Influence of High Frequency Peening on Fatigue of High-Strength Steels

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Post weld treatment methods like the high frequency peening technology (HFP) increase the fatigue strength in the finite lifetime and even in the high-cycle fatigue region. In this study the fatigue improvement of HFP on three different weld seam geometries made of thin-walled high-strength steel is shown. Extensive experimental fatigue tests are investigated to gain a comparison of the fatigue behavior of the base material, as welded and post treated condition. Different fatigue approaches are applied including the nominal stress method and the local notch stress concept. For the HFP treated condition an obtained key result is that the fatigue strength enhancement at joined components increases with a higher stress concentration factor at the post treated weld toe.

Keywords: *fatigue behavior, welded joints, high-strength steel, local fatigue assessment, post weld treatment, high frequency peening.*

1. INTRODUCTION

The fatigue behaviour of welded high-strength steel joints is in the finite lifetime regime beneficial due to the increased yield limit. In the high-cycle fatigue region the notch topography, the microstructure in the heat-affected-zone (HAZ) and the residual stress state influences the fatigue lifetime in a major way.

To assess the influence of the local stress concentration on the local fatigue strength of welded and high frequency peened high-strength steel joints fatigue tests using three different thin-walled weld specimen types are investigated. According to the IIW-recommendation [1], the fatigue strength enhancement is well defined when using the nominal stress concept. In this contribution an evaluation of the increase using the nominal and the notch stress concept for the different investigated joints is given to estimate the benefit of the HFP peening as post treatment method for thin-walled high-strength steels.

2. EXPERIMENTAL INVESTIGATIONS

In the investigated test series a low-alloyed high-strength steel S960 with a sheet thickness of 5 mm is used as base material. The rolling skin and remainders of rust inhibitors are removed with the help of sand blasting before welding.

Preliminary investigations [2] concerning the fatigue testing of welded joints showed that it is important to use a ratio of ten to one between width and thickness of the base plate. This ensures a plain strain state at the centre and encourages technical crack initiation in this homogenous region.

2.1 Specimen manufacturing process

The manufacturing of the three thin-walled and single-layered welded types; butt joint, T-joint and longitudinal attachment, is done by the aid of a welding robot (Figure 1). For quality control $t_{8/5}$-time measurements are arranged, which characterize the welding process and hence the resulting crystalline structure in the HAZ.

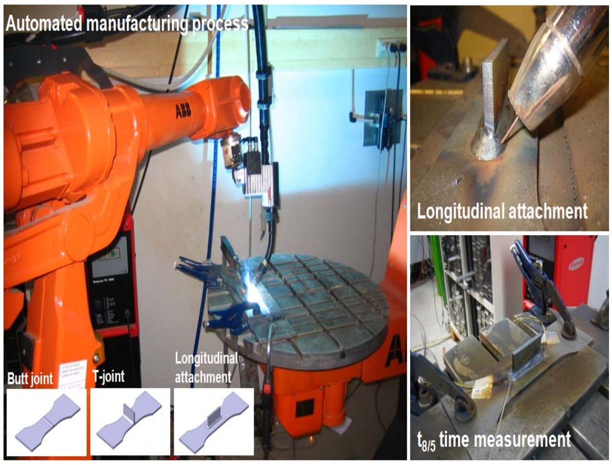

Figure 1. Automated manufacturing process

In the course of the welding process the electric voltage and the current has to be adapted for each specimen type. Therefore, an optimal weld seam performance with high quality welds and reproducible results were obtained to minimize the influence of weld quality on the fatigue behavior. [3].

2.2 Post weld treatment: High frequency peening

After welding and cool down to room temperature; half of each specimen lot is additional post treated by the HFP technology (Figure 2). For the pneumatic actuation energy a common industrial air pressure of 6 bar (0.6 MPa) is needed. For a sufficient post treatment quality a treatment velocity $v = 20$ to 30 cm per minute and a frequency of 90 Hz is applied. The radius of the hardened pin used in this study is $R = 2$ mm which fits to the weld seam size of the investigated specimens. The post treatment was applied on the welded specimens without additional static pre-stressing.

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Figure 2. HFP treatment of the investigated specimens

The benefit due to this post weld treatment method is based on two effects. The pulsed transaction of the hardened pin rounds out the curvature of the weld toe region and thereby reduces the geometric stress concentration factor. In addition, compressive stresses are induced which counteract the residual weld tensile stresses and external applied tensile stresses. [4,5].

2.3 Fatigue testing

For the fatigue tests a servo-hydraulic test rig with an accompanying strain gauge measurement at the weld toe region, to assess the technical crack initiation, is used (Figure 3). The stress ratio for all test series is tumescent with R = 0.1. The test abort criterion is total rupture and the run-out level is set to a number of fifty million load cycles.

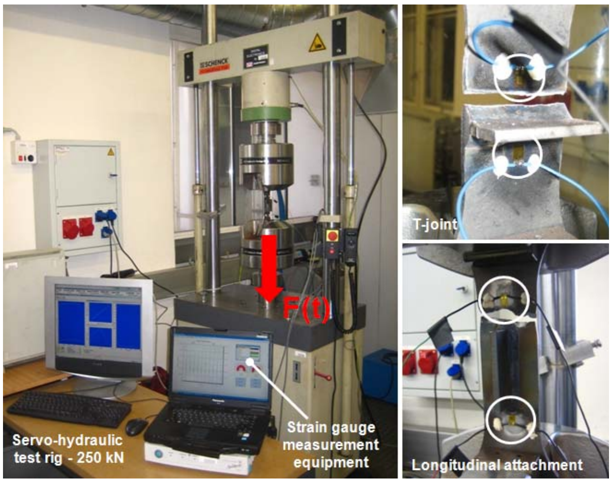

Figure 3. Fatigue test rig and applied strain gauges

2.4 Metallographic inspections

To estimate the amount of the fatigue cracking area and the rupture part, regarding the influence of the different weld seam geometries and the HFP treatment, an accompanying fracture surface analysis for each specimen was done. A comparison of the fracture surface of the T- and butt joint, tested at the same load level, is given in Figure 4. Thereby the two typical zones with the fatigue fracture (A) and the rupture area (B) are recognizable. For thise two specimen types multiple crack initiation appears along the weld toe line for the as welded and the HFP treated condition. Due to the reduced notch effect of the butt joint a minor increase of the number of load cycles at the same load level compared to the T-joint is achieved.

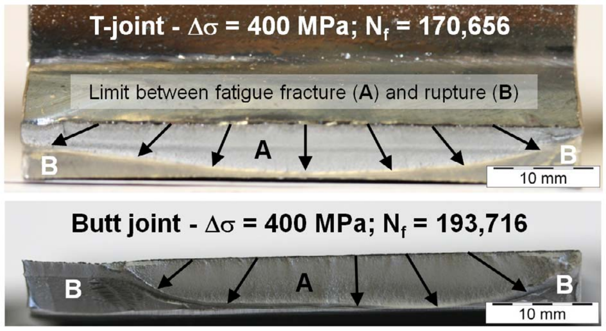

Figure 4. Fracture surface analysis of T- and butt joint for as welded condition

A detailed look at the fracture surfaces of the longitudinal attachment is displayed in Figure 5. In the as welded condition the crack initiates at the end-of-seam by the high local notch effect and a major change in stiffness at this region.

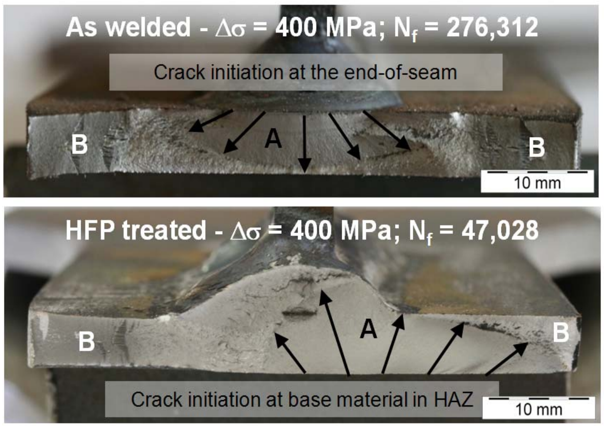

Figure 5. Comparison of fracture surface for as welded and HFP treated condition (longitudinal attachment)

In contrast at some of the HFP treated specimens the crack starts at the bottom side of the base sheet within the HAZ. The HFP post treatment leads to a shift of the critical area from the weld toe to the heat-affected base material. In this case the geometric notch effect is removed and subsequently the metallurgical notch is essential for the fatigue behaviour of the welded joint. Further investigations regarding failure modes on post treated welds are shown in [6].

3. NOMINAL STRESS APPROACH

In the finite life regime the fatigue assessment is conducted using the evaluation procedure according to [7] by a log-normal distribution for the number of fatigue cycles at independent stress levels. For comparison purposes the recommended $\Delta\sigma/N$-curve for the as welded and HFP treated condition, which considers a post treatment bonus factor of 1.5 in fatigue strength, is additionally displayed [8,1].

A classification of the $\Delta\sigma/N$-curves is based on the nominal stress range at two million load cycles using a survival probability of P_S=97.7%, which is defined as the characteristic FAT-class. The fatigue assessment in the high cycle fatigue region is done using a second slope of k'=22 which is suggested in [1]. In Figure 6 the nominal $\Delta\sigma/N$-curves for the butt joint are shown.

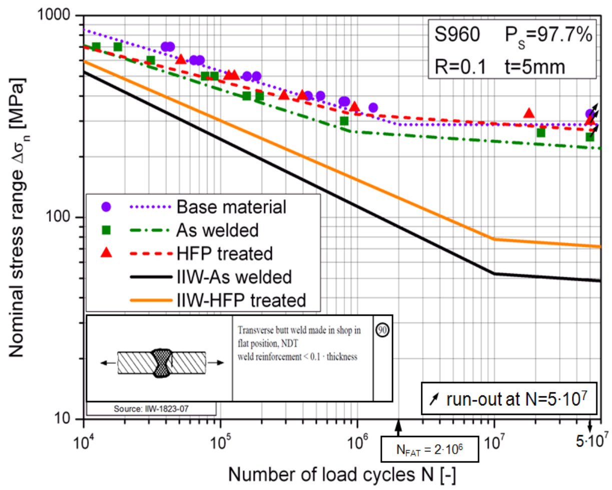

Figure 6. $\Delta\sigma/N$-curves for butt joint (nominal stress)

Due to the HFP treatment a minor increase of the FAT-class by a factor of 1.2 can be stated in the low-cycle fatigue region. The HFP treated condition is almost similar to the fatigue strength of the untreated base material which defines the upper limit of the reachable fatigue behaviour. Both, the as welded and the HFP treated condition exceed the recommended values for this thin-walled joints. A summary of the fatigue test results for the butt joint according to the nominal stress approach is given in Table 1.

Table 1. Fatigue test results for butt joint (nominal stress)

	FAT [MPa]	k [-]	N_k [-]	$1/T_S$ [-]
As welded	260	4.6	$9 \cdot 10^5$	1.11
HFP treated	315	5.9	$9 \cdot 10^5$	1.09

A significant improvement in fatigue by HFP as post treatment method show the test results for the T-joints (Figure 7). Thereby the FAT-class increases by a factor of 1.6. In addition the transition knee point N_k shifts to a lower number of load cycles implying a significant increase in endurable strength limit. In accordance with the butt joint results, it is observed that the HFP treated fatigue strength is almost the same as the untreated base material.

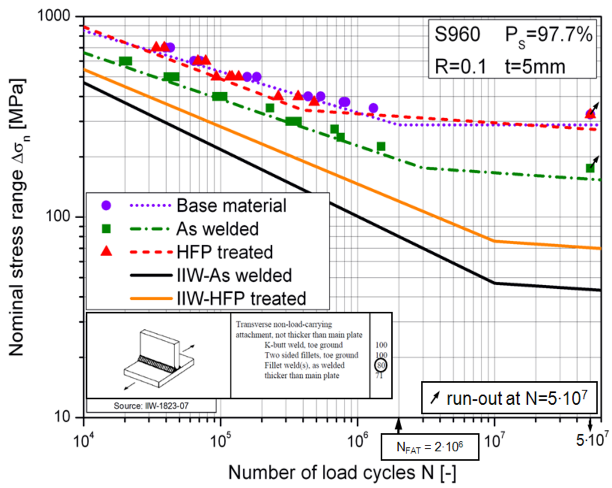

Figure 7. $\Delta\sigma/N$-curves for T-joint (nominal stress)

The fatigue test results for the T-joint assessed by the nominal stress approach are summarized in Table 2.

Table 2. Fatigue test results for T-joint (nominal stress)

	FAT [MPa]	k [-]	N_k [-]	$1/T_S$ [-]
As welded	195	4.3	$3 \cdot 10^6$	1.08
HFP treated	315	3.9	$4 \cdot 10^5$	1.12

Finally the nominal $\Delta\sigma/N$-curves for the longitudinal attachment are displayed in Figure 8. This type of weld seam geometry offers the up most potential using HFP as post treatment method caused by the high stress concentration and the major change in stiffness at the weld toe region.

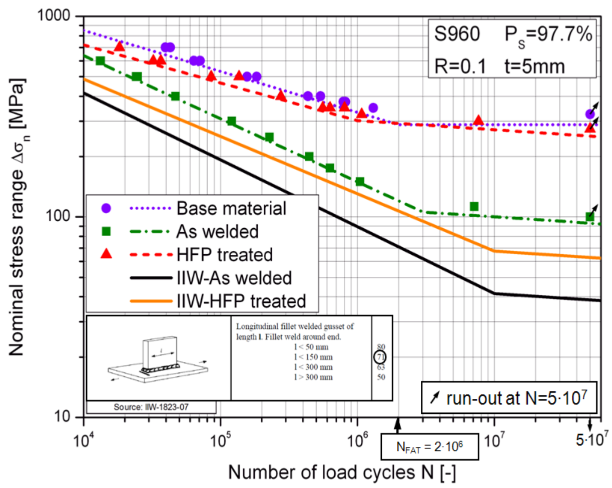

Figure 8. $\Delta\sigma$/N-curves for long. attachment (nominal stress)

For the longitudinal attachment an improvement factor of 2.5 by HFP compared to the as welded condition is achieved caused by an increase of the slope k in the low-cycle fatigue regime and a shift of N_k regarding high-cycle fatigue. A summary of the fatigue test parameters for the longitudinal attachment according to the nominal stress approach is given in Table 3.

Table 3. Fatigue test results for longitudinal attachment (nominal stress)

	FAT [MPa]	k [-]	N_k [-]	$1/T_S$ [-]
As welded	120	3.2	$3 \cdot 10^6$	1.04
HFP treated	295	5.3	$1 \cdot 10^6$	1.09

The evaluation according to the nominal stress approach indicates an increase of the fatigue strength due to the HFP technology for all three investigated weld seam geometries. The evaluated benefit factors when using the nominal stress as assessment criterion are summarized in Table 4.

Table 4. Fatigue strength increase factor HFP/AW for the investigates specimen geometries (nominal stress)

	Butt joint	T-joint	Long. attachment
HFP/AW [-]	1.2	1.6	2.5

3.1 Evaluation of the notch effective stress concentration factor $K_{t,r}$ = 1mm

For the evaluation of the notch stress concentration factor $K_{t,r=1\ mm}$ a quarter-symmetric model for all specimen geometries with a hexahedral element mesh and a unified tension load is used. The application of a reference radius of r_{ref} = 1 mm is based on the micro-support theory [9,10] and statistically proved by experimental analysis [11]. The numerical modeled geometries depict the technical cross-section of the seam, local deviations from the design geometry are not considered. In the investigated numerical evaluations a number of four elements for the butt joint and five elements for the T-joint and longitudinal attachment are applied (Figure 9). This is in accordance with the modeling guidelines [12].

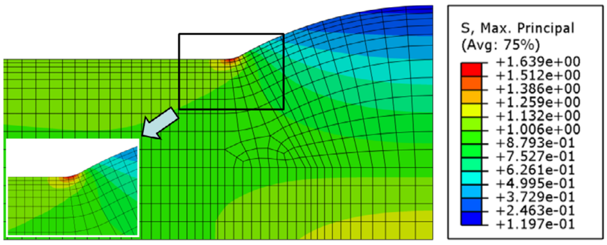

Figure 9. Mesh of the weld toe region (butt joint)

Due to a pretension of the specimens at the manufacturing process a misalignment of the welded joints was minimized and thereby no additional deviation factor is used in this evaluation. The results for the three investigated weld seam geometries using the principal stress hypothesis are shown in Figure 10.

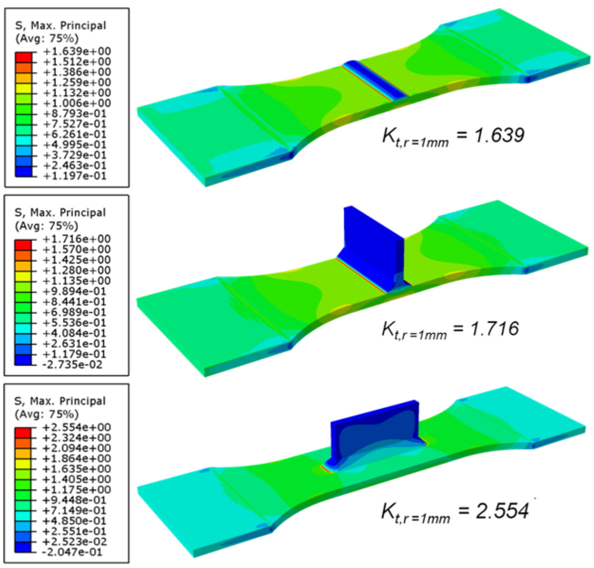

Figure 10. Results of the numerical evaluation for $K_{t,r=1mm}$

The evaluated notch stress factors show a relatively low stress concentration at the weld toe of the butt and the T-joint and a higher stress concentration at the end-of-seam of the longitudinal attachment. This is in accordance with the recommendation [1] where the FAT-class in the nominal stress concept decreases with a higher local stress concentration at the weld toe region.

To estimate the increase of the fatigue strength by HFP treatment the evaluated benefit factors in dependency of the stress concentration factors $K_{t,r=1mm}$ are displayed in Figure 11. The results show an increase of the effectiveness due to HFP at higher notch factors. A linear fitted distribution delivers an estimated increase for the investigated thin-walled specimens.

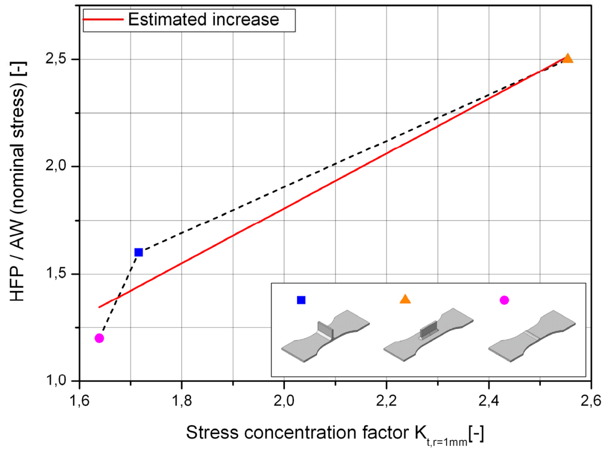

Figure 11. Estimated increase factor of nominal fatigue strength in dependency of the notch stress concentration

Based on these results it can be stated that the enhancement of the HFP treatment is addictive to the weld seam geometry and the local weld toe notch effect of the joint.

4. LOCAL FATIGUE ASSESSMENT

For an estimation of the fatigue behavior of welded structures different design concepts exist. The nominal stress approach as global concept, uses the nominal stress range with the corresponding notch cases. Local concepts like the structural stress approach uses the hot-spot stress at the weld toe to assess fatigue strength. The common used notch stress approach takes the notch effect of the weld toe or root into account and is therefore recommended for the estimation of the fatigue behavior including different welding seam geometries.

4.1 Notch stress approach

By using this concept for the fatigue assessment a definition of the local notch stress range $\Delta\sigma_{loc}$ combines the experimental nominal stress range $\Delta\sigma_n$ with the numerical notch stress analysis [13]:

$$\Delta\sigma_{loc} = \Delta\sigma_n \cdot K_{t,r=1mm} . \quad (1)$$

For post weld treated joints the modeling of the real toe radius plus one millimeter and an evaluation of the principal stress range against the approvable value of FAT200 is recommended in [1]. This procedure is preferable for relatively sharp notches and has not been thoroughly verified. An alternative procedure for assessing post weld treated joints using the notch stress approach is investigated in [14] and maintains the reference radius of r_{ref} = 1 mm in addition to use a higher FAT-class due to the post weld treatment including an enhancement factor. Hence, the same stress concentration factors for the as welded and HFP treated joints are used for the local fatigue assessment.

In Figure 12 the resulting local master $\Delta\sigma/N$-curve for the as welded condition is pictured. The result shows that in the finite lifetime region the local fatigue behavior of all three investigated weld geometries is in a relatively small scatter band of $1/T_S$ = 1.30 and delivers a good compliance with the recommended curve.

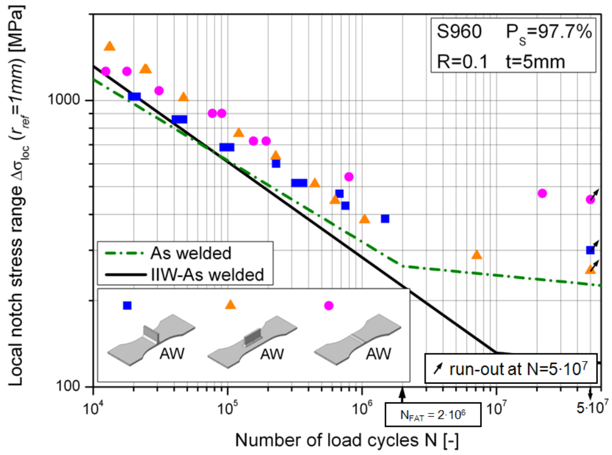

Figure 12. Master Δσ/N-curves for as welded condition

Contrary, in the high-cycle fatigue region the notch stress factor has a wide influence on the fatigue behavior and therefore the butt joint with the lowest stress concentration factor $K_{t,r}$ = 1 mm at the weld toe shows a local higher endurance strength compared to the T-joint and the longitudinal attachment. The resulting local master *Δσ/N*-curve for the HFP treated condition is displayed in Figure 13. In this case the local fatigue results show that a significant gap between the data points of the high notched longitudinal attachment and the comparatively lower notched T- and butt joint exists.

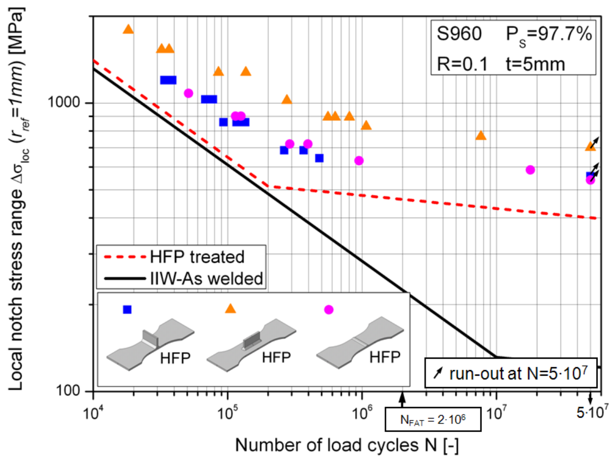

Figure 13. Master Δσ/N-curves for HFP treated condition

In the low- and in the high-cycle fatigue region a superior scatter band of $1/T_S = 1.91$ is recognizable caused by the different effectiveness of the HFP treatment regarding the three investigated specimen types. Summarized the local fatigue assessment according to the notch stress approach results an increase in the local fatigue strength from FAT265 for the as welded up to FAT460 for the HFP treated condition mainly caused by a shift of the transition knee point N_k to lower cycles.

An overview of the resulting local fatigue parameters is given in Table 5.

Table 5. Results of master Δσ/N-curves (notch stress)

	FAT [MPa]	k [-]	N_k [-]	$1/T_S$ [-]
As welded	265	3.5	$1{\cdot}10^6$	1.30
HFP treated	460	3.0	$2{\cdot}10^5$	1.91

For the as welded specimens the notch stress approach delivers a master Δσ/N-curve with a relatively small scatter band compared to the recommendation [1].

The assessment of the HFP results by the notch stress approach shows an increased scatter band of the test points due to the differing effectiveness of the HFP post treatment at the investigated joints.

To gain more accurate results especially when using HFP the applicability of local approaches like the notch stress intensity factor [15] or the strain energy density approach [16] is investigated in future work.

5. CONCLUSION

The fatigue behavior of three thin-walled weld specimen types made of high-strength steel *S960* is assessed. An additional HFP post treatment at the weld toe region is done to analyze the influence of the fatigue strength enhancement by HFP for different weld seam geometries.

The HFP-fatigue test results using the nominal stress concept show a significant dependency of the increase in fatigue behaviour, expressible by the stress concentration factor $K_{t,r}$ = 1 mm. Thereby the up most potential of HFP is shown for the longitudinal attachment due to the high notch factor and the major change in stiffness at the weld toe region. Especially in the high-cycle fatigue region the effectiveness of HFP indicated a major progression of the fatigue strength by a shift of the transition knee point N_k to a lower number of load cycles. In comparison, a minor increase for the T- and the butt joint is recognizable which is caused by the reduced stress concentration.

In all three investigated specimen types the HFP treated condition is almost similar to the fatigue strength of the untreated base material which defines the upper limit of the reachable fatigue behaviour.

In addition, both the as welded and the HFP treated condition exceed the conservative recommended values for the investigated thin-walled high-strength steel weld joints.

An application of the notch stress approach verifies the applicability of the master Δσ/N-curve for the as welded specimens within a relatively small scatter band. The HFP treated condition shows an increased scatter of the test results due to the differing effectiveness of the HFP post treatment with raising notch stress factors. For the local notch stress assessment a fatigue strength enhancement due to HFP by a factor of 1.7 is reached, mainly caused by a shift of the transition knee point N_k to lower cycles.

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УТИЦАЈ ВИСОКОФРЕКВЕНТНОГ САЧМАРЕЊА НА ЗАМОР ЧЕЛИКА ВЕЛИКЕ ЧВРСТОЋЕ

Мартин Литнер

Методе које се примењују након заваривања, као што је високофреквентно сачмарење, имају за циљ повећање чврстоће на замор третираних делова. У овом раду су испитиване три различите геометрије завареног споја делова израђених од танкозидног челика велике чврстоће. Показано је да високофреквентно сачмарење заварених спојева утиче на побољшање њихових заморних карактеристика. Експериментална испитивања су имала за циљ поређење понашања, при заморном оптерећењу, основног материјала, материјала споја након заваривања и материјала споја након третирања сачмом. При поређењу су примењени различити приступи, укључујући метод номиналних напона и концепт утицаја зареза на напонско стање. Резултати показују да код заварених спојева третираних сачмом чврстоћа на замор расте са са вишим фактором концентрација напона.