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Quality assurance of HFMI-treatment regarding fatigue strength of fillet welds

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Abstract

The beneficial effect of high-frequency-mechanical-impact (HFMI) treatment on fatigue loaded fillet welds made of common up to ultra-high strength steels has been thoroughly researched in the last decade. This paper deals with the effect of HFMI treatment parameters, in particular penetration depth, on constant amplitude fatigue strength. To reflect good workmanship conditions, the experimental investigations focus not only on high-quality, semi-automatic welded fillet welds, but take also end-of-seams of longitudinal stiffeners into account.
It was found that even a comparably under-treated HFMI weld groove increases the high-cycle fatigue strength almost to the same level as a properly HFMI-treated weld toe groove; but in the finite life region the effect of HFMI-treatment quality is more pronounced. The conducted work supports the theory that compressive residual stresses in the work-hardened, HFMI-treated groove affect the high-cycle fatigue primarily. As most crack propagation life occurs within the HFMI-treated surface layer, the effect of indentation depth seems to be secondary. This hypothesis was supplemented by fracture mechanical calculations using the weight function approach for the HFMI-treated, most-stressed surface layer volume.

Keywords: Fatigue improvement, High-Frequency-Mechanical-Impact (HFMI) treatment, Quality assurance, Structural steels, Weight-function approach.

1 Introduction

In the last decade, numerous researchers conducted work on the fatigue and service strength of HFMI-treated welds. This was driven by industrial demands and the results are internationally compared by a Round-robin study [1] – [9]. Beside extensive experimental based results, accompanying simulation showed that the introduction of compressive residual stresses, work hardening and shallower groove geometry are the three main beneficial contributions from this high-frequency-mechanical-impact treatment [10] – [12].

A fatigue strength assessment guideline was drafted [13] and presented as notch stress approach in [14]. Another complementing HFMI-treated fatigue assessment approach is discussed in [15, 16], but both design methods lead to comparable results highlighting that the beneficial effect of HFMI-treatment increases the smaller the most-stressed region and the higher the base and filler material strength is. In addition, the effect of HFMI-treatment quality and quality assurance is a current topic worth further research to ensure the industrial applicability of the method [17] – [20]. For as-welded structures, the principal relations between fatigue and weld quality are discussed in [1, 21] – [26].

The goal of the present work is to contribute to the effect of HFMI-treatment quality on fatigue of fillet welds made of steel. Hence, two different thin-walled sample geometries made of common construction steel are investigated.
At first, a non-load carrying transversal joint is investigated. The effect of weld quality is also examined as some specimens possess overlapping start-stop-ends within the loaded region.
At second, the fatigue strength of longitudinal stiffeners with different HFMI-treatment quality settings is analyzed. Both specimen types posses a base plate thickness of five millimetres.
The specimen geometry of transversal joint and longitudinal attachment is depicted in [27, 2] in detail. It should be noted that the width to thickness specimen ratio is ten to one to enable crack propagation along the surface with high a/c-ratios. In addition, the specimen edges and lateral faces have to be grinded to avoid crack initiation in case of HFMI-treated weld toe groove.

2 Experimental work

The fatigue tests focus on the combined effect of HFMI post-treatment quality on different kind of weld toe geometries. Hence, the experimental work is split up on non-load carrying transversal attachments, or labelled as T-joints, and longitudinal attachments. Both weld types enforce basic fillet welds, but the weld process specification is different for each joint due to the varying weld paths.

2.1 T-Joints

The desired variation in weld toe groove geometry is realized by manufacturing an overlapping start-stop ends within the fatigue tested fillet weld, see Figure 1. This supplements the basic fillet weld investigation. The heat-input per unit length of the continuously manufactured fillet weld is about *0.7kJ/mm* featuring a throat thickness of $a = 4\ mm$. The overlapping start-stop-end of the fillet weld increases the molten zone and respectively the local throat thickness by about one third, but the weld flank angle keeps similar with a value of about forty-five degrees. The point of technical crack initiation for these two as-welded samples is marked by a red circle. It is clearly recognizable by the macroscopic a/c-ratio of fatigue crack propagation that the most-stressed region is narrowed at the start-stop ends.

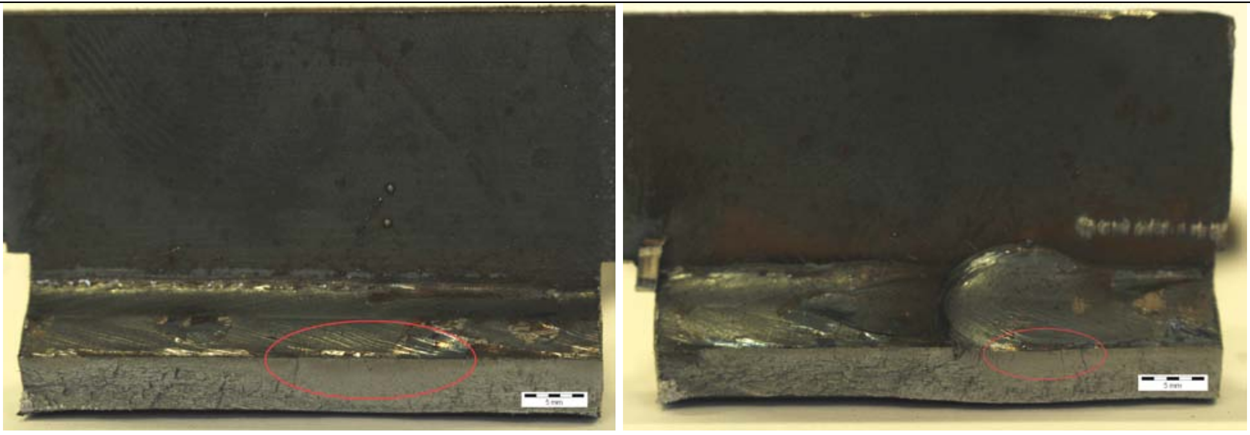

Figure 1: Fillet weld in as-welded condition (fillet; start-stop overlap); no HFMI

By use of the start-stop-overlapping seams as additional fatigue test lot it is possible to study the effectiveness of HFMI-treatment quality on fillet welds which may also possess local weld process based heterogeneities. Such start-stop ends occur in commercial workmanship environment tasks regularly.

Besides, the corresponding HFMI-treatments cover three different process parameter settings. At first, the standard HFMI procedure given by the HFMI contractor is applied [28, 29]. This leads to an average indentation depth of about *0.15 mm* for mild construction steel S355 and a tool tip radius of $R = 2$ *mm*. At second, the under-treated HFMI process condition reduces the indentation depth to about *0:02 mm*. Finally, the over-treatment by HFMI-processing the same weld toe line at least three times, increases the indentation depth to about *0.3 mm* and widens the treated region. The given indentation depth values were measured by laser-scanning-microscopy. The measurement is exemplified for an under-treated HFMI groove in Figure 2. The height information is measured by the laser signal, the reflected optical emission defines the perceived colour. The un-sufficiently treated HFMI areas, one groove at the base material and one at the filler metal, are not connected and therefore the crack initiates at the weld toe.

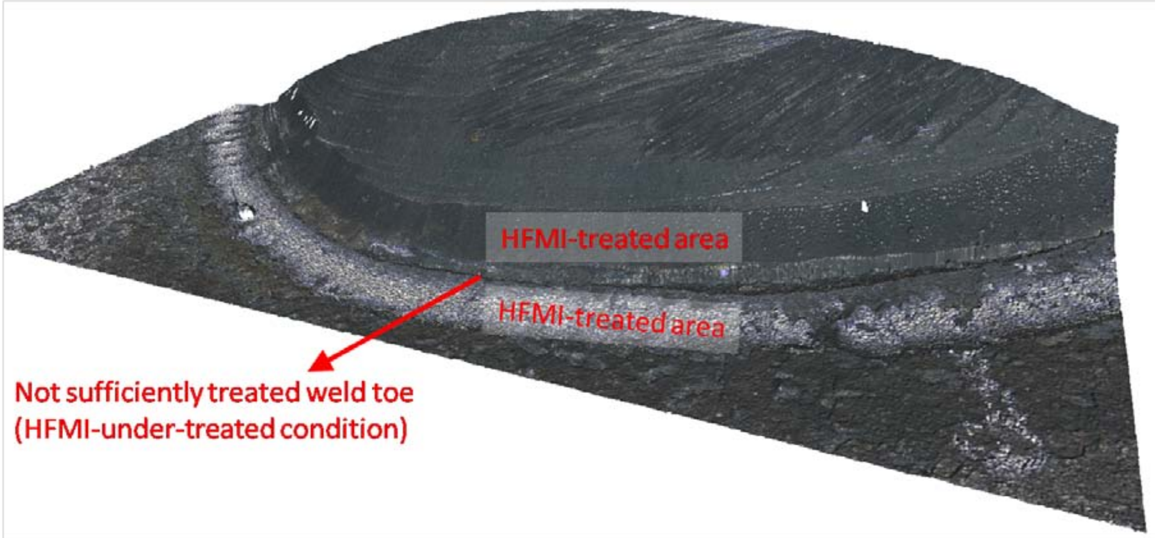

Figure 2: Spatial laser scanning of under-treated HFMI weld toe region (examplified for a longitudinal attachment sample)

Similar measurements regarding indentation depth and HFMI quality were conducted for the non-load carrying transerval attachments, with and without start-stop ends. The results are similar and state an independency of the HFMI-treatment process of the weld type. Figure 3 displays transversal joint specimen failures for the three different HFMI process configurations ranging from under-treated, over regular to over-treated conditions. The evaluated constant amplitude S/N-curve at a tumescent stress ratio of $R = 0.1$ is depicted in Figure 4. All tests were conducted up to a run-through limit of twenty million load cycles. The benign thinness effect for transversal joints is not included in the drawn IIW-curves for the as-welded and HFMI-treated condition to simplify comparability to the standards. Although the number of investigated specimen is limited, some trends are recognizable as follows.

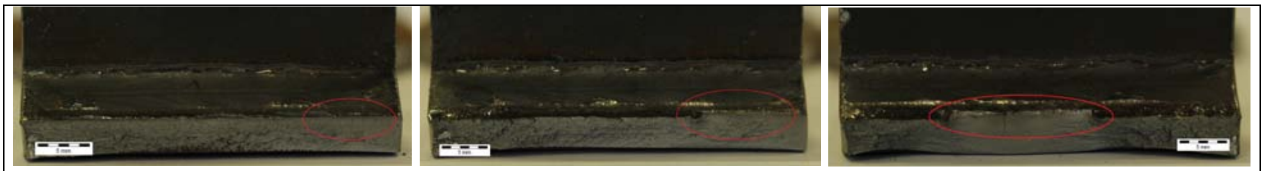

Figure 3: HFMI-process study of fillet welds on T-joints (under-treated, regular-treated, over-treated)

At first, the as-welded specimens are clearly above the conservative IIW-recommendation, even though a benign thinness factor of *1.38* can be considered. The characteristic fatigue stress range of the as-welded specimen corresponds to a fatigue class of about *FAT145*, which is still higher than the recommended value of *FAT110* in case of benign thinness effect multiplier. This states a high quality manufactured fillet weld for these transversal joints. But in case of start-stop ends without HFMI-treatment, the evaluated fatigue strength class reduces to *FAT115* which gets close to the recommended fatigue strength for transversal fillet welds without start-stop regions. Summing up, in the as-welded condition the overlapping start-stop end leads to fatigue strength reduction of about fifteen percent. The natural inverse slope of the transversal attachments changes from $k = 4$ to *3.5* in case T-joint samples with start-stop ends.
At second, the effect of HFMI on the fatigue strength of non-load carrying transverse attachment is studied. These results are also sketched in Figure 4. In case of under-treated HFMI T-joints, the corresponding fatigue class evaluates to *FAT180*. The inverse slope changes to about $k = 6$, which meets the requirements of a shallower slope for HFMI-treated specimen compared to the as-welded state. The IIW-recommended FAT class for HFMI-treatments would lead to *FAT120*, but if the benign thinness effect is taken into account it increases up to *FAT165*. Hence, the under-treated HFMI process satisfies already the conservative HFMI recommendation guidelines.

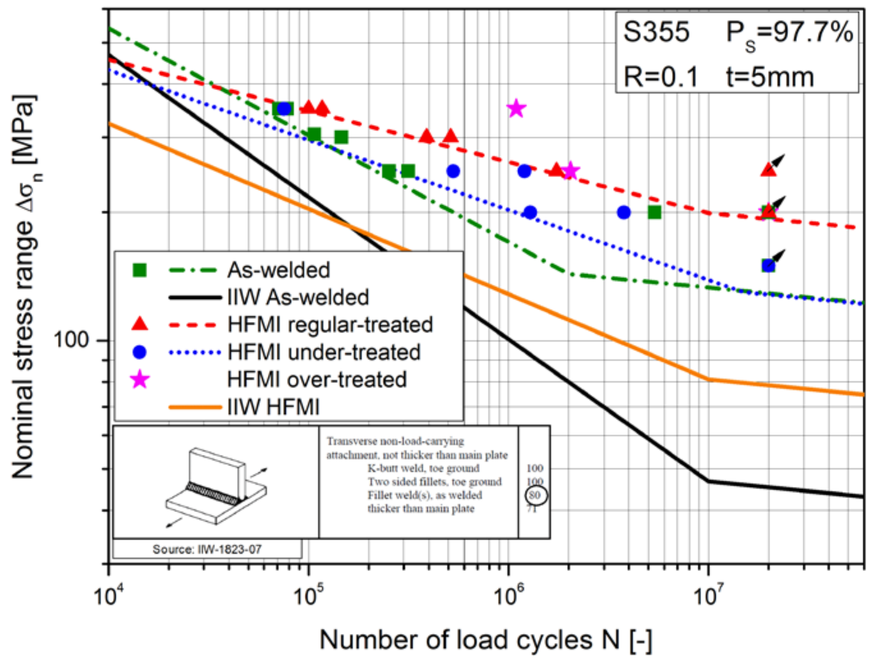

Figure 4: Non-load carrying transversal attachment results in as-welded vs. HFMI-treated condition (both without start-stop ends)

At third, the effect of HFMI process quality is determined. For regular HFMI process application, the evaluated fatigue strength ranges up to *FAT180*. If an excessive over-treatment is applied, the conducted fatigue tests are above or within the upper scatter band of the regular HFMI test results. It seems that a further improvement in the finite life region might be possible, but the high-cycle fatigue limit remains unchanged. Hence, even severe HFMI over-treatment seems to have no disadvantageous effect on fatigue strength of fillet welds made common construction steel.

A scanning-electron-microscopy fracture analysis was conducted to study the point of technical crack initiation and the effect of local HFMI-treatment in more detail; compare to Figure 5. The HFMI treated groove is clearly recognizable using the field mode setting.

In the under-treated condition the crack initiates at the weld toe line extends along this sharp geometric notch. In case of HFMI-treatment, the crack initiates and the compressive stress state enforces a more elliptical a/c-shape. At the under-treated HFMI weld toe region the observed a/c ratio is comparably larger. The point of crack initiation in case of excessive over-treatment can change to flattened cold laps in the HFMI groove. In case of under-treatment, the molten filler metal surface is clearly recognizable and thus the indentation depth should be increased to treat the weld toe line also. In case of HFMI over-treatment, the crack initiates near the cold lap but seems not be affected strongly by it.

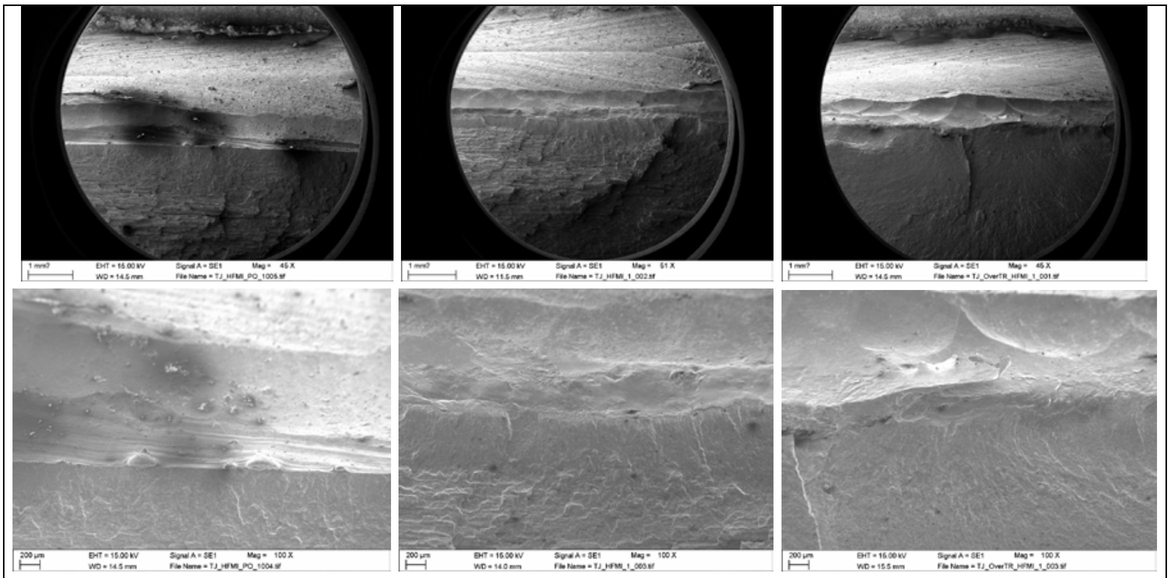

Figure 5: SEM-images of HFMI-treated transversal attachments (under-, regular, over-treated HFMI process settings) without start-stop ends

Finally, Figure 6 depicts the condensed fatigue test results of all transversal attachments in different weld process quality and post-treatment conditions. Due to the limited number of up-to-now evaluated specimen, only the finite life regime up to two million cycles is evaluated.

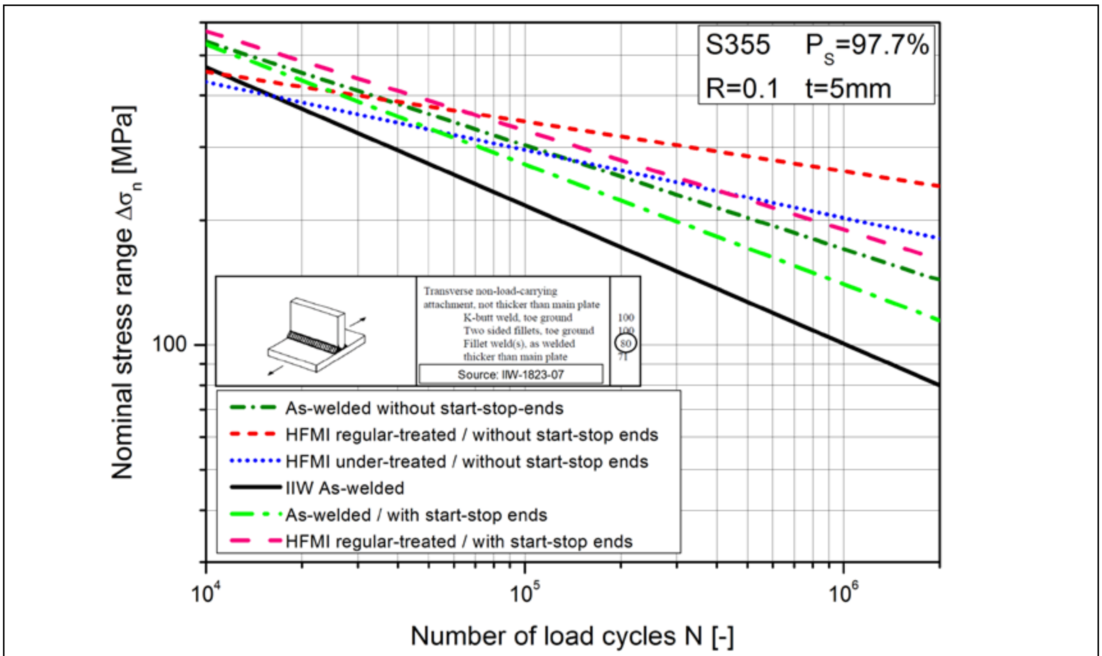

Figure 6: T-joint results (AW, HFMI) with and without start-stop overlap

Whereas the geometric heterogeneity of the start-stop end region has a significant effect on finite fatigue strength, a regular-treated HFMI process is capable to enhance the both S/N-curves. Proper HFMI-treatment leads to a unification of, comparably small, weld process manufacturing effects into a single design curve.

Concluding, the fracture surface of transversally loaded, overlapping start-stop seam ends is shown in Figure 7. As stated before, the HFMI-treatment narrows the a/c-ratio of crack propagation towards a more elliptical shape. The HFMI treatment grooves are clearly recognizable, the crack initiates at the most-stressed volume at the start-stop end.

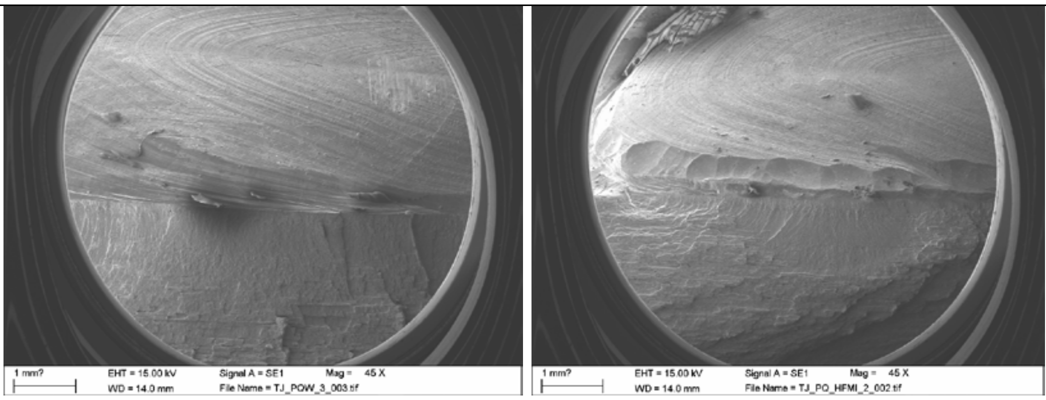

Figure 7: Fracture surface of T-joint with start-stop overlap (as-welded versus regular-treated HFMI condition)

2.2 Longitudinal stiffeners

Aside from these transversal joint investigations, the effect of HFMI process quality was studied for longitudinal stiffeners. These specimens exhibit an increased HFMI fatigue strength because of the reduction of most-stressed volume and the subsequent improved effectiveness of HFMI-treatment in this region. The fatigue test results are displayed in Figure 8. The start-stop ends of the longitudinal attachments are manufactured in a way to ensure that these are not in the most-stressed region.

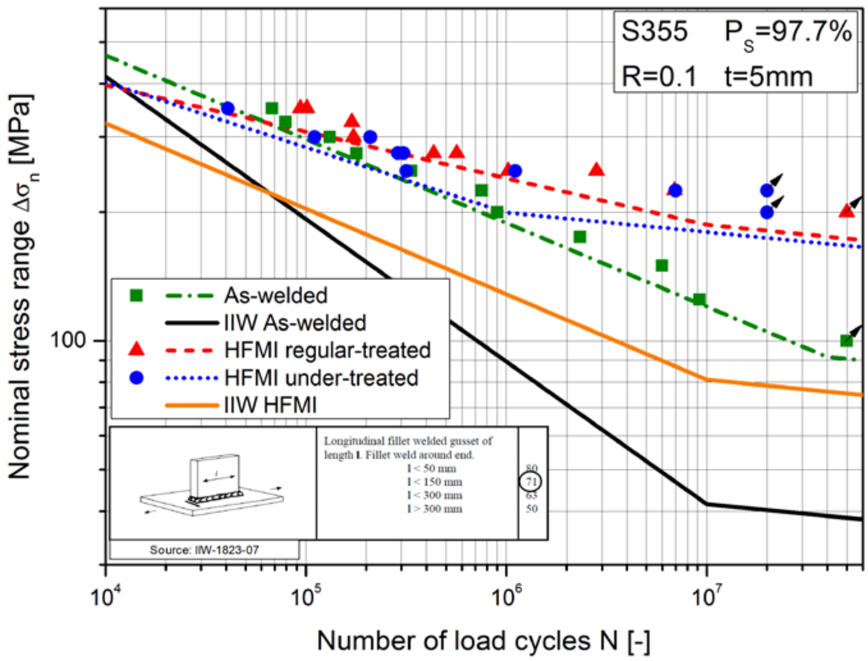

Figure 8: Longitudinal stiffener fatigue strength results (as-welded vs. HFMI process settings)

As already observed in case of non-load carrying transversal attachments, the tested as-welded condition is still slightly above the conservative IIW-recommendation even if the benign thinness factor is applied. In this case, the thinness-enhanced IIW-recommendation leads to a fatigue class of *FAT145*, whereat the fatigue tests revealed *FAT165* and inverse slope value of $k = 5$ for the as-welded condition. The regular HFMI-treatment enables *FAT220*, whereat the under-treatment reduces the fatigue class to *FAT180*. The corresponding inverse slope values reduces from $k = 10$ to 7 as drawn in the figure.

In addition, the fracture surface of the cyclic loaded longitudinal stiffener is shown in Figure 9. Again, the completely treated HFMI groove is recognizable in the fracture surface. In the study of longitudinal stiffeners, only regularly HFMI-treatment process settings were applied.

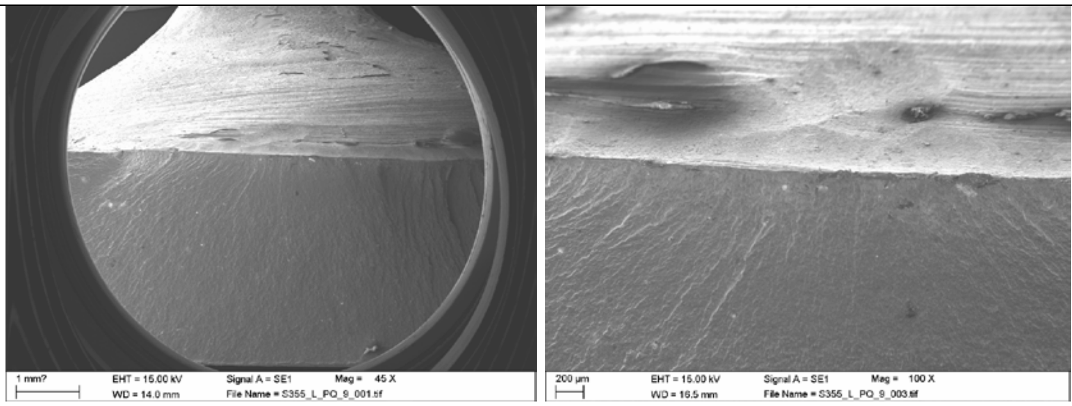

Figure 9: Fracture surface of longitudinal stiffener with HFMI-treatment

The not obvious statement in Figure 8 is that the high-cycle fatigue limit of HFMI-treated specimen seems to be nearly equal and hence independent from the applied HFMI process quality. As depicted in the SEM-images, the under-treatment leads to a shaper geometric weld toe. Thus, the shallower geometric notch contributes primarily to the finite life and the compressive residual and work-hardening states enforce the increase in fatigue strength in the high-cycle region.

3 Fracture mechanical assessment

This hypothesis is checked by fracture mechanical crack propagation analysis using the weight function approach [30, 31]. Herein, the stress intensity factor K is calculated by integrating the product of the stress distribution $\sigma(x)$ and the weight function $m(x,a)$ for each crack increment during cyclic loading, see Equ. 1.

$$K = \int_0^a \sigma(x) \cdot m(x,a) \cdot dx \qquad \text{Equ. 1}$$

Details in regard to the applied formulae and calculation parameters are provided in [32]. On the basis of the methodology suggested in [33, 34] the local residual stress condition is incorporated in the calculation of the crack propagation rate by an effective stress ratio R_{eff} at the crack tip, is applied, see Equ. 2.

$$\frac{da}{dN} = C \cdot \left(\frac{\Delta K}{1.5 - R_{eff}} \right)^m \qquad \text{Equ. 2}$$

with

$$R_{eff} = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}} \qquad \text{Equ. 3}$$

whereby, K_{min} is the minimum and K_{max} the maximum stress intensity factor, and K_{res} equals the stress intensity factor due to the local residual stress condition. Subsequent, this approach is applied in order to calculate the stress intensity factor at the beginning of the testing comparing this value with the threshold for welded joints in the small crack regime.
The analysis is conducted for both types of investigated specimen, starting with the longitudinal stiffener possessing the higher notch-stress concentration factor but also the smaller most-stressed volume.

3.1 Longitudinal stiffener analysis

Previous investigations in [2] exploited the applicability of the weight-function method for this specimen geometry in depth. Thereby, it was concluded that for the as-welded condition an initial crack size of a_i*=0.1 mm* should be applied; which is conform to the IIW-recommendation. The purpose of the analysis in this work is to investigate the effect of HFMI under-treated weld toe paths on fatigue. Herein, the initial as-welded crack size is reduced due to the round-out by the HFMI-treatment at the weld toe area leading to an initial crack size of a_i*=0.05 mm*. In [2] the stress distribution $\sigma(x)$ is taken for a notch radius of $\rho = 0.05$ *mm*, but however, in this study the weld toe is HFMI-treated equalling a notch radius of $\rho = 2$ *mm*, which is applied herein. Cyclically relaxed local residual stress values are taken from [35] for a number of five thousand load-cycles, investigated for the same specimen type and denoted as $\sigma_{res}(N=5e3)$ in this study. The effective stress ratio at the initial crack size is calculated on the basis of Equ. 3 and further on, the resulting, residual stress dependent stress intensity factor is determined using Equ. 2 and related to the threshold value ΔK_{th} for short cracks with a crack depth below one millimetre.
Table 1 summarizes the results for a nominal stress range of $\Delta\sigma_n$*=250MPa*, equalling the run-out level for the specimens in the as-welded state and post-treated with poor HFMI-quality, and of $\Delta\sigma_n$*=325MPa* as upper load-level in the finite lifetime regime.

Table 1: Estimation of crack growth at initial crack size of a_i=0.05mm for HFMI under-treated specimens reflecting poor HFMI process quality

$\Delta\sigma_n$	σ_{res} (N=5e3)	R_{eff}	$\Delta K / (1.5-R_{eff})$	ΔK_{th} (a<1mm)	$\Delta K/(1.5-R_{eff}) / \Delta K_{th}$
250 [MPa]	*-268 [MPa]*	*-0.85 [-]*	*60 [$Nmm^{-2/3}$]*	*63 [$Nmm^{-2/3}$]*	*0.95 [-]*
325 [MPa]	*+215 [MPa]*	*+0.32 [-]*	*155 [$Nmm^{-2/3}$]*	*63 [$Nmm^{-2/3}$]*	*2.46 [-]*

The results reveal that at *250MPa* nominal stress range the cyclic stress intensity factor is below the threshold value and thereby no crack propagation ought to occur. Although the HFMI-treatment quality is comparably poor and the weld toe is not sufficiently post-treated, the compressive residual stresses lead to a significant decrease of the local stress ratio to *-0.85* at the crack tip. Thus, the crack arrests and for validation the testing results exhibited a run-out at this load level for specimen with regular HFMI-treatment quality.
On contrary, at an increased load-level of *325 MPa* in the finite life region, the compressive residual stresses relax and the local stress ratio at the initial crack size turns from *-0.85* to *+0.32*. This enhances the threshold value by a factor of *2.46* and the initial crack propagates at this finite life load level.

3.2 T-joint evaluation

In case of an non-load carrying transversal attachment with continuous fillet seam, implying the best weld quality without start-stop ends, residual stress measurements in [36] revealed compressive residual stresses in loading direction of about *-150 MPa* before any cyclic loading. As the numerical analysis of the notch stress condition at the weld toe for a radius of $\rho = 2$ *mm* equals a stress concentration factor of K_t*=1.43*, the resulting upper local stress at the expected run-out load-level of $\Delta\sigma_n$*=150 MPa* equates to a local upper stress value of about *260 MPa*. As this value does not exceed the local, especially work-hardened yield limit in the HFMI-treated area of the common construction steel S355, it is deduced that the compressive residual stress state is stable and no major cyclic stress relaxation occurs during loading.
A similar calculation of the stress intensity factor, corrected by the effective R-ratio at the crack tip, shows that only at the run-out load-level of $\Delta\sigma_n$*=150 MPa* the threshold value for short cracks is not exceeded and therefore, the run-out level of the HFMI-under-treated joints equals the as-welded condition. This calculation confirms the fatigue test results depicted in Figure 4 and indicates that for HFMI under-treated fillet welds, the level of compressive residual stresses at the weld toe region are of utmost importance whether the crack of the not-sufficient-treated weld toe growths or not.

Additionally, the same procedure is applied for the T-joints exhibiting a poor weld quality. Due to the start-stop-region a slightly local increased stress state and an adverse residual stress condition arises, which rises on the one hand the local stresses but lowers on the other hand the endurable threshold of the stress intensity factor additionally. A rough estimation of the course of residual stresses in loading direction is given in Figure 10 using the software package *simufact.welding*. It takes the weld process sequence, the clamping conditions, and especially the metallurgical phase transformation in the heat-affected zone by thermo-mechanical coupled simulation runs into account. The computed values are in line with investigated measurements and support the local changes in weld process dependent effective threshold value.

With this combined analytical-numerical methodology, it is basically possible to calculate the fatigue S/N-curve for a specific weld process setting taking local heterogeneities such as start-stop ends into account.
As the stabilized residual stress state of HFMI post-treated specimen is significant, further work deals with the set-up of an improved numerical assessment for HFMI-treated seams to cover the stabilized, local mean stress effect more properly.

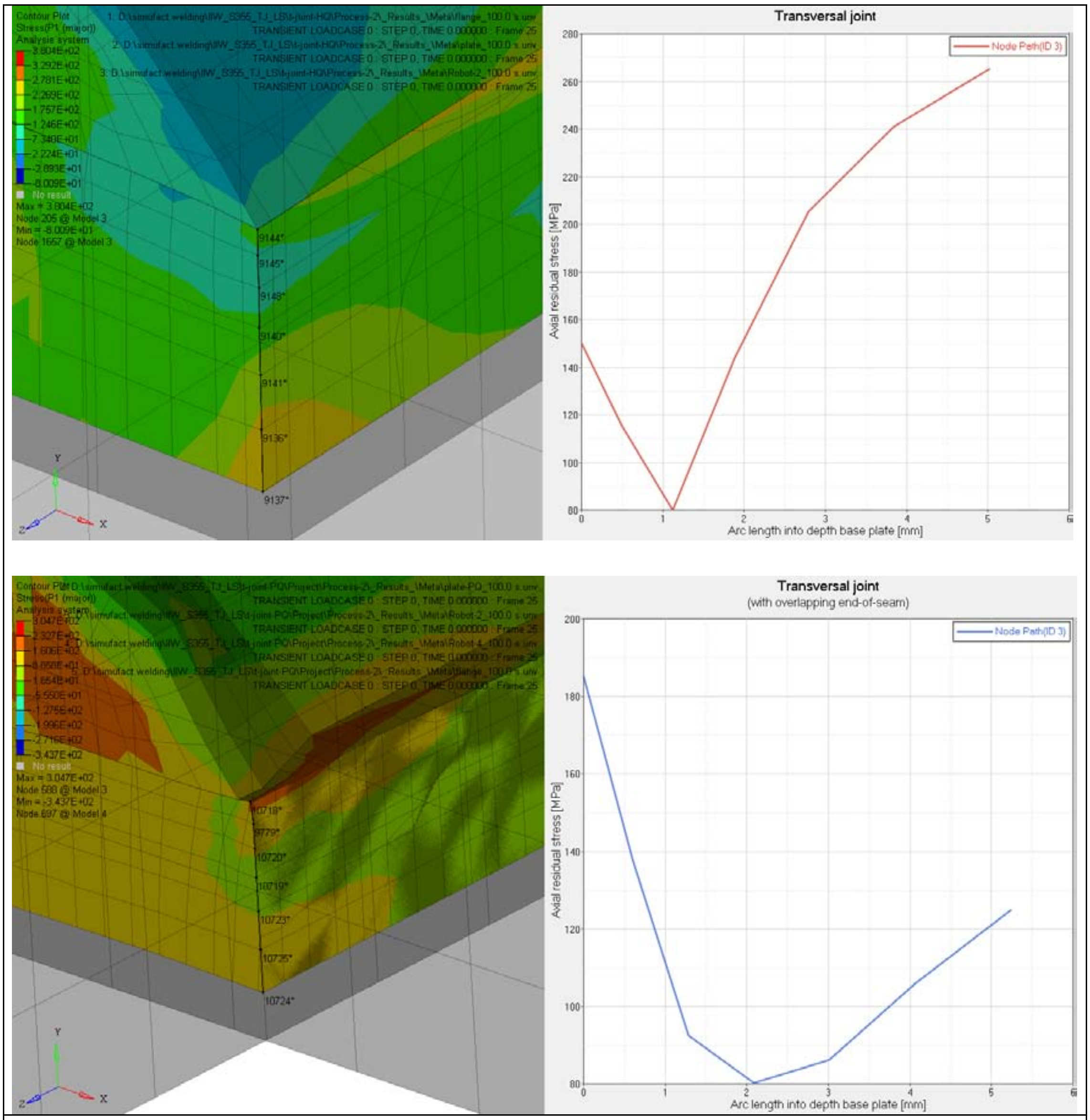

Figure 9: Structural weld simulation and section cut results of homogenuous fillet seam vs. start-stop end (as-welded condition)

4 Conclusion

The presented investigations focussed on the effect of HFMI-treatment quality on fatigue strength of fillet welds. The results are only valid for joints made of common construction steel plates with a thickness of five millimetres. The findings are as follows:

- HFMI-treatment can be considered sufficient if a minim indentation depth of about *0.1 mm* is achieved in engineering. This recommendation is well above the measured value of at least *0.02 mm*, but the increased limit is given due to enable engineering applicable measurements in the field of structural and HFMI-treated frameworks.
- An over-treatment using HFMI-equipment, more precisely by using the tool introduced in [29], is in common tolerable and does not reduce the endurable fatigue strength. It should be kept in mind that through severe treatment the nominal wall thickness may be reduced.

- The weld toe topography can be accurately measured by laser-scanning and subsequent evaluated by digital image correlation. This enables an automated assessment of HFMI groove and notch factors which may be used to qualify the HFMI-equipment further on.
- Fatigue test results and fracture mechanical calculations indicate that the level of the compressive residual stress state around a HFMI-under-treated weld toe is of utmost importance by influencing the stress intensity factor. If the compressive residual stress is too low or gets cyclically relaxed during loading, the stress intensity factor threshold is exceeded and the crack propagates leading to a reduced fatigue strength; in worst case down to the as-welded condition. Hence, the effect of overloads and in-service load spectra on the resulting stabilized residual stress condition is a great majority, which can be either assessed by measurements or numerically as presented in [35].

5 References

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