Simon Sedmak[1], Radomir Jovičić[1], Aleksandar Sedmak[2], Mihajlo Aranđelović[1], Branislav Đorđević[1]

INFLUENCE OF MULTIPLE DEFECTS IN WELDED JOINTS SUBJECTED TO FATIGUE LOADING ACCORDING TO SIST EN ISO 5817:2014

UTICAJ PRISUSTVA VIŠE VRSTA GREŠAKA U ZAVARENOM SPOJU OPTEREĆENIM NA ZAMOR U SKLADU SA STANDARDOM SIST EN ISO 5817:2014

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Adresa autora / Author's address:
[1)] University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Belgrade, Serbia email: simon.sedmak@yahoo.com
[2)] University of Belgrade, Faculty of Mech. Engng., Belgrade, Serbia

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Ključne reči
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- SIST EN ISO 5817:2014
- integritet konstrukcija

Abstract

Structural integrity of pressure vessels is of great importance in ensuring their safe exploitation. Due to this, a number of standards are developed in order to define the criteria according to which materials, technologies and test methods are selected for pressure vessels, particularly when it comes to welded joints. Because of the nature of the welding process, welded joints will typically contain different types of defects, some of which could greatly endanger their integrity. Cracks in particular are the cause of pressure vessel failure.

The goal of this paper is to present the standard SIST EN ISO 5817:2014 and emphasize the changes and additions that are made, compared to the previous version, SIST EN 5817:2007. The standard includes recommendations and requirements related to the presence of multiple types of defects in welded joints subjected to fatigue loading. Since fatigue crack growth greatly contributes to failure of pressure vessels, for the first time this standard covers a very important topic. Some of the earlier work related to multiple defects in welded joint is also shown in the paper, and used as examples.

Izvod

Integritet posuda pod pritiskom je od velikog značaja za obezbeđivanje njihovog bezbednog rada. Usled toga, razvijeni su brojni standardi kojima su definisani kriterijumi izbora materijala, tehnologija i metoda ispitivanja vezanih za posude pod pritiskom, sa naglaskom na zavarene spojeve. Zbog prirode procesa zavarivanja, zavareni spojevi sadrže različite vrste grešaka, od kojih neke mogu ozbiljno da ugroze integritet posude. Prsline su naročito opasne u pogledu rizika od otkaza posuda pod pritiskom.

Cilj ovog rada je da predstavi standard SIST EN ISO 5817:2014, sa naglaskom na promenama i dodacima u odnosu na prethodnu verziju standarda, SIST EN ISO 5817: 2007. Ovaj standard sadrži preporuke i zahteve vezane za prisustvo više različitih vrsta grešaka u zavarenim spojevima opterećenim na zamor. S obzirom da rast zamorne prsline u velikoj meri doprinosi opasnosti od otkaza posuda pod pritiskom, može se zaključiti da ovaj standard obuhvata veoma značajnu oblast. U radu su takođe, kao primer, prikazani i prethodni radovi vezani za prisustvo više grešaka u zavarenom spoju.

INTRODUCTION

Safety of pressure equipment has been greatly improved in the recent years up to a point where the frequency of catastrophic failure is as low as 10^{-6} per year of exploitation /1/. This is achieved by developing new and improved standards, which in turn enable the development of better materials, technologies and test methods related to manufacture and exploitation of pressure vessels. Standards in question are developed based on extensive experience gathered through the testing of pressure vessels and determining the reasons behind their failure.

Initially, the factors taken into account when designing pressure equipment include working stresses, mechanical properties of materials, their heterogeneity, plasticity, corrosion, etc. These methods, however do not take into account the presence of defects that could under certain conditions lead to crack initiation, which could in turn result in unstable crack growth and failure of pressure equipment /2/. This is of great importance for welded joints typically used to connect various parts of pressure equipment, since defects in them are unavoidable. Welded joints, therefore, represent critical locations in pressure vessels, especially those with the highest stress concentration, which typically depends on the type of applied load. Such welds need to be investigated thoroughly using non-destructive test methods, including visual inspection, ultrasonic tests, penetrant testing, etc. Once the imperfections in welded joints are determined using any of the above methods (or their combinations), their influence on the structural integrity of pressure vessels should be assessed, in order to determine if it is safe to continue with exploitation, and also to determine the remaining work life of the pressure equipment in question. Data obtained in this way can also be used for the purpose of repairing parts of the equipment, if necessary, /3, 4/.

The purpose of the standard presented here is to provide recommendations on how to prevent these defects from causing failure, i.e. how to keep them within acceptable boundaries. The standard discussed here, SIST EN ISO 5817:2014, developed in Slovenia in 2014 /5/, is an improvement to the previous standard, SIST EN ISO 5817: 2007, /6/. This standard is based on the Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welds excluded) - Quality levels for imperfections standard, ISO 5817:2014), and is approved by the European Committee for Standardization. As mentioned above, the purpose of these standards is to define the sizes of commonly encountered defects in welded joints, in accordance with quality level requirements that depend on the application of welded elements, and are defined by the responsible designers and/or manufacturers. These quality levels are related to a number of factors, such as the type of defects in the welded joints, the working conditions (different types of load), potential failure consequences (which are typically catastrophic in the case of pressure vessels, /7/).

SIST EN ISO 5817:2014 - SCOPE AND CHANGES

Both standards SIST EN ISO 5817:2007 and 5817:2014 provide the requirements for quality levels of imperfections in fusion welded joints (excluding beam welding). Welded joints in question are butt and fillet welds made of steel, nickel, titanium and their alloys, /3/. Quality levels given in the standards are B, C and D, whereas the B quality is the highest.

These standards are applicable to the following materials, welded joint geometries and welding technologies:

- Non-alloyed and alloyed steels
- Nickel and its alloys
- Titanium and its alloys
- Butt welds, fillet welds and branch connections
- All welding positions
- Metal arc welding (with or without shielding gas)
- Submerged arc welding
- Plasma arc welding
- TIG welding
- Oxy-fuel gas welding (for steel only).

Standards SIST EN ISO 5817:2007 and 5817:2014 do not cover the microstructural properties, such as grain size and hardness of these metals and their alloys.

The main difference between the two standards is the addition of Annex C in SIST EN ISO 5817:2014. This annex defines the additional requirements for welded joints subjected to fatigue loading. The Annex defines the quality levels required in order to meet the fatigue class (FAT) requirement, whereas FAT has a value corresponding to the acceptable stress range for two million cycles, a two-sided survival probability of 95%, determined from the mean value based on the two-sided 75% tolerance limit of the mean corresponding to IIW Recommendation (IIW-1823-07, /8/).

Taking into account the effects of fatigue on welded joint results in the need to adopt additional requirements for B and C quality levels, for the purpose of adjusting the acceptable defect dimension limits. The adjusted values of defect dimension limits can be seen in detail in Annex C of standard SIST EN ISO 5817:2014, /4/.

PRACTICAL EXAMPLES OF INTEGRITY ASSESSMENT FOR WELDED JOINTS WITH MULTIPLE DEFECTS

In this section, some of the previous research regarding the subjects of fatigue loading, multiple defects and the application of standards to them is shown using several examples, /9-11/.

Cracks in the fusion line of a cylindrical CO_2 tank

This research involved the numerical analysis of the stress state in welded joints with certain imperfections, which were a part of a cylindrical tank used for storing carbon dioxide, /8/. The tank is made steel P460NL1, a low-alloyed high strength ductile steel with good weldability. Cracks detected using NDT methods, located between the shell and the head of the tank, can be seen in Fig. 1, whereas the geometry of one of the welds can be seen in Fig. 2. As can be seen from this figure, the welded joint contains a crack in the fusion line, as well as a linear misalignment of the parent material (P460NL1).

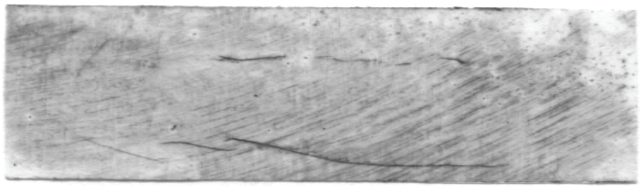

Figure 1. Location of cracks in the CO_2 storage tank, /8/.

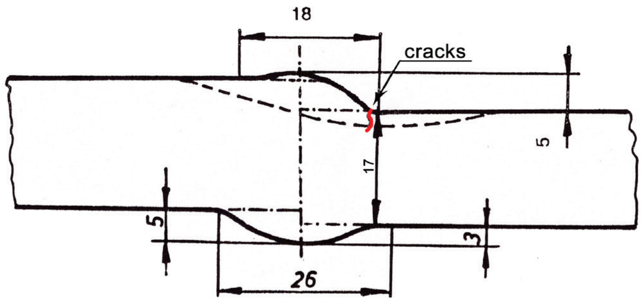

Figure 2. Geometry and dimensions of a welded joint with linear misalignment.

In addition to the model based on the geometry seen above, an another one is made of a welded joint with acceptable (negligible) linear misalignment, but with a noticeable weld face overhang. The test pressure used for the tank is 2.6 MPa, and based on this value, along with the sizes of the tank, /8/, the normal stress was determined to be 115 MPa (for the purpose of numerical simulation). Residual stresses in the welded joint (with a magnitude of 383 MPa) are also taken into consideration while interpreting the obtained results. The maximum stress values obtained for both models accounted for the presence of cracks in the first and their lacking in the second one (since they were above the parent material tensile strength for the linear misalignment model, and below it for the overhanging model). It is concluded that the cracks were caused by the combined effect of defects and residual stresses.

This analysis was also used in order to illustrate how numerical analysis of welded joints can show the differences between welds with different types of defects in terms of stress magnitudes and their distributions, showing the importance of the use of NDT methods in detecting imperfections that shall be taken into account during further analyses.

Effects of geometry and residual stresses in welded joints subject to fatigue loading

This paper focuses on developing of a model for predicting fatigue behaviour of welded joints due to the combined effects of geometry (and defects resulting from it), residual stresses and various loading cases. This behaviour is based on determining the stress intensity factor (from the Paris-Erdogan power law) in the case of a specimen with several different types of defects (undercuts), all of which include a semi-elliptical surface crack, /9/. The classification of the defects considered is shown in Fig. 3.

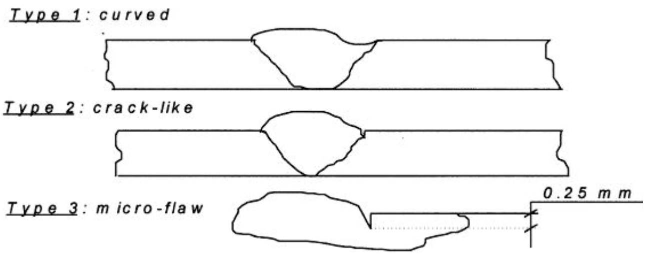

Figure 3. Classification of undercuts in the case of a butt welded joint, /9/.

Types of undercuts discussed in this paper typically occur in manual metal arc welded joints, and manifest in the form of a lack of sufficient weld metal deposit, as seen in the above figure. Of the three types shown, the first is adopted as representative for the model, since it is the most commonly encountered type. In addition, the misalignment of the butt joint in question is taken into account (including linear and angular misalignments). Such misalignments can cause additional loads (forces) acting in the welded joint, which should be included in the stress concentration factor K_t, as shown in literature, /9/.

The next step involves the determining of fatigue strength of butt welds subjected to combined loading and residual stresses. This strength is dependent on a number of factors, including weld geometry, load conditions and residual stress. Fatigue strength obtained in this way, /9/, is then used as the basis for developing a mathematical model for the S-N curve.

Welded specimens are made of ASTM A36 structural steel, and are designed for constant load amplitude fatigue tests in accordance to standard E466-82. Submerged arc welding procedure is used for welding plates from which the specimens are cut.

Tests are performed using an universal MTS-testing system which can record all of the relevant dynamic results in digital form. The experiment involved static tests in order to determine the properties of the specimens, along with fatigue tests which were performed at several constant loading levels, with the stress ratio $R = 0.1$.

Shown in Figs. 4-6 are the test results, including the dependence of the S-N curve from the undercut radius, the residual stresses and welded joint misalignment, respectively. It can be seen that the reduction in the undercut causes the S-N curve to move left to right, suggesting that fatigue strength and life of the observed butt-welded joints can be improved by removing the undercut defect.

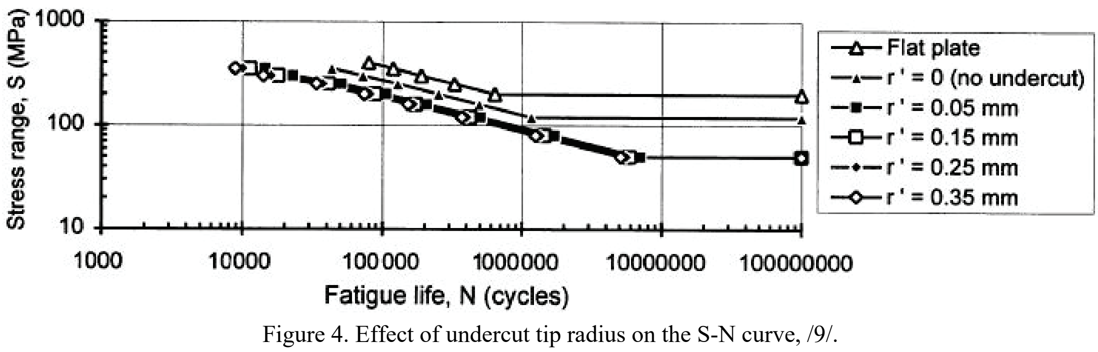

Figure 4. Effect of undercut tip radius on the S-N curve, /9/.

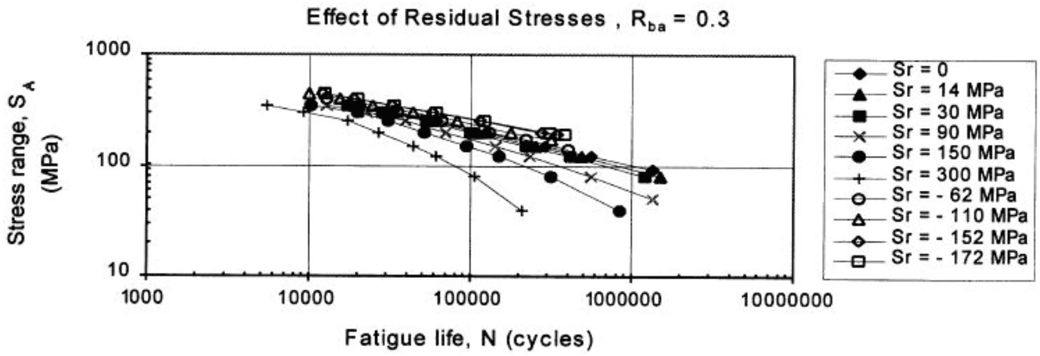

Figure 5. Effect of residual stress on the S-N curve, /9/.

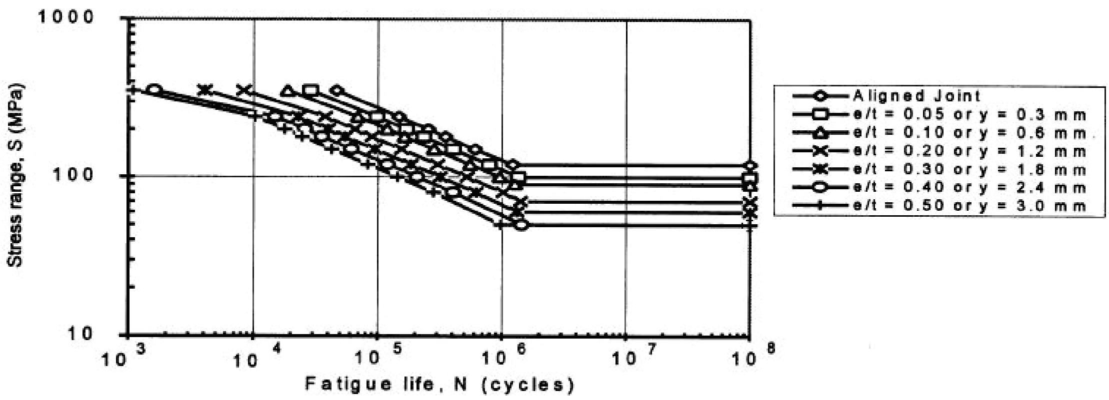

Figure 6. Effects of combined loading due to misalignment.

As can be seen in Fig. 5, residual stress tests are performed by using varying stress magnitudes, ranging from –172 to 300 MPa, whereas 300 MPa corresponds to the parent material yield strength. Based on curves shown in this figure, it can be concluded that compressive residual stresses improve fatigue life, whereas tensile residual stresses reduce it, as expected. This suggests that the introduction of compressive residual stresses could further improve fatigue strength and life.

Results in Fig. 6 indicate that the increased misalignment leads to decreased fatigue life, as S-N curves tend to move to the left with the increase in *e/t* and *y*, which represent misalignments.

In the case of undercut and misalignment defects, it is determined that by reducing or eliminating them, the fatigue life of the butt-welded joints can be increased significantly, up to 300% for complete undercut elimination and 150% for misalignment elimination, /9/.

After the results of the aforementioned tests are obtained and analysed, it is concluded that the fatigue strength and life of butt-welded joints can be greatly improved by decreasing the size of defects (in this case, undercuts and linear or angular misalignments), or by eliminating them. An additional measure that could be utilised in order to improve the fatigue properties of the welds in question involved the introduction of compressive residual stresses to the surface through various methods. It is confirmed that the mathematical model developed in this study could be used effectively in predicting the overall effects of geometry parameters (various defects) and residual stresses of butt-welded joints, subjected to combined loading (due to the presence of the previously mentioned defects).

Results presented in this research brought up the question of what would happen if multiple imperfections (defects) of significant size are present in welded joints? In what way would this affect the fatigue properties of such welds?

IIW recommendations for fatigue assessments of welded joints and components

Research described in this paper is inspired by the need to review and update current integrity assessments of welded joints. It is focused on combining all of the previous recommendations regarding the test methods, fracture mechanics assessment methods and safety, /10/. One particular goal of the standard updates is to include fatigue behaviour of welded structures in a way that would ensure it is independent from the selected assessment method (nominal stress, structural hot spot stress, notch stress, fracture mechanics, …).

Determination and interpretation of fatigue properties of welded joints is influenced not only by the adopted assessment method, but also by the application of the structure in question, as well as the (un)availability of the necessary material properties. The aim of the updates to the previous IIW recommendations is to address all these issues, making the determination of fatigue behaviour universally applicable.

A different way of assessing fatigue properties covered by this documentation is shown in Table 1, /10/. It is necessary to ensure that all of the elements of fatigue assessment correspond to each other, as well as to take into account all regulations related to various factors that are important for each method.

Table 1. Consistent application of IIW recommendations.

Assessment	Type of fatigue action	Information
Component test	Load on component	No information
S-N curve of detail	Nominal stress	Structural detail
S-N curve of weld	Structural hot-spot stress	Type of weld
S-N curve of mater.	Notch stress	Effective notch stress
Paris power law	Stress inten. at crack tip	Material parameters

Additional details about each of these fatigue assessment methods can be found in corresponding literature. These methods should also take into account residual stresses, which are factored into fatigue behaviour analysis through previously mentioned FAT values.

Once fatigue properties are determined, it is necessary to re-evaluate the existing data in order to establish a code for application of various methods that can be used to improve fatigue strength and life of welded joints (by improving surface geometry, residual stresses and shape). Geometry and shape changes are often related to the presence of imperfections (defects) in welded joints. According to previous standards in the ISO 5817 series, there are 26 different types of defects, with their corresponding acceptable dimensions for quality levels B, C and D.

The problem with these standards is that they are developed based on DIN 8563 standard, which has classified welded joints depending on the difficulty and the cost of manufacture and testing of these welds using NDT methods, without taking fatigue into account. Hence, ISO 5817 could not apply to problems related to fatigue properties, and there is a need for improvements. The solution proposed by IIW is to extend the scope of typical fatigue related codes by describing fatigue properties of welded joints with different imperfections, such as undercuts and misalignments as described in the previous examples.

It is concluded that the process of updating existing recommendations in terms of fatigue behaviour and defects, has provided a number of innovative benefits, some of which include: detailed recommendations for FEM meshing of structural hot spot stress method models, the expansion of effective notch stress method to aluminium welded joints, direct fatigue assessment of components without the need for subsequent testing, etc. /10/. These conclusions inspire future work on ultimately developing a standard that would include the above aspects, which is the point of the implementation of the improved version of SIST EN ISO 5817:2007, i.e. the SIST EN ISO 5817:2014.

CONCLUSIONS

The purpose of this paper is to introduce the newly implemented standard SIST EN ISO 5817:2014 which contains recommendations and regulations related to the presence of imperfection, i.e. defects in welded joints. The previous version of the standard, SIST EN ISO 5817:2007 contains the same limitations for acceptable sizes of various defects, depending on the type of welded joints, however, it lacks any information regarding fatigue loading.

As can be seen from the literature reviewed herein, the presence of defects could result in the increased stress concentration and contribute to crack initiation and unstable growth. Furthermore, the second and third example emphasize the considerable significance of fatigue to the structural integrity of welded joints, and its dependence on numerous factors, such as geometry, application, load and exploitation conditions.

For reasons mentioned above, it is of great importance to present the standard in question to any and all who are involved in designing and testing pressure equipment, as its main goal is to further improve the safety of such equipment by taking into account factors previously not considered sufficiently (or at all).

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