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Fatigue behaviour of high frequency hammer peened ultra high strength steels

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ABSTRACT

Existing design recommendations for the consideration of high frequency hammer peening (HFHP) are limited to steel grades of S960 and plate thicknesses of 5 mm and higher. The influence of HFHP treatment on the fatigue behaviour of welded ultra high strength steels with yield strengths of 960 MPa and higher – loaded in the upper finite and low cycle fatigue life region – has not been investigated sufficiently so far. For this reason, fatigue tests have been performed on four typical welded notch details of mobile crane structures made of 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. A fatigue life improvement due to HFHP treatment can be observed at load cycles of 10,000 and higher. In accordance with existing investigations, the slope of the *S*–*N*-line increases to approximately $m \sim 5$ due to HFHP treatment if the fatigue cracks start from the treated weld toes. The classification of the test results for the HFHP treated toe condition shows, that fatigue classes (FAT) of existing design proposals are conservative. Further improvements of the proposed FAT classes are possible which shows the potential use of UHSS with steel grades higher than S960 in combination with HFHP treatment.

1. Introduction

The fatigue behaviour of welded steel joints is predominated by crack propagation from crack like imperfections at the weld toe and weld root regions. Therefore, the fatigue design of welded steel joints is independent from the yield strength according to different design rules [1,2]. Existing FAT classes for welded joints base predominantly on fatigue tests covering the mid and lower part of the finite fatigue life region. Currently, modern ultra high strength fine grained structural steels (UHSS) with yield strengths up to 1300 MPa are offered by steel producers. The use of UHSS in welded, fatigue loaded structures is only reasonable for applications with high dead loads or high stress ranges like mobile crane structures, see Fig. 1a. Due to applied fatigue loads during operation the lifetime of these welded structures, see Fig. 1b, is limited and can be classified into the upper finite and low cycle fatigue (LCF) life region. One possibility to improve the fatigue behaviour is the application of post weld treatment methods like high frequency hammer peening (HFHP). HFHP mainly induces compressive residual stresses in the treated weld toe region resulting in a translation and a rotation of the *S*–*N*-curve. Therefore, the *S*–*N*-curves of as welded ($m \sim 3$) and HFHP treated ($m \sim 5$) notch details intersect theoretically in the upper finite fatigue life region. Up to now, the influence of HFHP on the fatigue behaviour has mainly been investigated on steels with yield strengths less than or equal to 960 MPa within research activities. Consequently, existing design recommendations for the influence of HFHP on the fatigue strength are limited to steel grades of S960 and plate thicknesses of 5 mm and higher. For this reason, further investigations on four mobile crane typical notch details have been performed to transfer the results and applicability of HFHP to welded UHSS with steel grades up to S1300 and plate thicknesses higher than or equal 4 mm in the LCF and upper finite fatigue life region.

2. State of the art

2.1. High frequency hammer peening

High frequency hammer peening represents an advancement of common hammer peening methods [3,4] concerning its effectiveness, Fig. 2(a) and (b). In comparison to established post weld treatment methods like grinding, TIG dressing or shot

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Nomenclature

σ	nominal stress
$\Delta\sigma$	nominal stress range
$\Delta\sigma_C$	reference value of fatigue strength at 2×10^6 load cycles corresponding to 95% survival probability
$\Delta\sigma_m$	mean value of fatigue strength at 2×10^6 load cycles corresponding to 50% survival probability
AW	as welded
EC 3	Eurocode 3 – EN 1993-1-9
f_y	yield strength
FAT	fatigue class referred to *S*–*N*-line of fatigue design standards, which is the stress range in MPa at 2×10^6 load cycles corresponding to 95% survival probability
HFHP	high frequency hammer peening
HiFIT	high frequency impact treatment
IIW	International Institute of Welding
LCF	low cycle fatigue
m	slope of *S*–*N*-line in finite fatigue life region
n	number of fatigue tests
N_f	load cycles until failure
$N_{f,\text{AW,exp.}}$	load cycles until failure of the test specimens with as welded toe condition
$N_{f,\text{HFHP,exp.}}$	load cycles until failure of the test specimens with high frequency hammer peened toe condition
PIT	Pneumatic Impact Treatment
R	stress ratio defined by $\sigma_{\min}/\sigma_{\max}$
t	plate thickness
UHSS	ultra high strength steels

peening, HFHP yields in a combined effect of weld toe rounding, modification of the residual stress distribution and edge layer hardening. The influence of HFHP on the fatigue behaviour of welded joints has been increasingly investigated scientifically in the past years. By the application of HFHP the local, critical weld toe surfaces are plastically deformed, Fig. 3. The depth e of the treatment line is approximately 0.1–0.3 mm [5–8] and depends on the geometric shape of the indenter's tip and predominantly on the strength of the treated material and its hardness, respectively. The plastic deformation of the weld toe region results in cold hardening of the near surface microstructure. Micro hardness measurements show that the hardened zone can reach depths up to 1.5 mm [7,9]. The application of HFHP yields a modified residual stress state by inducing compressive residual stresses influencing the fatigue behaviour of the treated weld toes significantly. Compressive residual stresses transverse to the welding direction are decisive for the effectiveness of the treatment method as these stresses superimpose with the stresses resulting from operational fatigue loads. The magnitude of compressive residual stresses depends on the yield strength f_y of the treated material and increases with increasing yield strength. Residual stress measurements [5–8,10–14] show that compressive residual stresses at the treated surfaces transverse to the welding direction can reach values of approximately 75% of f_y and values that are higher than f_y because the local strength can be increased due to cold hardening. Induced compressive residual stresses can appear up to a depth of 1–2 mm from the treated surfaces. The plastic deformation of the weld toe geometry can also result in rounding of the weld toe decreasing the local stress concentration.

The *S*–*N*-lines of HFHP treated notch details have a shallower slope with $m \sim 5$ in comparison to FAT classes of as welded notch details with $m \sim 3$, Fig. 4. This rotation of the *S*–*N*-line can be attributed particularly to the modified residual stress state resulting in an extension of the crack initiation period. In highly stressed structures, e.g. with high stress peaks or high mean stresses, residual stresses can relax resulting in a decrease of the beneficial effect of HFHP. In addition to the rotation of the *S*–*N*-line, the reference fatigue strength $\Delta\sigma_C$ translates to higher fatigue strengths, Fig. 4. The favourable effect on the fatigue strength due to HFHP treatment increases with increasing material's yield strength [15] as this is related to the higher induced compressive residual stresses for higher steel grades.

2.2. Fatigue design concepts considering HFHP treatment

The positive effect of a HFHP treatment on the fatigue strength of a welded notch detail is actually not incorporated into the fatigue design rules, yet. However, within the literature different proposals exist to consider the influence of a HFHP treatment. Here, the FAT class (detail category) of the as welded notch detail is increased by an improvement factor k depending on the steel grade, the geometry of the notch detail, the stress ratio R, the applied stress level and, if applicable, the slope of the *S*–*N*-line is increased to $m = 3.5$ [16] or $m = 5$ [3,6,17,18]. In order to be consistent with the uni-spaced FAT classes of fatigue design guides [1,2] the fatigue strength improvement can be also expressed by an improvement of the reference FAT class of the as welded toe condition to the next higher FAT classes. The yield strength dependent,

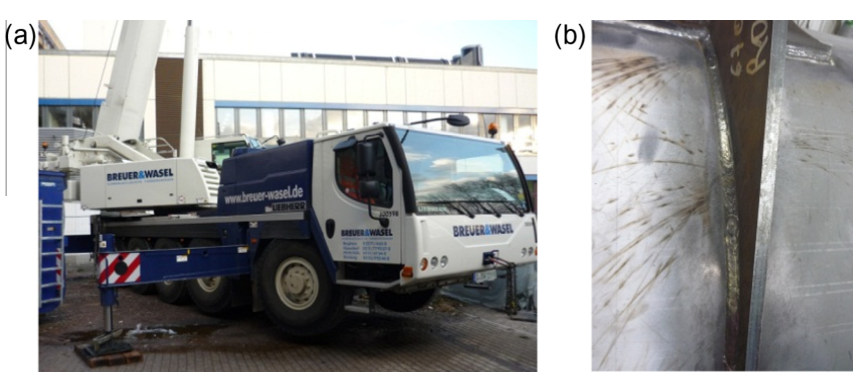

Fig. 1. Application of ultra high strength fine grained structural steels in mobile crane structures (a) and detail of a telescopic boom with welded stiffeners on a box-girder (b).