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Fatigue strength of welded ultra high strength steels improved by high frequency hammer peening

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Abstract

Existing design recommendations for the influence of high frequency hammer peening (HFHP) on the fatigue strength are limited to maximum steel strengths of S960 and plate thicknesses of 5 mm and higher. The influence of HFHP on the fatigue strength of welded ultra high strength steels with yield strengths of 960 N/mm^2 and higher - loaded in low cycle fatigue (LCF) respectively upper finite fatigue life region - has not been investigated sufficiently so far. For this reason, the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen has performed fatigue tests on four different welded details a) butt weld, b) transversal stiffener, c) longitudinal stiffener and d) cover plates made of ultra high strength steels S960, S1100 and S1300 to determine the influence of HFHP on the fatigue strength. The fatigue strength of HFHP treated specimens was at least twice the fatigue strength of the as welded toe condition. In comparison with existing investigations for steel strengths S960 and lower, the results of the fatigue tests at HFHP-treated specimens showed the same trend: the slope of the S-N-curve increases to approximately m = 5. Furthermore, after HFHP treatment in some cases the location of crack initiation changes from the weld toe to the weld root or to notches in the base material.

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Keywords: high frequency hammer peening; post weld treatment; ultra high strength steels; low cycle fatigue; fatigue life improvement; crack initiation.

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1. Introduction

Currently, modern fine grained structural steels with yield strengths up to 1300 N/mm^2 are offered by steel producers. These ultra high strength steels are often used in mobile crane structures to reduce dead loads and to maximize the ratio of operative loads to dead loads. The lifetime of welded notch details used in these structures is limited due to applied fatigue loads during operation. Their fatigue life can be classified into the upper finite respectively low cycle fatigue life region. The fatigue design of welded steel joints according to EN 1993-1-9 (2010) and Hobbacher (2008) is independent from the yield strength. One possibility to improve the fatigue behavior is the application of post weld treatment methods like high frequency hammer peening (HFHP). The S-N-curves of as welded (m = 3) and HFHP treated (m =5) notch details intersect theoretically in the upper finite fatigue life region. The influence of HFHP on the fatigue behavior of welded UHSS with steel grades up to S1300 in the LCF and upper finite fatigue life region has not been investigated sufficiently so far.

2. State of the art

Existing fatigue design concepts do not consider an influence of the yield strength for fatigue design of welded steel joints. Fatigue tests at welded steel joints, that are the basis for fatigue classes in fatigue design rules, do not cover the LCF respectively upper finite fatigue life region of UHSS with yield strengths greater than 960 N/mm^2 sufficiently.

By the application of HFHP the weld toe surface is plastically deformed resulting in induced compressive residual stresses, cold hardening of the near surface area and rounding of the weld toe. The size of compressive residual stresses depends on the yield strength f_y of the treated material and increases with increasing yield strength. Residual stress measurements in Yildirim et al. (2013), Ummenhofer et al. (2011), Kuhlmann and Günther (2009) and Kuhlmann et al. (2006) show that compressive residual stresses at the treated surface transverse to the welding direction can reach values of approximately 75 % of f_y and values that are higher than f_y because local strength can be increased due to cold hardening. The application of HFHP results in a shallower slope of the S-N-line with m ~ 5 due to the modified residual stress state. The improvement effect of the fatigue strength due to HFHP treatment increases with increasing material´s yield strength as this is related to the higher induced compressive residual stresses at higher steel grades. Therefore, existing design recommendations for the consideration of the positive effect due to HFHP treatment propose fatigue class improvements depending on the steel grade (Haagensen and Maddox (2010), Dürr (2007), Ummenhofer et al. (2011), Yildirim (2013)). However, these design proposals are limited to maximum steel strengths of S960 and plate thicknesses of 5 mm and higher, see Fig. 1. Further investigations are necessary to transfer these design proposals to UHSS with steel grades S960 and higher.

The analysis of existing fatigue tests at as welded and HFHP treated notch details of UHSS shows demand for further research activities. Within this contribution the following questions will be clarified:

- How much is the influence of HFHP on the fatigue strength improvement at UHSS with yield strengths of 960 N/mm^2 and higher?
- At which loading cycles do the S-N-lines of untreated and of HFHP treated notch details intersect?
- Does the application of HFHP also result in a fatigue life increase in the LCF respectively upper finite fatigue life region?

3. Experimental investigations

Fatigue tests at ultra high strength fine grained structural steels S960, S1100 and S1300 have been performed to determine the influence of HFHP on the fatigue behavior of different welded notch details, see Table 1. The weld toe condition of the test specimens varied in as welded and HFHP treated. In total 119 fatigue tests have been performed. The test specimens have been produced from ultra high strength, waterquenched and tempered fine grained heavy plates of steel grades S960, S1100 and S1300 and with plate thicknesses of 4 mm to 8 mm. Before welding the plates have been cutted into stripes by water jet cutting to avoid influences due to thermal cutting. All test specimens have been welded manually by MAG process with filler material X90. Herewith, the nominal value of the yield strength of the filler material is below the yield strength of the base metal.

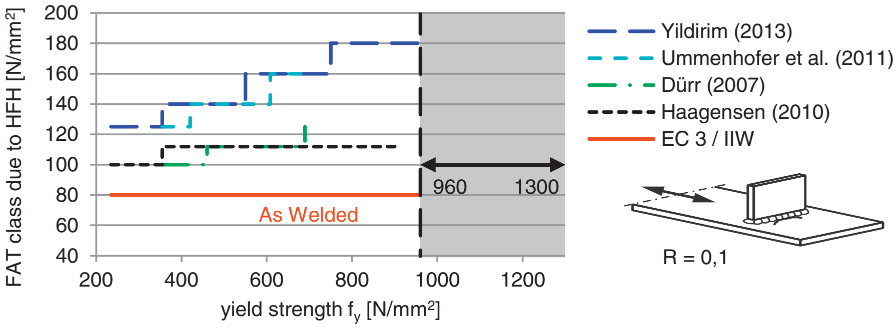
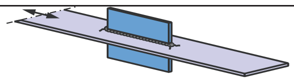
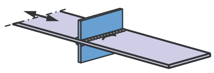
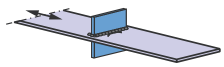
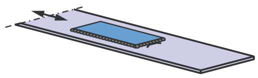
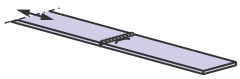
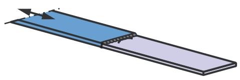


Fig. 1. Design S-N curves for HFHP treated notch detail of welded transversal stiffener according to different design proposals

Approximately half of all test specimens have been treated by HFHP at the weld toes, see Fig. 2. The HFHP treatment has been mainly performed by Pneumatic Impact Treatment (PIT) with 90 Hz and with radii of the indenters of 2 mm for the steel grades S960 and S1100 and 1,5 mm for S1300. Six specimens of test series S11-6-S have been treated by high frequency impact treatment (HiFIT) with a radius of indenters of 1,5 mm.

The fatigue tests have been performed with constant load amplitudes and with a stress ratio of R = 0,1. The fatigue loads were iteratively determined in order to reach loading cycles until failure of 10,000 to 40,000 for the as welded specimens to cover the LCF as this fatigue life region is an important operational region of the investigated steel grades, especially regarding fatigue stressed components of mobile crane structures. The HFHP treated specimens have been tested at the same fatigue loads to compare the loading cycles N_f to that ones of the as welded toe condition.

Table 1. Test programme

Notch detail		Test series	No. of tests [1)]	Steel grade	t [mm]	σ_{max} / f_y
Longitudinal stiffener		S11-6-LS	5 / 6	S1100	6	25-55 %
		S13-4-LS	5 / 5	S1300	4	30-50%
Transversal stiffener		11-6-QSd	5 / 6	S1100	6	45-70 %
		11-6-QS	5 / 5	S1100	6	35-75 %
		S13-4-QS	5 / 5	S1300	4	30-50 %
Cover plate		96-7-La	4 / 5	S960	7,5	40-65 %
		S11-6-La	6 / 6	S1100	6	30-55 %
		S13-4-La	5 / 5	S1300	4	30-45 %
Butt weld		96-7-S	4 / 4	S960	7,5	35-65 %
Butt weld with transition in thickness		S11-6-S	6 / 12	S1100	6 / 8	35-60 %

[1)] Number of tests in as welded respectively high frequency hammer peened toe condition.

4. Experimental results and discussion

As expected all as welded specimens failed due to crack initiation from the weld toes to the base material. Due to HFHP treatment the crack initiation changes in 32 % of all cases to edge or surface notches in the base material or the clamping area (transversal stiffener) or the weld root area (longitudinal stiffener and cover plate). This crack

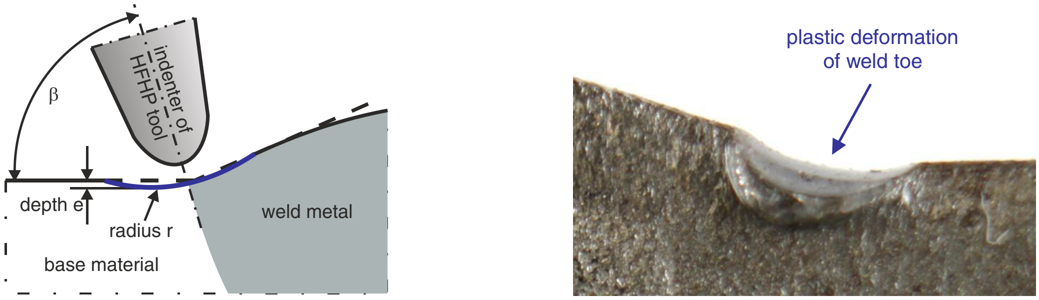


Fig. 2. Local application of high frequency hammer peening at weld toe region

initiation change mainly occurs at relatively low stress ranges as the induced compressive residual stresses do not relax the same way as at higher loads. For the notch detail of welded transversal stiffener of S1100 only 2 of 11 HFHP treated specimens failed due to crack initiation from the weld toes. Consequently, especially at lower stress ranges the fatigue life of HFHP treated weld toes can be limited due to adjacent notches in the base material or in the weld root.

The loading cycles until failure for as welded specimens range from 5,000 to 110,000 and cover the LCF and upper finite fatigue life region. The statistical analysis of test results from all as welded test specimens shows good agreement with relative FAT classes according to EC 3 (EN 1993-1-9 (2010)) and IIW (Hobbacher (2008)), see Fig. 3. As expected, the yield strength does not influence the fatigue strength of as welded specimens.

The loading cycles N_f of HFHP treated specimens increase rapidly in comparison to the as welded toe condition. Due to an increasing influence with decreasing stress range the slopes of the S-N-lines are much shallower than for the as welded toe condition. With exception of the notch detail of transversal stiffener (test series 11-6-QSd, 11-6-QS) with mainly crack initiation from notches in the base material or clamping area, the slope of the S-N-lines increases to m ~ 5. The mean value of the fatigue strength $\Delta\sigma_m$ has been evaluated with a fixed slope of m = 3 for the as welded and m = 5 and additionally with variable slope for the HFHP treated toe condition for each test series, see Fig. 3. Because of the relatively low number of fatigue tests per test series all results of each test series have been used for the statistical analysis which includes results with crack initiation from different notches.

In comparison to the as welded toe condition, the mean value of the fatigue strength $\Delta\sigma_m$ increases due to HFHP treatment by factors of 2,16 to 2,65 when a fixed slope of m = 5 is used. An influence of the yield strength on the fatigue strength improvement can be observed for the notch details longitudinal stiffener and butt weld where the fatigue strength improvement increases by approximately 15 % and 10 % with an increase of yield strength from 1100 to 1300 N/mm^2 (longitudinal stiffener) respectively 960 to 1100 N/mm^2 (butt weld). The results of notch details transversal stiffener and cover plate do not show any increasing effect of HFHP treatment with increasing yield strength.

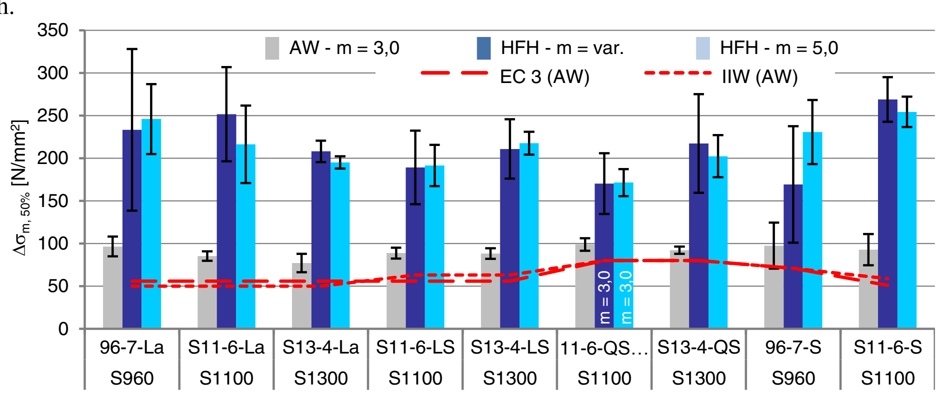


Fig. 3. Comparison of the fatigue strengths $\Delta\sigma_{m,\,50\,\%}$ with the FAT classes according to EC 3 and IIW

The loading cycles until failure of the test specimens with as welded respectively HFHP treated toe condition are shown for each notch detail in Fig. 4. The loading cycles intersect theoretically in the LCF region with loading cycles from 3,300 to 4,700 depending on the notch detail. In the upper finite fatigue life region with loading cycles N_f of 10,000 to 40,000 for the as welded toe condition, the fatigue live can be improved by factors of 2 to 10 due to HFHP treatment.

Due to different plate thicknesses and partially different local weld geometries the influence factor of the yield strength cannot be analyzed explicitly. At relatively low plate thicknesses it is assumed that the residual stress state due to HFHP treatment cannot be realized in the same way as at larger plate thicknesses. The scatter of local weld geometries at different test series and partially observed angular distortion due to the low plate thicknesses are not covered on the action part within the nominal stress design concept which influences the comparability of test results. Furthermore, all specimens have been welded with the filler material X90. Therefore, the strength at local weld toe which influences the compressive residual stresses due to HFHP treatment is limited by the material properties of the filler material.

The classification of the test results for the HFHP treated toe condition shows that proposed FAT classes of design recommendations are conservative. The results of HFHP treated specimens of notch details cover plate and butt weld with transition in thickness are displayed in Fig. 5 considering design S-N-lines of the different design proposals. The results at HFHP treated cover plates show that existing recommendations according to Haagensen and Maddox (2010) are too conservative especially in the finite fatigue life region. A further improvement of the fatigue class due to HFHP treatment with a change of the slope to m = 5 is possible if crack initiation from the weld root side can be excluded. The design proposal of Yildirim (2013) shows the best agreement with the test results of all other notch details because this approach covers yield strengths up to 960 N/mm^2.

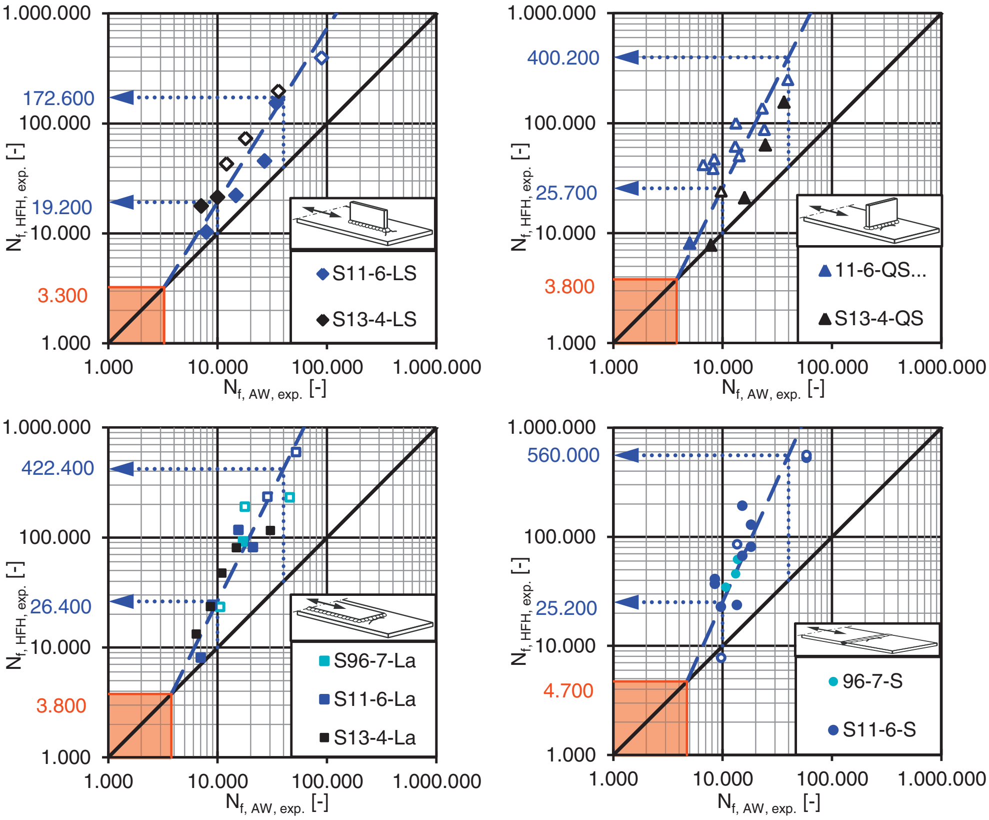


Fig. 4. Comparison of loading cycles until failure of the test specimens with as welded respectively high frequency hammer peened toe condition

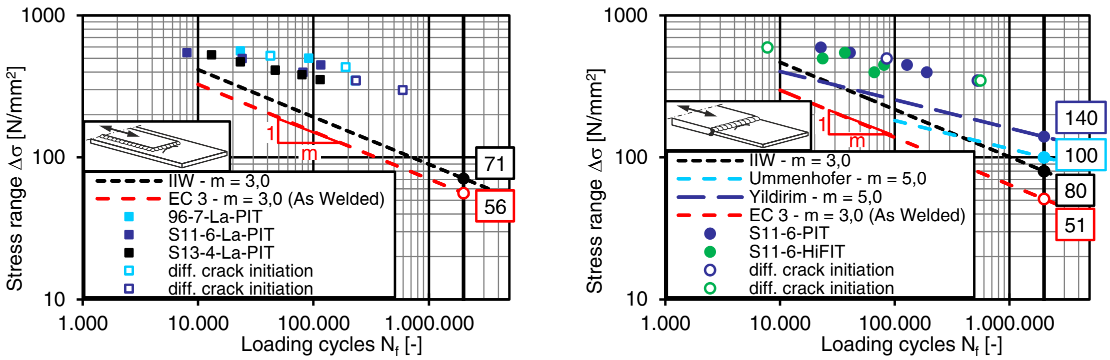


Fig. 5. Comparison of test results in existing design proposals for high frequency hammer peened toe condition

For the notch detail of butt weld with transition in thickness a further improvement to FAT class 160 is possible, see Fig. 5. During design of HFHP treated weld toes adjacent notch details like cut edges or weld roots can be relevant for design which limit the lifetime of cyclic loaded structures.

5. Conclusions

Within this contribution the results of fatigue tests at as welded and HFHP treated specimens of UHSS S960, S1100 and S1300 have been discussed. The slopes of the S-N-lines of HFHP treated specimens increase to m ~ 5 when crack initiation starts from weld toes. The fatigue strength of HFHP treated specimens was at least twice the fatigue strength of the as welded toe condition. For the notch details longitudinal stiffener and butt weld the fatigue strength improvement increases by approximately 15 % and 10 % with an increase of yield strength from 1100 to 1300 N/mm^2 (longitudinal stiffener) respectively 960 to 1100 N/mm^2 (butt weld). Due to different slopes the S-N-lines of as welded and HFHP treated toe conditions intersect theoretically at approximately 4,000 loading cycles. In the LCF region with loading cycles N_f of 10,000 and 40,000 for the as welded condition the fatigue life due to HFHP treatment can be increased by the factors 2 and 10 depending on the notch detail and yield strength. Existing design recommendations for the consideration of HFHP treatment are conservative in comparison to the test results at HFHP treated specimens. Further investigations are necessary to prove the influence of HFHP treatment at variable amplitude loading considering overloads and preloads.

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