Further enhancing fatigue properties with HFMI by customized edge treatment

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Abstract
Free corners and edges are potential weak points for fatigue crack initiation at High Frequency Mechanical Impact (HFMI) treated welded joints even if the treated welded seam itself shows a high fatigue strength. In this study the residual stress state around cutting edges of HFMI-treated notched and welded specimens were investigated. For this, X-ray diffraction (XRD) technique and Finite Element (FE) Analysis were used. It is verified that no compressive residual stresses close to the edges were present. Fatigue tests were performed at notched specimens made of S960QL steel. Some specimens were HFMI-treated at the cutting edges with a concave pin. This additional treatment leads to a shift of the crack initiation location from the edge to the center of the specimen and to a significant increase of fatigue life. HFMI edge-treatment of welded joints showed in some cases that the edge treatment may also cause defects that could lead to crack initiation even from treated edges.

Keywords: High Frequency Mechanical Impact treatment, Cutting edges, Residual stresses, Fatigue

Introduction

Besides welds seams free cutting edges are potential weak points for fatigue crack initiation of steel welded structures [1]. Due this reason, the current IIW-recommendation [2] and Eurocode 3 [3] for the fatigue design of welded structures recommend grinding of corners or edges to remove potential defects and decrease the stress concentration. Experimental investigations show that the fatigue strength of the cutting surface is often related to the condition of the edges or corners, where pre-dominantly fatigue cracks initiate [1], [4]. Furthermore edges of High Frequency Mechanical Impact (HFMI) treated weld seams show as well in many cases fatigue failure from the edges [5]. Therefore, belt or disc grinding was usually performed to avoid fatigue crack initiation from the edges. However, it is obvious that the quality of grinding is strongly related to the user. For this reason, this investigation is focused on the edge-treatment by HFMI with special concave pins to provide an alternative method to improve the edge condition that expect a high reliability compared to grinding methods.

Specimen and mechanical treatment

High strength steel S960QL (1.8933) according to DIN EN 10025-6:2018-07 with a bainitic-martensitic microstructure was used in this investigation. The mechanical properties of the material are summarized in Table 1. Simple Notched and welded specimens (double-sided transverse stiffener with single-layer fillet welds) were manufactured of S960QL. The geometrical notch of the notched specimen was manufactured by electrical discharge machining (EDM) and has a stress concentration factor (SCF) of 2.26. The dimensions are illustrated in Figure 1 (a). Further details are given by Schubnell et al. [6]–[8].
Edge treatment was performed with a pneumatic impact treatment (PIT) device Pitec Weld Line 10, illustrated in Figure 1 (b). The recommended working pressure for steel was decreased from 6 bar to 4 bar to avoid an over-treatment of the edges. The impact frequency was 90 Hz. The impact angle was around 45° and the radius of the concave-pin was 2 mm. After edge-treatment the edges of some notched specimens remain in untreated condition (unt. edge). After edge-treatment defects were removed (chamfering) and the very

rough edges were polished (edge-treatment condition, HFMI-edge). The complete process is illustrated in Figure 1 (c).

Table 1. Mechanical properties of the investigated materials

Material	Yield strength [MPa]	Ultimate tensile strength [MPa]	Elongation [%]	Hardness [HV10]
S960QL	1011	1060	14	316

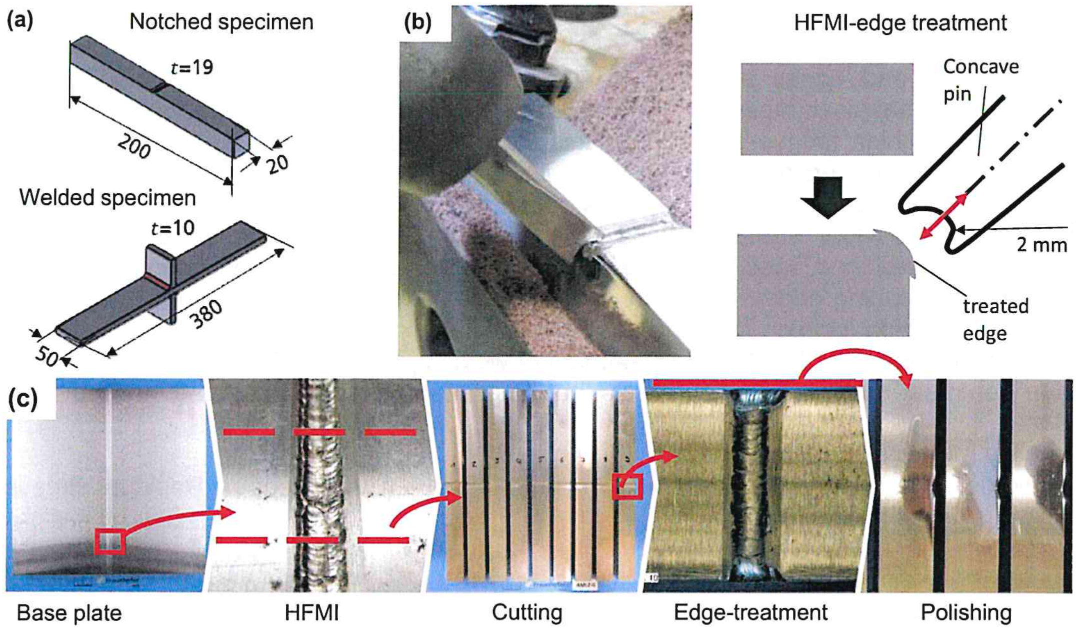

Figure 1. (a) Dimensions of specimens, (b) HFMI edge-treatment, (c) Manufacturing process of notched specimen

HFMI-process simulation

The residual stress state after HFMI-treatment, especially at the edges of the specimen, were analyzed by Finite Element (FE) process simulation. For this, the force-controlled FE-model implemented in ABAQUS according to Ernould et al. [9] and Schubnell [10] was used. With this simulation technique the vertical pin movement of the pin was controlled by a defined force. A combined isotropic-kinematic constitutive model with strain rate dependent flow stress according to Chaboche [11] modified by Maciolek [12] were used. The local material properties of the heat affected zone (HAZ) for the welded specimen from S960QL [13] were taken into account. Details of the process models are given by Schubnell et al. [6] (welded specimen) and by Schubnell et al. [7] (notched specimen).

The process simulation contains two steps: First the simulation of the HFMI-process, see Figure 2. Second, the deletion of the edges to simulate the re-distribution of the residual stress caused by the cut of the single specimen out of the base plate. The deletion of the edge was performed via a VUMAT-subroutine (vectorized user material) that set the stress on defined elements to zero. As shown in Figure 2, compressive residual stress was induced by HFMI-treatment up to a depth of around 1.5 mm for both types of specimens. However, compressive residual stresses are not determined close to the edge of the specimen. Here high residual stresses were induced by HFMI-treatment close to the specimen's edge. High tensile residual stresses were also present after deletion of the edge (simulation of cutting process).

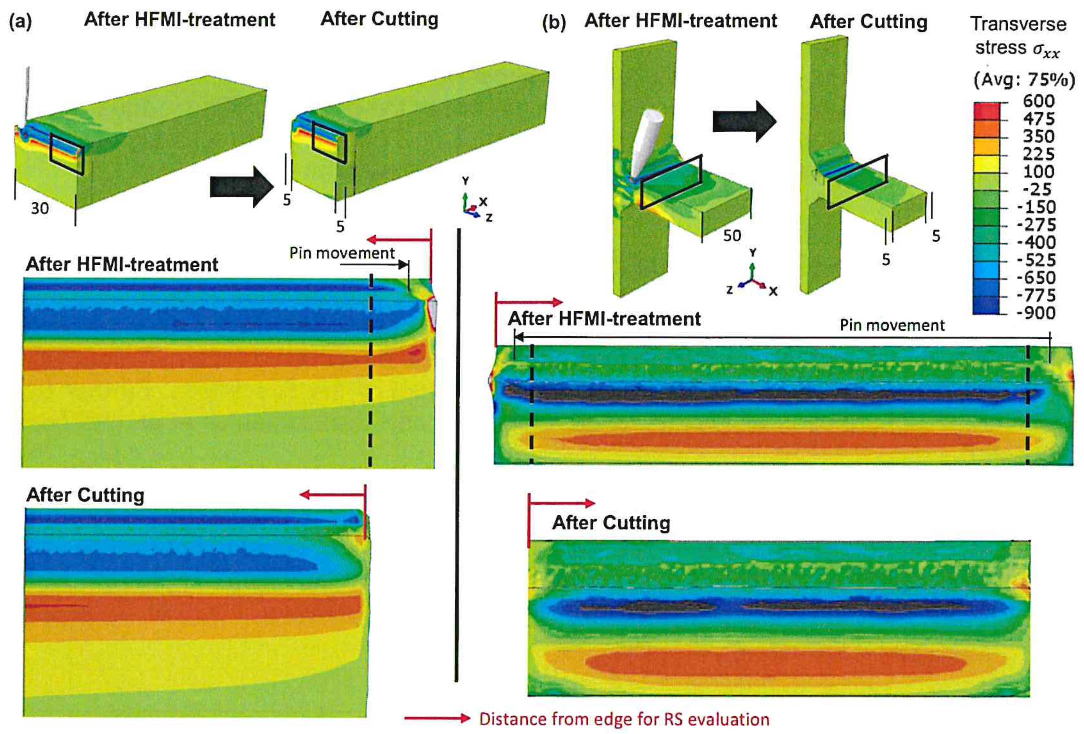

Figure 2. Finite Element Simulation of the HFMI-treatment and cutting of the notched specimen (a) and welded specimen (b)

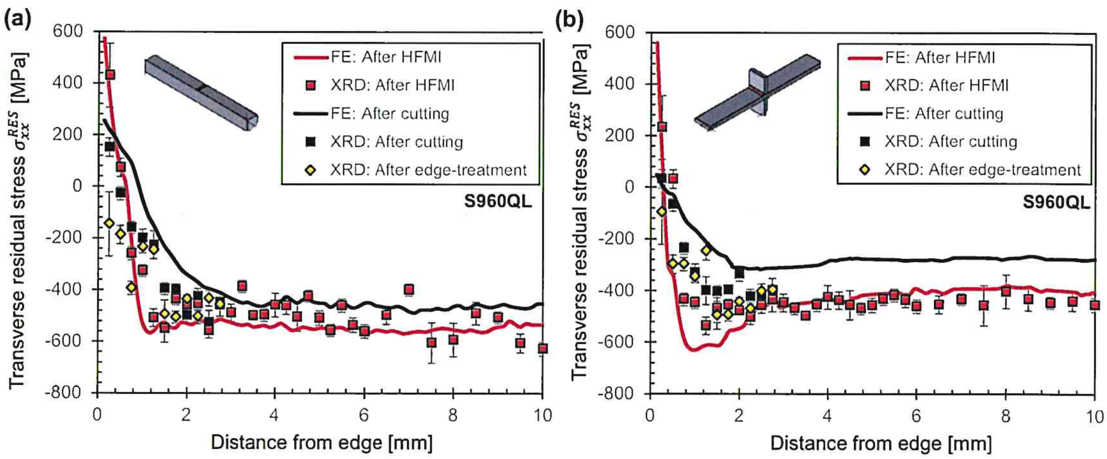

Figure 3. Residual stresses at the surface of the HFMI-treated groove from the distance of the edge (see Figure 2) of the notched specimen (a) and welded specimen (b)

The results of the numerical determined residual stresses were compared to experimental determined values. For this, surface near residual stress measurements of the S960QL specimens were performed using X-ray diffraction with CrKα-radiation at the {211}-ferritic lattice plane. The measurements were performed with a diffractometer type Pulstec μ-360, based on the cosα-method [14], [15].The reliability of this method in combination with the 2D-detector compared to the commonly used $\sin^2\psi$-method was evaluated by Matsuda et al. [16]. The collimator diameter (measurement diameter) was 0.2 mm and the X-ray incident angle was ψ = 35° for all measurements. As elastic constants for the evaluation E = 220 GPa and ν = 0.29 were used. The results are presented in Figure 3. As shown, high residual stresses appear in a distance of 0.5 mm from the edge of the HFMI-treated groove by XRD-analysis. After the cutting process (in order to obtain single specimens from the base plate), the tensile residual stresses close to the edge are decreasing. HFMI-edge treatment, the removal of defects and polishing leads to compressive residual stresses. However, it cannot be stated if this is related to the HFMI-edge treatment or the polishing of the edges. Also, the compressive residual stresses after edge treatment and polishing are less significant than the compressive residual stresses in distance of 1 mm away from the edge.

Fatigue tests

Fatigue tests were performed to quantify the influence of the edge-treatment technique on the fatigue strength of notched and welded specimens. All fatigue tests were performed with a stress ratio of R=0.1. The fatigue tests of the notched specimens were performed under 4-point bending load and for the fatigue tests of the welded specimen pure tensile loading was used. The fatigue tests were performed until the fracture of the specimens. Further details are given by Schubnell et al. [17] (notched specimen) and Gkatzogiannis et al. [18] (welded specimen).

The fatigue tests results are summarized in Figure 4. As shown, only a slight improvement was determined from the as-welded condition to the HFMI-treated condition without edge-treatment (unt. edge). Especially for the notched specimen several specimens do not exceed the range of fatigue life compared to untreated condition. However, with an additional HFMI-treatment and polishing of the edges a significant increase of fatigue life was determined for both types of specimens.

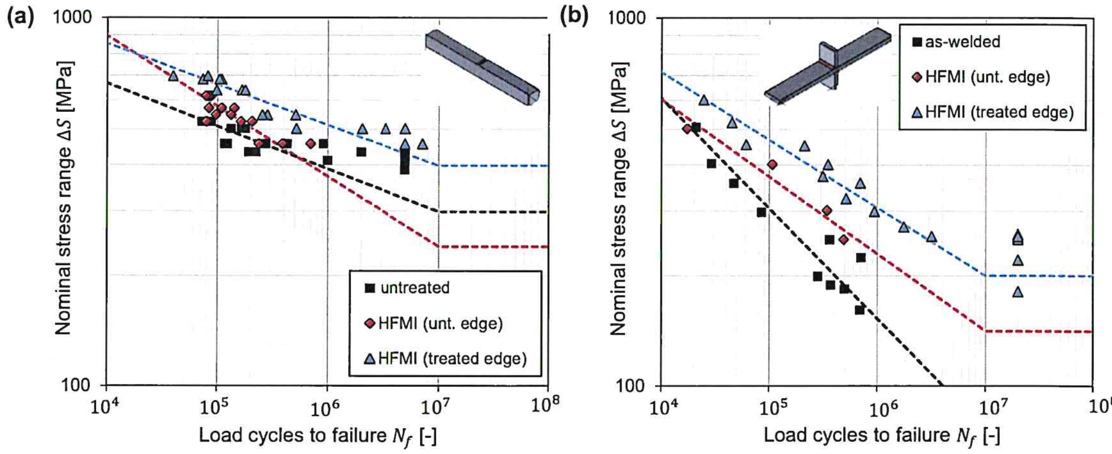

Figure 4. Fatigue test results of notched specimen (a) and welded specimen (b)

So-called beach-mark tests were performed for visual detection of the crack initiation location and crack propagation after the fracture of the specimen. For this, the load ratio was temporarily changed from R=0.1 to R=0.7. The crack propagation and the number of load cycles during R=0.7 was neglected for the evaluation. The fracture surfaces of one specimen of each condition were displayed in Figure 5 (a) (notched specimen). The displayed fracture represents the typical location of crack initiation (crack starter) of each condition. As shown, the location of crack initiation shifts from the middle of the notch (untreated condition) to the edges (HFMI (unt. edge)). After HFMI-edge treatment and polishing of the edge the crack starter shifts again to the middle of the HFMI-treated notch. Similar behavior was investigated for the welded specimen. However, in this case no additional removal of defects or polishing of the edges were performed after HFMI-edge treatment. The investigated fracture surfaces show still a crack propagation from the edge to the center of the specimen in some cases. For further investigation, the location of crack initiation was detected with by scanning electron microscopy. For all investigated specimen a high number of crack starters were determined along the HFMI-treated weld toe, see Figure 5 (b). However, in some cases crack like defects were determined as a reason of

HFMI-edge treatment, see Figure 5 (c). In this case it is strongly assumed that such a crack-like defect is the dominant failure mechanism.

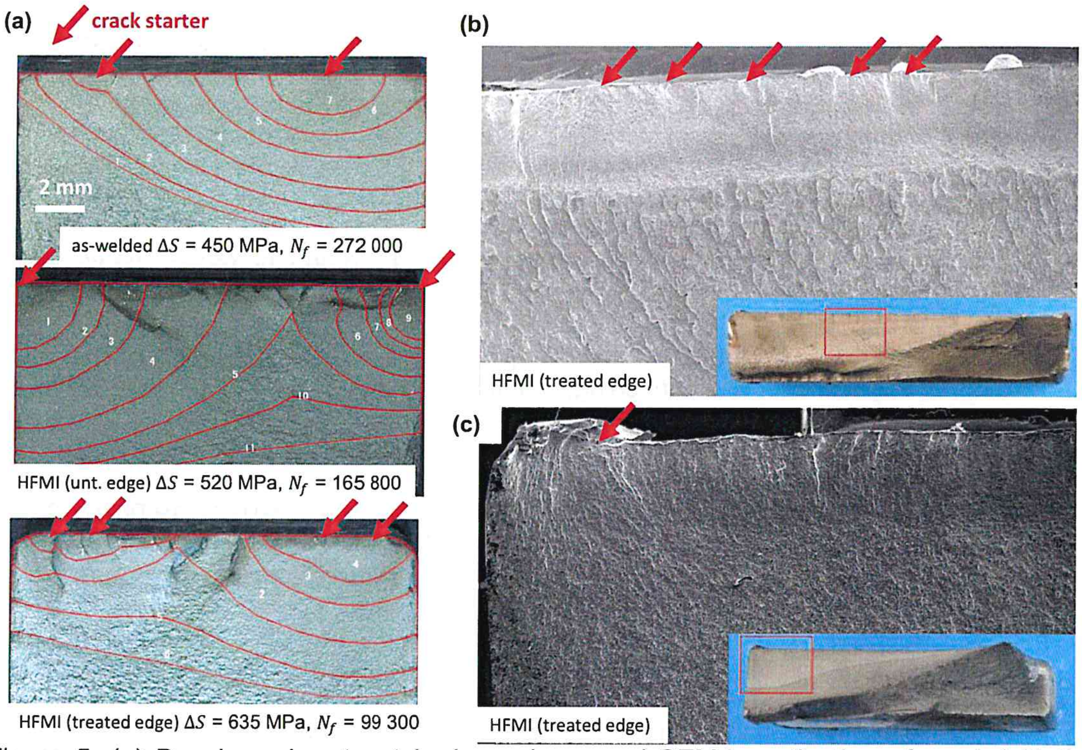

Figure 5. (a) Beach-marks at notched specimen and SEM-investigation of crack initiation locations from specimen center (b) and specimens' edge (c)

Discussion and Conclusions

Geometrical edges and corners are potential weak points in welded and non-welded constructions. This study verifies that no compressive residual stresses are present after HFMI-treatment in the vicinity of the edges based on FE simulation and XRD measurements. Two different specimen types (notched and welded) from S960QL steel were investigated. It is assumed that the lack of compressive residual stresses, the presence of defects and roughness at the edge leads to a comparable low fatigue strength and to crack initiation at these positions. An additional HFMI-edge treatment with special concave-pins was performed to eliminate these weak points. Tensile residual stresses at the edge of the HFMI-treated specimen were removed by this edge-treatment in combination with polishing of the edge but the compressive residual stress level was still low compared to the center of the HFMI-treated specimen. However, a significant improvement of fatigue life was determined for notched and welded specimens. The location of crack initiation shifts from the edge of the center of the specimen. SEM investigations of the fracture surface of the welded specimen shows that cracks also initiate at defects induced by HFMI-edge treatment. Thus, it is assumed that this kind of edge-treatment should be performed with an additional polishing of the edge and a removal of such crack-like defects.

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