Fatigue strength assessment of TIG-dressed high-strength steel cruciform joints by nominal and local approaches

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Abstract
According to the IIW recommendation, the fatigue strength of welded steel joints is defined as independent of the base material in case of the as-welded condition. However, post-treatment techniques can improve the fatigue performance of welded structures, especially for increased base material strengths. Therefore, this paper investigates the effect of TIG dressing, as common post-weld treatment method, on the fatigue strength of high-strength steel S700 cruciform joints. The statistically evaluated fatigue test results reveal a significant increase of the nominal fatigue strength from FAT 90 for the as-welded up to 182 MPa for the TIG-dressed state. The experiments are further compared to recommended and suggested design curves applying both nominal as well as local stress approaches. Focusing on the TIG-dressed state, the suggested increase in nominal stresses is well validated leading to a conservative assessment. In addition, the proposed slope in the finite life region with a value of \( m_1 = 4 \) shows a sound fit to the statistically evaluated value of \( m_1 = 4.7 \) for the test results. The local fatigue strength estimation is performed based on a recent proposal using the theory of critical distances. Therefore, linear elastic numerical analysis of the investigated specimens is performed. Again, the resulting S-N curves agree well to the experiments validating the proposed local design approach.

Keywords Fatigue strength assessment · TIG dressing · High-strength steel · Local approach

1 Introduction
According to the IIW Recommendations for Fatigue Design of Welded Joints and Components [1], the fatigue resistance of welded steel joints in as-welded condition is defined as independent of the base material strength. However, post-weld treatment methods can improve the fatigue strength, whereas further recommendations are provided, for example, in [2]. An overview of common post-treatment techniques is presented in [3]. Thereby, a subdivision in weld geometry improvement and residual stress methods is shown. In regard to the first-mentioned, techniques affecting the local weld topography, such as burr grinding [4] or TIG dressing [5], are classified. Concerning the latter one, methods mostly influencing the residual stress condition [6] are considered, like shot peening [7], hammer/needle peening [8], HFMI treatment [9] as well as further non-mechanical techniques, such as post-weld heat treatment [10]. Especially in case of the methods based on an improvement of the local residual stress condition, special attention must be laid on increased stress ratios [11–13] or variable amplitude loads [14–16] mostly due to a possible relaxation of the compressive residual stress condition [17, 18].

This paper focuses on the TIG dressing as post-treatment technique focusing on the improvement of the weld toe geometry. A review of fatigue test data for TIG-dressed steel welds is given in [19]. Thereby, in total, 311 fatigue data points involving longitudinal attachments, transverse non-load carrying welds as well as butt and T-joints are considered. Based on the statistical analysis it is concluded that a slope of \( m_1 = 4 \) within the finite life region fits well to the investigated TIG-dressed weld joints. Moreover, S-N design curves and the corresponding fatigue strength values at two million load cycles at a survival probability of \( P_s = 97.7\% \), denoted as FAT class, are proposed in case of constant amplitude loading. It is also mentioned that more fatigue test data is needed to verify the given proposals.

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Due to the lack of available fatigue tests, no design method for variable amplitude loading can be suggested. In Fig. 1, the proposed maximum possible improvement in number of FAT classes for TIG-dressed steel welds in dependence of the base material yield strength $f_y$ is shown. In case of a high-strength steel with a base material yield strength of $f_y = 700$ MPa, as used within this study, a maximum possible improvement of four FAT classes is proposed.

A method to assess the fatigue strength of TIG-dressed weld joints by local approaches is presented in [20]. Based on a simplified numerical modeling, considering only a rough estimation of the weld profile and the fillet radius, a linear elastic finite element analysis acts as fundament for the local assessment. Further, two different procedures for the fatigue design are proposed, which fundament on the theory of critical distances [21]. This approach was already successfully applied for joints in as-welded condition [22] and is now also applied for TIG-dressed weld joints.

First, the local stress in a distance of $a = 0.7$ mm below the surface at the weld toe should be used. Thereby, the fatigue strength assessment is performed applying a value of FAT 160. Second, the local stress in a distance of $a = 0.6$ mm below the surface at the position of the maximum stress should be used. In this case, a value of FAT 180 is applicable for design. An additional factor is also introduced covering the effect of the base material strength. It is finally stated, that further fatigue test data are needed to verify the presented approach. In this paper, the fatigue assessment for the as-welded condition is performed in accordance to the common effective notch stress approach as recommended in [1] applying a reference radius of $r_{ref} = 1$ mm [23].

Therefore, this paper scientifically contributes to the following working topics focussing on the fatigue strength assessment of TIG-dressed steel joints:

- Fatigue tests covering high-strength steel S700 cruciform joints in both as-welded and TIG-dressed condition to validate the proposed values given in [1, 19].
- Numerical analysis incorporating the local weld toe topography as well as global shape of the analyzed specimens to compute the local stress conditions.
- Local fatigue strength assessment to validate the presented methods given in [1, 20].

## 2 Base material and specimen design

The fatigue tests were conducted with cruciform joints made of high-strength steel alform® 700 ME according to EN 10149–2. The specimens were manufactured from thermomechanically rolled panels with a sheet thickness of 10 mm. The mechanical properties and the chemical composition of the fine-grained steel according to the EN 10204 3.1 certification are presented in Tables 1 and 2.

The test specimens were manufactured by GMAW two plates, each with dimensions of $300 \times 350 \times 10$ mm$^3$, and a cross strip ($50 \times 350 \times 10$ mm$^3$). Subsequently, each assembly is cut into three test samples with machined surfaces all around the contour. In a final step, the specimens were sandblasted. The final geometry of the investigated specimens is presented in Fig. 2.

The weld assemblies are GMAW using a robot with a M21 shielding gas (82% Ar + 18% CO$_2$) and filler material alform® 700-IG with a diameter of 1.0 mm. Nominal

| Table 1 Chemical composition (in weight %) of alform® 700 ME steel |
|------------------|-----|-----|-----|-----|-----|-----|-----|
|                  | C   | Si  | Mn  | P   | S   | Al  | Cr  |
|                  | 0.067 | 0.031 | 1.900 | 0.007 | 0.0017 | 0.057 | 0.032 |
| Ni               | 0.022 | 0.008 | 0.019 | 0.007 | 0.050 | 0.139 | 0.0002 |

| Table 2 Mechanical properties of alform® 700 ME |
|---------|-----|-----|-----|-----|
| Yield strength $f_y$ | Ultimate strength $f_u$ | Elongation at fracture $A_5$ | Impact toughness at $-40$ °C |
| 772 MPa | 807 MPa | 19.8% | 112 J |

Fig. 1 Proposed improvement due to TIG dressing according to [19].
mechanical properties and nominal chemical composition of the used pure filler material are summarized in Tables 3 and 4.

A schematic of the joint design and welding sequence of the two-sided fillet weld is presented in Table 5. The weld assembly is welded in position PA or PB according to ISO 6947 [27] with maximum inter-pass temperature of 150 °C.

An optical analysis of the welded specimens revealed that not all samples exhibit a complete joint penetration.

3 Post-weld treatment (TIG dressing)

To improve fatigue strength, TIG dressing (Table 6) is applied by smoothing the transition between the plate and the weld face and by reducing the weld toe flaws by re-melting the material at the weld toe. Figure 3 shows a comparison of the transitions of the as-welded specimen and the TIG-dressed specimen. The TIG dressing process was performed according to IIW Recommendations [2] and prior to cutting out the samples of the weld assembly.

| Table 3 | Typical chemical composition (in weight %) of alform® 700-IG filler metal |
|---------|--------------------------------------------------------------------------------|
| C       | Si      | Mn     | P   | S   | Cr   | Mo   |
| 0.08    | 0.65    | 1.67   | 0.009 | 0.01 | 0.29 | 0.53 |
| Ni      | V       | Cu     | Ti  | Al  | Zr   |
| 1.71    | <0.01   | 0.04   | 0.07 | <0.01 | <0.01 |

| Table 4 | Typical mechanical properties of alform® 700-IG filler metal |
|---------|-----------------------------------------------------------------|
| Yield strength $f_y$ | Ultimate strength $f_u$ | Elongation at fracture $A_f$ | Impact toughness at $-50 \, ^\circ C$ |
| $\geq 790 \, MPa$ | $\geq 880 \, MPa$ | $\geq 16\%$ | $\geq 47 \, J$ |

Table 5  Schematic of joint design and welding sequence

Joint Design  Welding Sequence
Fatigue tests

The fatigue tests were performed with a servo-hydraulic universal testing machine under load-controlled uniaxial constant amplitude loading (CAL) at a load stress ratio of $R = 0.1$. As already mentioned, two test series of load carrying cruciform joints of alform® 700 ME with and without post-weld treatment were investigated. The fatigue tests were performed until macro crack initiation or without failure until a defined run-out limit of ten million load cycles. It was evaluated by a defined increase of the maximum stroke of the test cylinder leading to a surface crack length of certain millimeters. This abort criterion is similar to total fracture of the specimen as only a small amount of total lifetime is spent in the further crack propagation after technical crack initiation. Figure 4 shows a typical fracture pattern with crack initiation at the weld toe (transition region between weld metal and HAZ) as dominant failure criterion for all tests. A total number of 50 tests were carried out, equally divided between the two series, as-welded and TIG-dressed.

| Table 6  | TIG dressing parameters |
|----------|-------------------------|
| Current type/polarity | Electrode diameter | Welding current | Voltage | Travel speed | Heat input | Shielding gas | Gas flow rate |
| Direct current/plus | 2.4 mm | 160 A | 17 V | 200 mm/min | 0.53 kJ/mm | 100% Ar | 14 l/min |

Fig. 3 Typical shapes in cross sections of as-welded and TIG-dressed welded joints

Fig. 4 Typical fracture behavior and representative fracture surface of the TIG-dressed specimens
The statistical data processing of the fatigue test data in the finite life region is executed by using the method given in [1]. In order to consider scattering of the test results, the statistical evaluation of the fatigue strength is conducted for a survival probability of \( P_S = 97.7\% \) with a \( k \) value of 2.02. Figure 5 shows the test results and the statistically evaluated S-N curves for the cruciform joints with and without post-weld treatment. The results and S-N curves relate to nominal stresses. For both series, as recommended for CAL, a second slope of \( m_2 = 22 \) is applied after the knee point at \( 1 \times 10^7 \). For the slope in the finite life region, a value of \( m_1 = 3.9 \) is calculated in the case of the as-welded condition and of \( m_1 = 4.7 \) for the TIG-dressed specimens. The variances of the exponent \( m_1 \) of S–N curve to 3 can be partly related to the sheet thickness of the investigated specimens. A corresponding investigation can be found in [24]. The nominal fatigue strength \( \Delta \sigma_n \) at two million load cycles results in 90 MPa for as-welded specimens, and 182 MPa represents the characteristic fatigue strength for TIG-dressed condition.

### 5 Numerical analysis

Based on pictures, taken with a camera with telecentric lenses, and a geometry measurement of the welded specimen, 20 finite element models are generated. The simulations are performed as 2D plain strain with 8-node quadrilateral elements according to [25, 26]. All models are calculated with a nominal stress \( \sigma_n = 1 \) MPa using linear elastic solutions [20]. The maximum principal stress is used for the evaluation. The TIG-dressed specimens are evaluated at two positions. First, perpendicular at the weld toe in a depth of \( a = 0.6 \) mm, see [20]. Finite element models regarding the as-welded geometry are evaluated at the point with the maximum notch stress.

All simulations were carried out with the CAE Software Siemens NX Version 1980. The material for the finite element simulation is defined as steel with a Young’s modulus of \( E = 206 \) 940 MPa and a Poisson’s ratio \( \nu = 0.288 \); both values are from the material database of the CAE software.

#### 5.1 Geometry measurements

The extraction of the geometry for both cruciform joints, as-welded and TIG-dressed, was performed with the CAE software. Importing the pictures into the CAE software allows to measure angles and distances and transforms it to a true to scale model. Due to the non-perspective distortion of the telecentric lenses, all photos exhibit a fixed scale. The generated cross section of the TIG-dressed cruciform joints includes the local weld geometry. It is generated with spline curves based on the imported photos taken during the test series (Fig. 6). The transverse and longitudinal sheets are designed with lines.

The as-welded cruciform joints are created with an idealized geometry based on geometry measurements of 26 specimens taken from the photos. For the geometric quantities, such as throat depth and flank angle, the mean value of the geometric measurements is used (Table 7). The
notch root radius is defined with $r_{\text{ref}} = 1$ mm [23]. As the manufactured specimens showed that the fillet welds feature incomplete penetration, a small gap with a width of 2 mm and a height of 0.5 mm is modeled in order to accurately cover the local stress flow (Fig. 7).

### 5.2 Finite element model

In order to obtain a suitable mesh for the simulation and analysis of the local stress, the cross section is divided in two areas. One area is defined with an offset curve of 2 mm using the shape of the cruciform joint. It ensures the use of a mapped mesh with an element edge length of 0.1 mm (Figs. 8 and 9). The remaining area is meshed by quadrilateral elements (CPLSTN8 - plane strain quadrilateral element with 8 nodes) with an edge length of 0.1 mm to about 3.5 mm (Figs. 10, and 11).

Two rigid body elements (RBE) are created at both ends of the model for the force application of the tensile load. The reference nodes of the RBEs are used as grip points for the boundary conditions. One reference node of the RBE is used to apply the nominal force. It has a free displacement in longitudinal direction, whereas all other displacements are locked. The second reference node is locked in all translational and rotational displacements.
5.3 Numerical results

As aforementioned, the maximum principal stress (Fig. 12) is used for evaluation. The computed results for the as-welded condition (Fig. 13) results in a maximum stress concentration factor $K_t = 2.62$ at the surface of the weld toe radius at the upper fillet weld.

From the test results of the TIG-dressed specimens, it was observed that all specimens failed at the weld toe of the HY weld. Hence, the local stress results at the HY welds are considered. For this purpose, as indicated in [20], the maximum principal stresses at a depth of $a = 0.6$ mm and $a = 0.7$ mm are evaluated, starting from the location of the maximum stress at the surface and the weld toe, respectively. From these results, the arithmetic mean value of the stress concentration factor $K_t$ is calculated for differently analyzed TIG-dressed specimen leading to a representative average $K_t$ value (Table 8). Although there are no explicit measurement data of the transition radii for the specimens, the factor $K_t$ at the surface can be considered as an effect of the transition between the plate and the weld face.

6 Fatigue strength assessment

6.1 Nominal stress approach

Figures 14 show the nominal stress test results of the high-strength steel cruciform joints for the as-welded and the TIG-dressed state in comparison with the recommended [1] and proposed [20] values. In accordance to

| Table 8 | Evaluated stress concentration factors $K_t$ | Mean value of $K_t$ |
|---------|---------------------------------------------|---------------------|
| As-welded at surface | 2.62 |
| TIG-dressed at surface | 1.90 |
| TIG-dressed $a = 0.6$ mm | 1.26 |
| TIG-dressed $a = 0.7$ mm | 1.22 |
IIW recommendations [1], assuming high tensile residual stresses and therefore no strength correction based on the applied $R$ ratio, both cruciform joints correspond to structural detail 413 with a FAT class of 63 for steel. In the case of the nominal stress approach, an improvement of the fatigue strength can be achieved by considering the plate thickness as suggested in [1]. The corresponding Eq. (1) is given below, with a reference thickness of $t_{ref} = 25$ mm.

$$ f(t) = \left(\frac{t_{ref}}{t_{eff}}\right)^n $$

(1)

As shown in Fig. 14, the recommended S-N curve for the as-welded condition is close to the statistically evaluated test results. However, although both curves are intersecting in the finite life region, the test data points are still conservatively assessed. A more conservative and safe design would be ensured if the applied thickness correction factor would be neglected, which is also conform to the recommendations.

Focussing on the TIG-dressed state, the comparison reveals that the proposed S-N curve fits well to the fatigue test results leading to a conservative assessment. Moreover, the suggested slope value in the finite life regime of $m_1 = 4.7$ shows a sound match to $m_1 = 4.7$ based on the statistical evaluation.

### 6.2 Local stress approach

The results of the evaluation according to the local stress approach are shown in Figs. 15 and 16. Figure 15 depicts the comparison of IIW design curve for the effective notch stress approach and the fatigue test results applying the stress concentration factor obtained by numerical calculation as outlined in Sect. 5. It can be observed that the S-N curve for the effective notch stress approach is comparably close, respectively, partly below the recommended FAT class of 225. This is due to fact, among other aspects, that no global deformation, e.g., axial misalignments or angular distortion, is considered in the numerical computation of the stress concentration factor. As no such data was available, no implementation in the finite element modeling was executed. However, as explained in the case of the nominal

| $t_{ref}$ (mm) | $t_{eff}$ (mm) | $n$ | $f(t)$ |
|---------------|---------------|-----|--------|
| As-welded     | 25            | 10  | 0.3    | 1.32   |
| TIG-dressed   | 0.2           |     |        | 1.20   |

As shown in Fig. 14, the recommended S-N curve for the as-welded condition is close to the statistically evaluated test results. However, although both curves are intersecting in the finite life region, the test data points are still conservatively assessed. A more conservative and safe design would be ensured if the applied thickness correction factor would be neglected, which is also conform to the recommendations.

Focussing on the TIG-dressed state, the comparison reveals that the proposed S-N curve fits well to the fatigue test results leading to a conservative assessment. Moreover, the suggested slope value in the finite life regime of $m_1 = 4.7$ shows a sound match to $m_1 = 4.7$ based on the statistical evaluation.
stress approach, the fatigue test data points are mostly still conservatively assessed.

This once again underlines the fact that geometry measurements are very important for a fatigue assessment of welded structures. Further, a comprehensive planning, execution, and technical documentation of fatigue tests is utmost important.

The proposed S-N curves as shown in Fig. 16 rely on the suggested fatigue resistance as noted in [20]. The results for the TIG-dressed specimens with the evaluation point \(a = 0.6\) mm are compared against the fatigue class of FAT 180. The TIG-dressed specimens with the evaluation point \(a = 0.7\) mm are compared against the fatigue class of FAT 160 [20]. Considering the material strength, the fatigue resistance can be increased with the factor \(f\) (Eq. (2)) as given in [20].

\[
f = \frac{f_{Rm}}{355\text{ MPa}} \cdot R_m + 1 - f_{Rm}
\]

Using the mean value of tensile strength of alform® 700 (see Table 2), this leads to \(R_m = 807\) MPa. Considering a factor of \(f_{Rm} = 0.1\) [20], a fatigue increasing factor of \(f = 1.13\) is calculated, which raises the fatigue resistance from FAT 160 and FAT 180 up to FAT 181, respectively, FAT 203. Again, the suggested design curve as well as the slope in the finite life regime reveals a sound match to the experimental results, thus validating the suggested approach given in [20].

7 Conclusions

This paper investigates the effect of TIG dressing as post-weld treatment technique in order to improve the fatigue strength of welded joints. As specimen type a high-strength steel S700 cruciform joint is analyzed. Based on the conducted experimental and numerical work, the following scientific conclusions are drawn:

- The statistically evaluated S-N curves based on the fatigue test data reveals an increase of the nominal fatigue strength \(\Delta \sigma_n\) at two million load cycles from 90 MPa for the as-welded condition up to 182 MPa in case of the TIG-dressed specimens. Hence, a significant benefit in fatigue strength by TIG dressing for the investigated specimens is observed.

- An application of the nominal stress approach for the as-welded state shows that the recommended S-N curve based on [1] is close to the statistically evaluated test results. Nevertheless, the test data points are conservatively assessed. In case of the TIG-dressed condition, the comparison to the proposed design curve based on [19] shows a sound match to the fatigue test results leading to a conservative assessment. Further, the suggested slope of \(m_1 = 4\) in the finite life region fits well to \(m_1 = 4.7\) based on the statistical evaluation.

- Local fatigue strength assessment is conducted based on a numerical stress analysis according to [1] for the as-welded and based on the approach given in [20] for the TIG-dressed state. Applying the effective notch stress approach for the as-welded condition, again a similar behavior as shown in case of a nominal stress assessment is observed. In this conjunction, it can be concluded that global deformations, such as axial misalignment or angular distortion, may greatly impact the local stress concentration, hence influencing the local fatigue assessment. However, the fatigue test data points are again mostly conservatively assessed. Focusing on the TIG-dressed condition, the suggested approach, which is based on the theory of critical distances, is applied. Again, a sound match to the experiments can be concluded leading to a conservative assessment.

To sum up, the suggested design approaches as given in [19, 20] applicable for a fatigue assessment based on nominal and local stresses lead to a conservative estimation of the fatigue behavior in case of the analyzed specimens. Further focus may be laid on the modeling of global deformations, such as axial misalignment and angular distortion, in order to increase the accuracy in computing local stress conditions as basis for a local fatigue assessment.

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Declarations

Conflict of interest The authors declare no competing interests.
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