, appropriate formulas and auxiliary tables for the SINTAP/FITNET procedures have not been provided in this study. The inclusion of fracture mechanics when assessing the brittle cracking of pressure equipment or construction products is necessary, particularly where one does not want to use conservative material data at the design stage and, at the same time, wishes to ensure the safety of use in the event of detection or assumption of the presence of a hypothetical crack (which could be proven using analysis in accordance with the FAD diagrams).

This article outlines the basis for the selection of materials with respect to brittle cracking and provides examples related to pressure equipment. The second part will contain an example (using the fundamentals of fracture mechanics) concerning the analysis of a pipeline with imperfections. The second part of the article will also discuss issues related to construction products made of steel.

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