FAILURE CASE STUDIES OF WELDABLE EQUIPMENTS
– knowledge base model

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ABSTRACT

The reliability of welded construction during exploitation is an important due to safety of people, protective environments as well as material goods. One of approach to improve reliability of welded constructions is learning on former failures of welded constructions. Usually failures of welded constructions as well as the knowledge base model about accessible failures of welded constructions were explained in this paper. Case studies of failures at welded constructions are very important during education of students as well as engineers from practice. Recognising with failures cases and their analysis will improve reliability of welded construction currently in service, and also a new constructions. The example from practice - wrong chosen post weld heat treatment parameters at normalisation of chamber preheater of vapour boiler plant were also explained. Therefore, the models of safety (reliability) of welded joint on constructions were explained, as well as the models of base material weakening due to welding at welded joint position, by especially accent on the probabilistic approach to determinate the reliability of the pressure vessel.

1. INTRODUCTION

The failure of welded product i.e. the welded constructions appears in two basic cases:
- if operating and/or residual stresses exceed a limit of welded joint strength, and
- if during welding and/or exploitation of welded product appears significant weakening in the position of the welded joint.

Results of failures of the welded joints are the best often expressed in: immediate people losses, losses due to the contamination of the biology environment and property losses.
Failures could have fatal consequences. Here are some examples that happened during 1984:

- Explosion and destruction of storage of LPG (liquid gas) in Mexico City which caused death of 500 and wounded 7000 people.
- Tragedy of leaking poisoned materials in chemical factory in Bhopal, India, several thousands people died and many had series consequences to their health.
- In Chicago Oil Co. vertical pressure vessel exploded (amin-absorber) and 17 people died.

In this work, authors would like to give contribution to the reliability and the safety of the present and a new welded products by means of the knowledge base model about former failures of welded products and the degradation at the welded joints.

2. USUALLY WAYS AND FAILURES REASONS OF WELDED JOINTS

Usually failures of welded joints can be classification into two basic groups: the failures which reliability can be safetied by means of calculations (Table 1) and the failures which reliability is based on the experimental investigations and control tests (Table 2).

Table 1. Usually failures of welded joints which can be comprehensive by calculations and values for the safety from failure.

<table>
<thead>
<tr>
<th>FAILURE</th>
<th>PROPERTY</th>
<th>SIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Toughness fracture</td>
<td>Tensile strength</td>
<td>$R_m$ (MPa)</td>
</tr>
<tr>
<td>2. Brittle fracture</td>
<td>Fracture toughness</td>
<td>$K_{IC}$, $\delta_C$, $J_{IC}$, ... (MPam$^{1/2}$)</td>
</tr>
<tr>
<td>3. Permanent deformity</td>
<td>Yield strength</td>
<td>$R_t$, $R_{0.2}$, (MPa)</td>
</tr>
<tr>
<td>4. Fatigue</td>
<td>Threshold fatigue Increas crack</td>
<td>$R_u$, (MPa) $\frac{da}{dN}$, (mm/No. change of loading)</td>
</tr>
<tr>
<td>5. Creeping</td>
<td>Limit creeping</td>
<td>$R_m/100000/T$, $R_{1%/100000}/T$, (MPa)</td>
</tr>
<tr>
<td>6. Losses of stability</td>
<td>Stability of bars, plate and flake</td>
<td>$F_{critical}$ (N) $\sigma_{critical}$ (MPa)</td>
</tr>
<tr>
<td>7. General corrosion</td>
<td>Resistance to general corrosion</td>
<td>$C_r$, (mm/year)</td>
</tr>
</tbody>
</table>

Table 2. Usually failures of welded joints at which the reliability is safeting on the bases of experimental investigations and control tests.

<table>
<thead>
<tr>
<th>FAILURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. other forms of corrosion: stress corrosion cracking (SCC), intergranular corrosion, selective, pitting and crevice corrosion, ...</td>
</tr>
<tr>
<td>2. abrasion, erosion cavitation etc.</td>
</tr>
<tr>
<td>3. thermal shock and thermal fatigue</td>
</tr>
<tr>
<td>4. permeable of medias</td>
</tr>
<tr>
<td>5. turn over, slipping, gun effect</td>
</tr>
<tr>
<td>6. different combination of failures (SCC, corrosion fatigue...).</td>
</tr>
<tr>
<td>7. others failures</td>
</tr>
</tbody>
</table>

By analysis of former documentations about failures of welded joints and products to become known to knowledge that usually reasons of failures are:

1. Requirements for quality in agreement - contracts: (unadequate, unprecise..),
2. Construction: (concept, calculation and formation of details…),
3. Material: (wrong chosen of material, defect into material…),
4. Technology of making and controlling (chosen operations, conditions of work, series of operations…),
5. Means of production (equipment, tool, control instrument…),
6. Human factor (worker, constructor, controller…),
7. General conditions (temperature of environment, wind, humidity, powder, light…).

Although any of previously mentioned reasons are presented in failures reports but behind the every reason always is human error. For example, defect into the material or defect in the construction appears due to an unsufficient the knowledge or unconscience of human. All mentioned reasons of errors and failures can be classified into two reasons which depend of man: knowledge and conscience.

Knowledge is need because of adjustment correct the requirements to quality of product (characteristics, parameters, conditions, criteria of acceptance construction, dimensions, material, technology, control, conditions for exploitation, …).

The conscience is need due to the correct adjustment (described) requirements, procedures, other documents and criteria of acceptance would be carried out.

3. FAILURE “CASE STUDIES” KNOWLEDGE BASE MODEL

Before ten years an idea for the formation of the knowledge base model was appeared when authors in the papers [2,3] a part investigation activity were presented. The knowledge base model about failures and defects cases on weld joints and weld constructions was planned (projected) as open system by possible the expansion with a new failures cases. Experiences about failures and defects on welded constructions was not always formered. By analysis of failures cases we can improve level of the knowledge for students during their education and engineers in the practice as well as avoid to repeating the same errors at a new production processes. Figure 1 gives schematic illustration of the knowledge base. The base consisted of two basic parts: failures (errors) in production and failures in exploitation. By every failure case or error (in production or in exploitation) the analysis was saved with shows reasons and ways avoidance of error.

Figure 1. Schematic illustration of basic concept failure “case studies” knowledge base.

Figure 2 shows the analysis of possible errors observed in pressure vessels exploitation, which is used as the shell of the knowledge base about failures of welded joints on welded constructions (risk to failure).
Using “fuzzy logic control” the probability of failures formation can be calculated. Also, it is possible to put (save) in knowledge base practical examples which is in relation to an error effects or the failure, and also to take it into consideration on particular affected factors.

3.1. Errors due to an unadequate post weld heat treatment parameters

This error was appeared on the chamber of vapour preheater of the boiler plant. Boiler plant made from low-carbon and low-alloy (Mo and Cr) steels (for example X20CrMoV121 in accordance to DIN Std.). The chambers as the collector of the water and the vapour were loaded thermal, mechanic (cavitation) and dynamic (because often changes of pressure into the chamber).

Manufacture of boiler (operating pressure of 122 bars, operating temperature at 320°C) was in accordance to ASME Std. from SA 10Gr.B steel (St. 45.8 in accordance to DIN). (Figure 2). The chamber was produced by hot working and it was delivered in non-normalised state. Requirement of customer was that the chamber be delivered in normalised state. Normalisation was planned after all technological operations in workshop (flush welding of chamber, machine treatment etc.)

Before normalisation of chamber the replica of microstructure was made (Fig. 3a). Figure 3a shows coarse-grain ferrite-pearlite microstructure by grain size 5-7 in accordance to ASTM Std.

Normalisation of the chamber was carried out in accordance to diagram shown in Fig. 3c. However, the chamber is offer holding on normalisation temperature cooled in furnace and the cooling rate was lower than desirable. It was resulted that partition of ferrite is increased relation to a part of pearlit (Fig. 3b, wrong heat treatment parameters) which is resulted in decreasing of the hardness and strength. Since the normalised microstructure was not obtained, the chamber was spoiled casting. On this way a high property loss was made.

The chamber with microstructure degradation was rejected, and a new one was made. Post weld heat treatment parameters (normalisation parameters) for new chamber was shown at fig. 3d. After post weld heat treatment the fine-grain microstructure was obtained (Fig. 3e).

From this a typical example of human error can be seen significant precise to follow regulations of parameter post heat treatment of welded products as well as an important consistent the performing of parameters during operationalization.
Figure 2. Possible reasons of error/failure observed in exploitation of welded pressure vessel.
Computer aided welding technology projecting

a) Base material F/P structure before heat treatment

b) Base material structure after heat treatment (wrong parameters)

c) Diagram of normalisation with wrong parameters:
   - 890 - 910 °C; 150 min.
   - max. 75 °C/h up to 3000 Hlađenje na mirnom zraku Cooling on calm air

Post weld heat treatment diagram according to working instructions at first normalisation (wrong parameters + human error during normalisation providing).

d) Right heat treatment parameters:
   - 905 ± 15 °C; 130 min.
   - min. 150 °C/h up to 3000 Hlađenje na mirnom zraku Cooling on calm air

Right heat treatment parameters.

e) Base material structure after right heat treatment

Figure 3. An example of “case study” – error because of uncorresponding parameter of post heat treatment.

a) microstructure of base material before normalisation, magnification 200x,
b) microstructure of base material after normalisation by wrong parameters, magnification 200x,
c) diagram of normalisation with wrong parameters,
d) diagram of normalisation with valuable parameters,
e) microstructure of base material after normalisation in accordance to Fig. 3d., magnification 200x.
3. RELIABILITY MODELS OF WELDED JOINTS AND WEAKENING MODELS ON THE PLACE OF WELDED JOINT

Aim of analysis of the cases failures is increasing of the reliability of both welded joints and welded constructions. The reliability of welded joints and the weakening on the place of welded joint can be shown both qualitative and quantitative. At making of welded products (if we have a sufficient high number data about properties of the base material, welded joints as well as stresses for the dominant way of failure) the quantitative testify in the weldability of the base material and the reliability of the welded product. There are a several approaches to the quantitative [4-6]) testifying of the reliability and the weakening of welded joints: deterministic, semi-probabilistic and probabilistic approach (Figure 4).

The deterministic approach of weakening (E) of the welded joints is based on the relationship between minimum properties of welded joint (W) and minimum property of the base material (M) at the dominant failure of welded product. The theory value of the weakening (E) can be greater, equal or lower than 1. If is E>1, it means that case failure of product in exploitation appeared of the base material (at the bat weakest link chain in reliability). This case will not be observed due to it is not dominant failure of welded product. In practice is the oftenest that the welded joint is weak place on welded construction (concentration of stresses, microstructure and geometric errors...). In this case E<1.

Semi-probabilistic approach of the reliability also take the same relationship, as the deterministic approach, but at confidence level factor (γ).

Probabilistic approach of the reliability and the weakening is closer to a real because it has as base accidental values but fixed values. This approach using the theory of probability with basis of standpoint that exists the different ways of weakening and failures. They can be explained by noticeable of particular factors affects and reason-result connect can be to perceive.

At probabilistic approach the reliability of welded joint or product (R) was defined as a numerical values correct function of welded joint or product in predicted time and in predicted of conditions of exploitation.

It is desirable that the reliability is the closer to 1 e.i. 100%. Complementary to probability of the reliability is the risk (F). The weakening of welded joints in relation to the base material is indicator of the weldability of the base material and quality of welded joints. In the praxis at the same name can be found following names: the factor of weakening of welded joint and the quality factor of welded joint or the weldability factor.

Figure 4. shows approaches to modelling of weakening (E, η) the reliability (R) and the safety factor (Sf). F is the probability of failure (unreliability), η(E) is probability of W≥M and reflects measure of weldability.

\[
\begin{align*}
M & \text{ ... material property (strength), MPa} \\
S & \text{ ... stress (working stress), MPa} \\
W & \text{ ... weld joint property (strength), MPa} \\
\bar{W}, M & \text{ ... mean values for normally distributed sample population of W (welded joint property) and M (base metal property)} \\
\sigma_W, \sigma_M & \text{ ... sample standard deviations for W and M} \\
\gamma & \text{ ... accuracy parameter depends on selected confidence level} \\
U, z & \text{ ... derivated variabla (U= W – M; Z = U – \bar{U})} \\
\Phi (m) & \text{ ... Gaussian normal distribution} \\
m & \text{ ... argument of the reliability function} \\
\eta & \text{ ... weld joint efficiency (weldability) expressed as numerical probability} \\
E & \text{ ... weld joint efficiency factor as a single value (deterministic)} \\
\varepsilon & \text{ ... weakening (unweldability)=1-\eta} \\
F & \text{ ... unreliability} \\
R & \text{ ... reliability=1-F} \\
\sigma_U & \text{ ... sample standard deviations for derivated variable U}
\end{align*}
\]
Weakening ($E, \eta$) vs. Reliability ($R$) and Safety factor ($S_f$)

### Deterministic approach

$$E = \frac{W}{M}$$

- $E$ = welded joint property
- $M$ = base metal property

$$R_{\min} = M - \gamma \cdot s_M$$

- $R_{\min}$ = working stress
- $S_{\max}$

$$S_f = \frac{W}{S}$$

- $S_f$ = working stress

### Semi-probabilistic approach

$$W_{\min} = \frac{W - \gamma \cdot s_W}{M - \gamma \cdot s_M}$$

- $W_{\min}$ = working stress
- $S_f$

### Probabilistic approach

$$U_2 = M - W$$

$$\eta = \frac{1}{2} \cdot f(U_2) \, dU$$

Assuming normal distribution for $W$, $M$ and $S$, and due to table value using parameters, standardised normal distribution was applied.

$$z_2 = \frac{U_2 - \overline{U}_2}{s_{U_2}}; \quad (\sigma_{U_1} = 1; \quad \overline{U}_2 = 0)$$

$$z_2 = m_2 = \frac{0 - \overline{U}_2}{s_{U_2}} = \frac{-\overline{U}_2}{s_{U_2}}$$

$$z_2 = m_2 = -\frac{M - W}{\sqrt{s_M^2 + s_W^2 - 2 \cdot r_1 \cdot s_M \cdot s_W}} \quad \ldots (1)$$

$$\varepsilon = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_{m_2}^{\infty} e^{-\frac{z_2^2}{2}} \cdot dz_2 = \Phi(m_2) \quad \ldots (3)$$

$$z_1 = \frac{U_1 - \overline{U}_1}{s_{U_1}}; \quad (\sigma_{U_1} = 1; \quad \overline{U}_1 = 0)$$

$$z_1 = m_1 = \frac{0 - \overline{U}_1}{s_{U_1}} = \frac{-\overline{U}_1}{s_{U_1}}$$

$$z_1 = m_1 = -\frac{W - S}{\sqrt{s_W^2 + r_1 s_W s_S}} \quad \ldots (2)$$

$$F = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_{-\infty}^{m_1} e^{-\frac{z_2^2}{2}} \cdot dz_2 = \Phi(m_1) \quad \ldots (4)$$

Fig. 4. Approaches to modelling of weakening and reliability. $F$ .. probability of failure (unreliability) and $\eta (E)$.. probability of $W \geq M$. $\eta (E)$ reflects measure of weldability.
Depending on the obtained weakening value, the class requirement of weld product and requirements class of welded joint are in accordance to regulars to adopting scope of quality control on welded construction by non-destructive testing (NDT) methods.

The probabilistic approach of the weakening of welded joints \( (\varepsilon) \) was defined as a numerical probability that to take into consideration to the dominant failure, property of welded joint will be lower than one for the base material for predicted of the time in predicted conditions of exploitation. Desirable is that value of \( \varepsilon \) which is closer to 0, i.e. 0%. Complementary to probability of weakening is useable of property of the base material \( (\eta) \). When the value was \( \eta=\varepsilon=0.5 \) it means that properties of weld joint and the base material are same, i.e. that by means of welding the properties of base material are not disturbed. The case when is \( \eta>0.5 \) have not practical sense because of in this case the failure of welded product during exploitation appeared into the base material. In this case we could be meaning how chosen better the base materials if it is possible.

When we speaking about the weakening of welded joints in the relation to the base material need account the fact that the weld joint consists of a numerous zones which can be better, wrong (or some) to weld joint, to take into consideration to the dominant failure of welded product. To regret can be pointed out that at a numerous failures of welded products in exploitation the reason for failure is just into weld joint, i.e. the weakening of welded joints. Problem of the weakening especially is pointed at welding of weak weldability steels, reparation welding, welding of At-alloys, and in the last time at sticked joints.

### 4.1. Example using of probabilistic approach for determinate of the reliability of vessel pressure

For the vessel pressure (railway transport vessel of 110 m\(^3\)) was collected sufficient numerical data about yield strength for the base material and the welded joint. The data were subjugated to the normal distribution and for yield strength of the base material (M) and the welded joint (W) the average values and the standard deviation were calculated. Also the normal distribution of stresses in exploitation of welded joint was assumed. Figure 5 shows obtained data.

Using of the probabilistic model the reliability of the welded joints and the weakening of the base material due to the welding could be calculate:

1. the reliability of the welded joints to take into consideration to the dominant failure due to the permanent of strains,
2. the weakening on the place of the welded joint (it is the weldability of the material).

By means of the personal computer program (using equations 1 and 2 given in Fig. 4) for known the data about yield strength of the base material (M) and the welded joint (W) by assumed of distribution values of stress affect was calculated following:

1. The average value of the reliability for the critical failure because of the permanent strains \( R=0.9865876731 \times 10^{-9} \).
2. The average value of the weakening for possible failure due to the permanent strains \( \varepsilon=0.885 \). Factor useable for property of the base material is \( \eta=1-\varepsilon=0.015 \). Desirable is that the property of W closer or better than property of M. If W and M drooping into the same point it resulted that is \( \varepsilon=0.5 \). If is W>M the failure on construction appeared on the base material. In this case is \( \eta>0.5 \) which has not practical sense. However in the practice often any zone W is better than zone M, but total W is nevertheless poorer than M. The value \( \eta \) in our example shows sufficient weldability i.e. \( \eta=0.115 \) (11.5%). Decreasing value of \( \eta \) the weldability of the base material decreasing as well as the reliability of welded construction.
As can be seen from Fig. 5 the reliability of welded joints to take into consideration possible failure because of permanent strains is a very high (for case predicted conditions exploitation, for stochastic the determine the quality of welded joints by sufficient evaluation of the reliability).

5. CONCLUSION
In this work was given of the knowledge base model cases failures during exploitation and errors from production. System base data with analysis reason failure errors can be using during education of students as well as engineers in practice before the production of the welded constructions with higher possible errors (for example, high part people working, work in terrain and difficult conditions,...).

The base data was meaning due to the connection with the different user programme (for example plans of technology welding), but it can be used as independent. The probabilistic approach, the determination of the reliability welded joints and the weakening of the base material due to welding on vessel pressure was explained. The average reliability of the welded joints and the weakening of the base material due to welding for the dominant failure (failure because of too big permanent strains) was calculated.

REFERENCES

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