The influence of the base material - filler metal pairing on the fatigue crack propagation of 700 MPa strength category welded joints

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Abstract. In the field of welding of high-strength structural steels, the 700 MPa strength category represents a kind of boundary. Overmatched (OM) consumables are also available, but the behavior of various mismatch types under cyclic loading condition is not yet clear. In order to know the fatigue crack propagation resistance of 700 MPa strength category steels and their gas metal arc welded joints fatigue crack growth tests were performed on statistically representative samples. Matching/overmatching (M/OM) mismatch type was tested, the tests results were analyzed and fatigue crack propagation limit curves were determined. The different mismatch types, our and previous results were compared. It can be concluded that M type is the optimal and M/OM type is more beneficial than simple OM type.

1. Introduction
Nowadays, the reliability of a structural element or a structure is one of the most important, if not the most important, feature of the structural element or the structure itself. This is a requirement on the one hand; on the other hand this is a task for the structural and technological designers, manufacturers, operators and maintainers of the structure. The regrettable accidents always draw attention to this fact; and summary studies about these form global messages from which all stakeholders can learn [1].

Figure 1 shows based on [2] a non-exhaustive overview of different international organizations and groups working on prevention, preparedness and response to chemical and industrial accidents. The figure provides a summary of key tools and methodologies developed by the different organizations, which can be seen in accordance with the timeline of the accidents.

The purpose of the eMARS (Major Accident Reporting System, later renamed eMARS after going online) is to facilitate exchange of lessons learned from accidents and near misses involving dangerous substances in order to improve chemical accident prevention and mitigation of potential consequences [3]. There are other accident report sites in order to share the experiences and observations worldwide (e.g. The Central Reporting and Evaluation Office for Major Accidents and Incidents in Process Engineering Facilities (ZEMA) [4], The Japanese Failure Knowledge Database [5]).

The reliability of a structural element or structure is closely related to its integrity [6], and different structural types (e.g. bridges [7], transporting pipelines [8], ships [9], and vehicles [10]) exhibit characteristics. Material quality, construction, applied manufacturing technology and the inhomogeneities affect both the reliability and the integrity. This may be particularly the case for welded structures made of high-strength steels, where the manufacturing without material
discontinuities can be guaranteed only in principle. In addition, material discontinuities can occur during the operation of the structures, and the most dangerous of them are the cracks.

| Organisation | Prevention | Preparedness | Response | Post-accident | Learning |
|--------------|------------|--------------|----------|---------------|----------|
| OECD         | Guiding Principles for Chemical Accidents, Preparedness and response | eMARS      |          |               |          |
| UNECE        | Transboundary Effects of Industrial Accidents Convention | eMARS      |          |               |          |
| EU           | Seveso-III-Directive, Civil Protection Mechanism Environment Liability Directive | eMARS      |          |               |          |
| JEU          | UN Disaster Assessment and Coordination Mechanism, Flash Environmental Assessment Tool |          |          |               |          |
| UN Environment | Flexible Framework, APELL, Responsible production toolkit |          |          |               |          |
| UNSIDR       | Sendal Framework for Disaster Risk Reduction 2015-2030 |          |          |               |          |
| WHO          | International Health Regulation Event Management System (EMS) |          |          |               |          |
| EPSC         | Member network |          |          | Regulation/Legislation/Constitution |          |

Figure 1. Summary of key tools and methodologies according with the timeline of the accidents (based on [2])

In the field of welding of first generation high-strength structural steels [11], the 700 MPa strength category represents a kind of boundary. Overmatched consumables are also available for gas metal arc welding of such steels, but the behavior of various mismatch types under cyclic loading condition is not yet clear. This is especially true for fatigue crack propagation resistance of such high-strength steels and their welded joints.

The microstructural and strength inhomogeneities of the welded joint raise the question of how the local properties influence the global behavior. The question, though not with complete accuracy, can be answered using statistical approach.

A 0.08%C-1.5%Mn (weight%) microalloyed steel, designated as RD480, was tested under different microstructural conditions, both tensile and fatigue crack growth behavior were investigated. The various microstructural conditions were produced by means of heat treatments followed by water quench, in which the material samples were kept at the temperatures of 800°C, 950°C and 1200°C [12]. The different microstructures result characteristic differences on the exponent of the Paris equation [13].

A soft buffer layer (BL) between the weld metal (WM) and the high strength base material (BM) was prepared, and BM, welded BM without a BL and welded BM with a BL were investigated. Notches were cut both in the BM and the WM; therefore four different cases of the crack propagation were studied and compared with the BM and each other. Both the BL and the notch location have influenced the fatigue crack growth behavior of the configurations [14].

Seeing that high strength steels are more sensitive to notches or initial cracks, the study of fatigue crack growth behavior in the different microstructural zones of the heat-affected zone (HAZ) is essential. Single edge notched bend (SENB) specimens were used for the characterization of fracture mechanical behavior of thermally simulated heat affected zones [15]. Gleeble physical simulator was applied reproducing of different microstructures, based on previously measured heating curves on real welded joints. The effect of the stress ratio (R) on the threshold stress intensity factor range and the crack growth curves was analyzed and significant influences were observed.

Fracture toughness ($K_{IC}$) and fatigue crack growth rate data are the two key fracture mechanical values which are used for safe-life analysis of different engineering structures or structural elements. Testing on numerous specimens is costly, time dependent and time costuming way for the
determination of these necessary parameters. A numerical approach, called virtual testing technic has been developed which enables engineers to generate fracture analytically by eliminating unnecessary tests [16].

Based on the previously mentioned facts, the aims of this work are as follows:

- characterization the fatigue crack growth (FCG) resistance of different high strength steels and their gas metal arc welded (GMAW) joints in 700 MPa strength category;
- investigation of the mismatch effect on the fatigue crack growth characteristics of the GMAW joints;
- determination of fatigue crack propagation limit curves for the investigated steels and their GMAW joints, based on simple crack growth relationship [13], [17].

2. Investigations

The chemical composition and the basic mechanical properties of the investigated BMs and filler metals (FM) are summarized in Tables 1-2, respectively; the sources of the data are quality certificates. The thicknesses of the used RUUKKI Optim 700QL and SSAB Weldox 700E plates were 30 mm and 15 mm, respectively; the diameters of the applied welding consumables were 1.2 mm.

Table 1. Chemical composition of the investigated base materials and used filler metals (weight%)

| Material designation       | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Mo  |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| RUUKKI Optim 700QL         | 0.16| 0.31| 1.01| 0.010| 0.001| 0.61| 0.21| 0.205|
| INEFIL NiMoCr              | 0.80| 0.50| 1.60| 0.007| 0.007| 0.30| 1.50| 0.250|
| SSAB Weldox 700E           | 0.14| 0.30| 1.13| 0.007| 0.001| 0.30| 0.04| 0.167|
| Böhler Union X85           | 0.07| 0.68| 1.62| 0.010| 0.010| 0.29| 1.73| 0.61 |
| Böhler Union X90           | 0.1 | 0.8 | 1.8 | N/A  | N/A  | 0.35| 2.3 | 0.6  |

| Material designation       | V   | Ti  | Cu  | Al  | Nb  | B   | N   | Zr  |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| RUUKKI Optim 700QL         | 0.010| 0.016| 0.015| 0.041| 0.001| 0.0015| 0.003| N/A |
| INEFIL NiMoCr              | 0.090| N/A | 0.120| N/A | N/A | N/A | N/A | N/A |
| SSAB Weldox 700E           | 0.011| 0.009| 0.01 | 0.34 | 0.001| 0.002 | 0.003| N/A |
| Böhler Union X85           | <0.01| 0.08 | 0.06 | <0.01| N/A | N/A | N/A | <0.01|
| Böhler Union X90           | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Table 2. Basic mechanical properties of the investigated base materials and used filler metals

| Material designation       | Rp0.2 (MPa) | Rm (MPa) | A (%) | CVN impact energy (J) |
|----------------------------|-------------|----------|-------|-----------------------|
| RUUKKI Optim 700QL         | 809         | 850      | 17.0  | -40°C: 106             |
| INEFIL NiMoCr              | 750         | 820      | 19.0  | -40°C: 60; -20°C: 90; 20°C: 120 |
| SSAB Weldox 700E           | 791         | 836      | 17.0  | -40°C: 165             |
| Böhler Union X85           | ≥ 790       | ≥ 880    | ≥ 16.0| -50°C: ≥ 47; 20°C: ≥ 90|
| Böhler Union X90           | 890         | 950      | 15.0  | -60°C: 47; 20°C: 90    |

Matching (M), overmatching (OM) and matching/overmatching (M/OM) mismatch conditions were used, where the M/OM condition means matched (M) root layers and overmatched (OM) filler layers. The different base material – filler metal pairings were as follows:

- RUUKKI Optim 700QL – INEFIL NiMoCr (O7-INE-M): matching (M);
- SSAB Weldox 700E – Böhler UNION X85 (W7-X85-M): matching (M);
- SSAB Weldox 700E – Böhler UNION X90 (W7-X90-OM): overmatching (OM);
- SSAB Weldox 700E – Böhler UNION X85/Böhler UNION X90 (W7-X89/X90-M/OM): matching/overmatching (M/OM).

The welding equipment was a DAIHEN VARSTROJ WELBEE P500L power source. The dimensions of the welded plates were 300 mm long and 125 mm width. In order to attain approximately equal stress distribution (residual stress field) X-grooved (double V-grooved) welding
joints were used, with $80^\circ$ groove angle, 2 mm root opening, and 1 mm land thickness. During the welding, the plates were rotated, regularly, after each layer. Based on the industrial practice, solid wires and $18\% \text{CO}_2 + 82\% \text{Ar}$ gas mixture (M21) were applied in all cases. The root layers (2 layers for both thicknesses) were made by a qualified welder; while the other layers (16 layers for 30 mm and 6 layers for 15 mm thicknesses) were made by automated welding car. The welding technological parameters were selected based on both theoretical considerations and real industrial applications, as follows (root layers / filler layers):

- preheating temperature ($T_{pe}$) and interpass temperature ($T_{ip}$): $150 / 180^\circ$C;
- welding current ($I$): $130-140 / 280-300$ A;
- voltage ($U$): $19.0-20.5 / 28.5-29.5$ V;
- welding speed ($v_w$): $200 / 400$ mm/min;
- linear energy ($E_v$): $700-750 / 1000-1000$ J/mm;
- calculated critical cooling time ($t_{8.5/5}$): $7.0-8.0 / 9.0-11.0$ s.

The FCG tests were executed on single edge notch bend (SENB) specimens. The position of the notches in the BM specimens correlated with the rolling direction (marked: T-L, L-T, T-S, and L-S), and in the welded joints (WJ) with the 21 and 23 joint directions (marked: 21W and 23W). According to these designations the nominal width (W) values of the specimens were $13 / 18$ mm and $26 / 28$ mm for both BMs and WJs. The positions of the notches, the notch distances from the centerline of the WJs, were different; therefore, the positions of the notches and the crack paths represent the most important and most typical crack directions in a real WJ (either part of our statistical approach). Figure 2 shows the macro-structure of the M/OM welded joint with a notch location and hardness indentations (see later), as example. Tests were executed in as-welded conditions; post-weld heat treating was not applied after welding. The FCG investigations were performed with tensile stress, the stress ratio was $R = 0.1$. The test equipment was MTS type electro-hydraulic universal testing equipment (MTS 312); sinusoidal loading wave form was applied, at room temperature, and on laboratory air. The loading frequency was not constant during the FCG tests, it was higher at the two-thirds of crack growth ($f = 20$ Hz), and it was lower at the last third ($f = 5$ Hz). The length of the fatigue cracks during their propagation was registered with optical method, hundredfold magnification ($N = 100x$) was applied using industrial video camera.

**Figure 2.** Macro-structure of the M/OM welded joint with a notch location and hardness indentations (polished and etched, 2% HNO$_3$)

Reicherter UH250 hardness tester was used for measuring of Vickers hardness. $HV10$ values were measured along two lines, along sub-surface and root lines, in both T-L/21W and T-S/23W specimens.

3. Results
The hardness distributions along the sub-surface and root lines in both types of specimens can be seen in Figure 3. The curves reflect the influence of the applied matched and overmatched filler metals.
Figure 3. Hardness distributions of matched/overmatched (M/OM) welded joint

The crack length vs. number of cycles curves for SSAB Weldox 700E – Böhler UNION X85/Böhler UNION X90, matching/overmatching (M/OM) pairing in T-L/21W orientation shows Figure 4, and the calculated stress intensity factor range vs. fatigue crack growth rate values can be seen in Figure 5, in both orientations (T-L/21W and T-S/23W).

Figure 4. Crack length vs. number of cycles curves for SSAB Weldox 700E – Böhler UNION X85/Böhler UNION X90 pairing
Figure 5. Kinetic diagrams of fatigue crack propagation for SSAB Weldox 700E – Böhler UNION X85/Böhler UNION X90 pairing

In Figures 4-5 the specimen ID consists of two parts: the first part (635) means the number of welded joint, the second part (01-12) the serial number of the tested specimen cut from the joint. The “cloud” in Figure 5 demonstrates both the expanse of the calculated results and the partial overlapping of the results between the two investigated orientations.

Based on the experimental data and results, fatigue crack propagation limit curves were determined using a previously developed six steps method [18] (other part of our statistical approach). Table 3. summarizes the average values of Paris-Erdogan exponents ($n_{\text{average}}$) for all statistical samples and the parameters of the determined fatigue crack propagation limit curves. Based on these data Figure 6 demonstrates the limit curves for all cases.

Table 3. Average values of Paris-Erdogan exponents and the parameters of the determined fatigue crack propagation limit curves

| Material designation and mismatch condition | Orientation | $n_{\text{average}}$ (mm/cycle, MPa$^{1/2}$) | $n$ (mm/cycle, MPa$^{1/2}$) | $C$ | $\Delta K_{\text{fc}}$ (MPa$^{1/2}$) | Source |
|--------------------------------------------|-------------|--------------------------------------------|-----------------------------|-----|---------------------------------|--------|
| O7-INE-M                                   | T-S/23W     | 1.81                                       | 1.20                        | 6.52E-06 | 93                               | [19]    |
| W7-BM                                     | T-L, L-T    | 2.43                                       | 1.70                        | 8.09E-07 | 101                             | [20]    |
|                                            | T-S         | 2.19                                       | 1.50                        | 2.06E-06 | 75                              | [20]    |
| W7-X85-M                                  | T-L/21W     | 5.10                                       | 4.10                        | 1.12E-11 | 105                             | [20]    |
|                                            | T-S/23W     | 4.15                                       | 2.30                        | 4.93E-08 | 80                              | [20]    |
| W7-X90-OM                                 | T-L/21W     | 3.68                                       | 1.85                        | 4.02E-07 | 96                              | [20]    |
|                                            | T-S/23W     | 3.43                                       | 1.90                        | 3.19E-07 | 61                              | [20]    |
| W7-X89/X90-M/OM                           | T-L/21W     | 3.29                                       | 2.67                        | 8.88E-09 | 90                              | this study |
|                                            | T-S/23W     | 3.11                                       | 2.85                        | 3.87E-09 | 67                              | this study |
4. Conclusions

Based on our investigations and their results, the following conclusions can be drawn.

The results of the achieved fatigue crack growth (FCG) investigations justified the accuracy and necessity of statistical approaches. This means on the one hand the selection of notch directions and locations in the base material and welded joints (the number of the tested specimens), on the other hand the processing and evaluation of the measured data.

The applied gas metal arc welding (GMAW) technology, the different technological parameters during the welding of root and filler layers are appropriate for fabrication welded joints with adequate and repeatable quality. The adequate resistance to fatigue crack propagation is an important part of this quality. Neither welding discontinuities nor abnormal FCG behavior were not found.

The FCG resistance of the investigated Weldox 700E base material is in the longitudinal and transversal directions the same, however different in the thickness direction.

The welding causes disadvantageous influence on the FCG resistance of the investigated Weldox 700E high strength steel. The average values of the Paris-Erdogan exponents ($n$) of the matching (M), overmatching (OM) and matching/overmatching (M/OM) conditions of the investigated Weldox 700E welded joints were statistically higher than the exponent of the base material. The mismatch phenomenon has significant effect on the FCG characteristics on the Weldox 700E welded joints; M type is the optimal and M/OM type are more beneficial than simple OM type (see Figure 6). The FCG resistance of the investigated Optim 700QL and Weldox 700E matched welded joints was significantly different (see Figure 6 in that case, too).

Applying the previously developed method [18] and using the determined and evaluated results, fatigue crack propagation limit curves can be defined for both the base material and the GMA welded
joints. The calculated limit curves adequately reflect the FCG characteristics of the investigated materials (see Figure 6), and can be applied for safe-life or structural integrity calculations.

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