Fatigue design concepts for welds improved by high frequency hammer peening methods

Ummenhofer, T., Weich, I. [a]

[a] Institute of Rehabilitation of Buildings and Structures
Technical University of Braunschweig, Braunschweig, Germany

Abstract Research has been initiated on the effects of high frequency peening methods on the fatigue strength of welded connections. The investigated methods combine an improvement of weld toe profile with an initiation of compressive residual stresses and surface hardening. The results of two different procedures, High Frequency Impact Treatment (HiFIT) and Ultrasonic Impact Treatemnt (UIT) are compared. Laser measurements of the weld seam prove that these methods increase the overall weld toe radii. Further, residual stress measurements verify the introduction of compressive residual stresses at least up to a depth of 1 mm. The values meet the yield strength combined with an increase of the surface hardness. These material mechanical effects cause an increased crack resistance. Applied crack detection methods prove that the material mechanical effects yield to a retarded crack initiation. Fatigue tests show that these effects lead to a significant increase of the fatigue strength and reduced slopes of the SN-curves. Design methods which consider the positive effects of the improvement methods have to be developed. As an alternative to new generated experimental SN-curves, local concepts can be adapted to describe the effects of post weld treatments for various details. In this paper a concept based on the notch stress method is presented. The change of the weld toe geometry is respected by simulating the shape of the measured weld toe. The material mechanical effects are also incorporated in the model. For the fatigue strength calculation the effect of the residual stresses is compared to mean stresses, taking into account the residual stress relaxation under fatigue loading. As another simple method a local concept is presented, which considers the mechanical effects by applying reduction factors to the local fatigue strength. The concept has been developed for heat treated material but will be quantified in further fatigue tests for welded details treated by high frequent peening methods.

1 INTRODUCTION

The percentage of fatigue loaded structures in mechanical and civil engineering is high. Therefore, the fatigue strength of structural details are of great importance regarding the design. Due to the fact that welding has become one of the most important joining methods for steel constructions the reduced fatigue strength of welded connections has to be considered during design and often becomes decisive for welded constructions, i. e. for steel bridges, cranes or wind energy plants. In order to produce more economical constructions the fatigue strength of these details has to be increased. Secondly, the use of high strength steel is limited because the fatigue strength of welded high strength material is not higher than for common steel according to design codes. Therefore, methods which can increase the fatigue strength of welded structures have been investigated in the last decades. The results show that various weld improvement methods may have different beneficial effects. Recently, investigations focused on the effect of high frequency peening methods which seem to be very promising combining a geometrical improvement with an increase of the material resistance. In order to include these beneficial effects into the design rules, new SN-curves have to be derived by broad fatigue tests for various details. Alternatively local concepts are required so that the fatigue strength can be calculated for various details without conducting extensive tests. This paper describes the effects of high frequency peening methods and proposes design approaches based on finite element calculations and local fatigue strength approaches.

2 HIGH FREQUENCY PEENING METHODS

During the application of high frequency peening methods like the High Frequency Impact Treatment (HiFIT), Ultrasonic Impact Treatment (UIT) or Ultrasonic Peening (UP) hardened metal pins bounce with frequencies higher than 200 Hz against the metal surface and cause plastifications. The treatment is usually applied at the weld toe so that the weld toe is smoothened. Furthermore, the surface hardness is increased and compressive residual stresses are introduced. The pin diameters range between 2 and 5mm. The devices differ in their acceleration: the HiFIT device is an air driven tool using only one pin whereas two to four pins of the UIT

(Figure 2) and UP-devices are accelerated by ultrasound. The statement of the manufacturers that the ultrasound also influence the material structure could not be proved yet.

2.1 Fatigue strength

Recently research has been initiated on the effect of UIT and HiFIT on the fatigue strength of different welded details. The results proved that these methods combine a geometrical improvement with material mechanical improvements of the weld toe (1, 3, 12, 15). These effects lead to a high increase of the fatigue strength.

Several tests on 8 to 30 mm thick specimens of steel grade S355J2G3, S460TM and S690Q with butt welds and welded transverse stiffeners have been conducted by Ummenhofer et al. (15, 16). The fatigue strength could be doubled by applying UIT at the weld toe. Further more, it could be shown that the slope of the SN-curves of the UIT-treated specimens for the lower steel grades is noticeable flatter than for as welded specimens.

Tests of UIT-treated cruciform fillet welded specimens of steel grade S460 and S690 (7), showed that TIG-dressing and UIT can increase the fatigue strength of these details especially for high load cycles respectively smaller stress ranges. The improvement rates raised with higher yield strength of the basic material. First tests on full scale girder specimens indicate that the increase of the fatigue strength of transverse stiffeners is about 35% lower in comparison to the small test specimens.

Roy (12) showed a beneficial effect of UIT on the fatigue strength for cover plates and transverse stiffeners in small and large scale specimens that. An increase of the US-FAT-classes of these details for the infinite life by 1 to 2 classes (50 to 100%) and for the finite life by 0 to 1 class (meaning an improvement of 0 to 50%) has been proposed depending on the stress range and structural detail.

Investigations on one-sided and two-sided longitudinal attachments (8) proved that the fatigue strength at 2 Mio. load cycles based on a fixed slope of the S-N-curve of three can be increased by 45-50% applying UIT.

2.2 Design

Commonly, the fatigue design of welded structures is performed by the nominal stress approach, which is based on experimentally verified SN-curves. Regarding the IIW-Recommendations improvement factors for welds improved by different weld improvement methods are given, which linearly increase the fatigue strength. Besides this fatigue design concept design approaches based on the calculation of local notch stresses have been developed. Here, the structural stress concept, the notch stress approach and the notch strain approach can be named. The local stress- and strain approach respect for the local weld seam geometry so that local notch stresses can be calculated. These methods can be applied for any detail. For as welded details a fictive radius of 1mm has been proposed by Neuber (9) for any notch (i.e. at the weld toe and the weld root) in order to consider the smallest possible notch sizes. Studies by Olivier, Köttgen and Seeger (11) showed that this fictive radius of 1mm is in good agreement with the real mean of weld toe radii of weld specimens. The local stress approach is based on linear elastic finite element calculations. A FAT class of 225 for the local fatigue strength of welded details has been determined by Olivier, Köttgen and Seeger (11) in various tests.

Alternatively, the local strain approach considers the local strains based on the cyclic stress strain curves of the base material. The fatigue life until crack initiation is calculated. In order to define the final fatigue life, fracture mechanics has to be applied. The influence of surface hardening has been investigated by Seeger, Heuler (14). They included the influence of residual stresses by applying inherent strains to a thin surface layer. The surface hardness has been respected by considering the material properties of the hardened material for the surface layer.

Studies on the application of local approaches for welds which have been improved by high frequency peening methods have been published.

Roy (12) proposed a simplified stress life approach in order to respect the effects of UIT. Assuming linear elastic material behaviour the critical notch stresses have been determined by finite element calculations, respecting the local weld geometry. The residual stresses have been considered as mean stresses.

The notch strain approach combined with fracture mechanics has been applied by Dürr (3) and Lihavaien (8) in order to calculate the fatigue life of UIT-treated stiffeners. The cyclic material behaviour has been assumed based on the uniform material law. The notch factor has been estimated by a finite element model using Neuber's notch radius. The residual stresses have been considered by Neuber's approach, including the inherent strains before loading. The crack propagation model is based on experimentally determined crack propagation rate. In his study residual stresses are also valuated like mean stresses.

Nitschke-Pagel and Wohlfahrt (10) proposed a local fatigue strength approach for welds improved by post weld treatments based on a model developed for heat treated non welded steel. This existing model considers that every local element of a structure has its own fatigue strength which is correlated to the ultimate tensile strength and the residual stresses. Taking into account that the ultimate strength depends linearly on the hardness, Nitschke-Pagel and Wohlfahrt (10) proposes to adapt this model to post weld treated details, calculating the local fatigue strength depending on the depth beneath the treated weld toe. The influence of the hardness and of the residual stresses shall be weighted by influence factors.

3 RESULTS

3.1 Mode of functioning

Investigations on butt welds out of S355J2 and S690Q allowed to systematically analyzing the local effects of high frequency peening methods.

The geometric effect of the UIT and HiFIT procedure on the weld toe radius has been analysed by measuring the weld profile with a laser triangulation sensor system. Both methods cause plastic deformations which yield to a weld toe radius which strongly depends on the pin diameter. The commonly used 3mm pins yield to notch radii of 2 to 3mm and cause a smooth transition. Fig. 1 left shows the weld toe geometry in the as

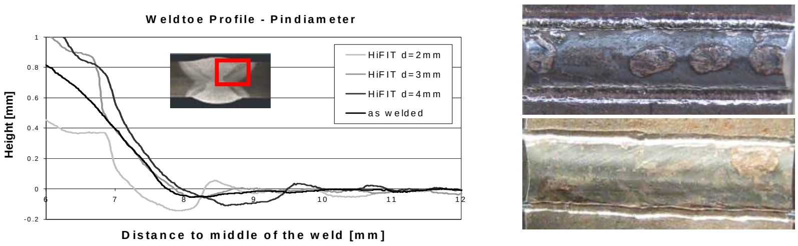

Figure 1. Weld toe profile before and after the treatment with different pin diameters (left), weld toe after UIT(upper right) and HiFIT (lower right)

welded state and after HiFIT treatment with various pin diameters. 2mm pins lead to deeper indents and smaller radii. Fig. 1 right shows pictures of the weld toe after HiFIT and UIT treatment. UIT causes single indents which may lead to single flaking of the surface material. But because these cracks are oriented parallel to the surface they do not cause an early crack initiation. HiFIT produces a smooth groove. The plastically deformed microstructure of the material edge layers after both treatments is similar.

Secondly, the treatment results in an increased surface hardness. This leads to an increase of the crack initiation resistance. Fig. 2 left shows the Vickers hardness after HiFIT and UIT-treatment of a weld toe of the S690 and S460TM butt weld specimens. The hardness is increased from 225HV to 325 HV (S460TM) and from 250 HV to 350 HV (S690Q). Furthermore, the treatment produces compressive residual stresses in the surface layers. These compressive residual stresses increase the crack resistance and retard crack propagation. Both methods induce high compressive residual stresses. The UIT-treatment causes compressive transverse residual stresses up to 450 MPa (steel S460 TM) respectively 500 to 700 MPa (steel S690Q). The results of the HiFIT procedure show transverse residual stresses of 450 to 600 MPa (steel S690Q). The maximum of the residual stresses occur due to the Hertzian stress approximately 0.2 to 0.4mm underneath the surface. Results of the whole drilling method prove that HiFIT and UIT produce transverse residual stresses higher than 200 MPa up to 1.2 mm for steel grade S690Q. For the butt weld S460TM nearly constant residual stresses after UIT-treatment could be shown up to a depth of 0.5mm, up to 1mm depth residual stresses of 100 MPa have been measured. Investigations of the residual stress relaxation prove that under practical relevant cyclic loading no residual stress relaxation occurs.

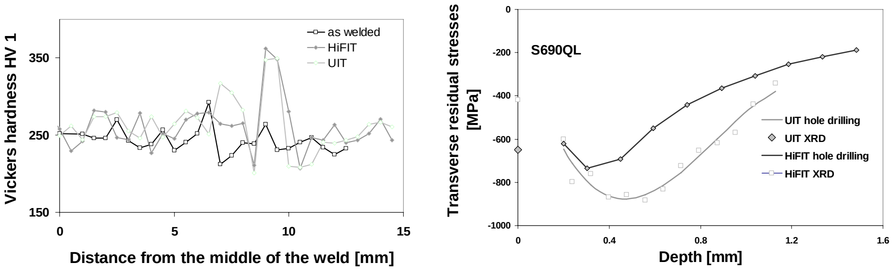

Figure 2 Vickers hardness (left) and residual stress profile (right)

3.2 Fatigue Strength

The effects of the peening methods on the fatigue strength have been analyzed by fatigue tests which have been performed on butt welds, transverse and longitudinal stiffeners. The test results showed that the fatigue strength could be doubled by applying high frequency peening methods. Fig. 3 shows exemplarily the SN-curves for as welded and UIT / HiFIT-treated butt welds steel grade S460TM and S690Q compared to the FAT class in the Eurocode. The SN-curves have been calculated with a free adjusted slope for a survival probability of 95% with a confidence level of 75%. The calculated fatigue strength could be increased from 90 MPa (S460) respectively 106 MPa (S690) for the as welded both details to 200 MPa after the treatment. The cracks of the as welded specimens as well as the UIT-treated specimens occurred at the weld toe in the treated zone. Single cracks in the UIT- and HiFIT-treated S690Q butt welds occurred in the basic material. The UIT-treated S460TM specimens feature a flatter slope of the SN-curve, with a calculated slope m=7.5. For the S690 specimens a slope of m=3 has been calculated. The influence of the steel grade on the slope of the SN-curves has to be analysed more detailed. The different slopes depending on the steel grade have also been determined by Dürr (3) for transverse stiffeners. In his study he determined a slope of m=5.2 for transverse stiffeners with UIT-treated welds out of steel grade S460 and a m=3 for the same details out of S690. In the experiments published in this paper the applied maximum load stresses do not cause notch stresses larger than the yield strength for the S690Q but are at least close to the yield strength for the S460TM. Analyses for treated specimens out of S690Q prove that the induced residual stresses are nearly constant for comparable load levels. Therefore, the improvement rates of the HiFIT or UIT-method are independent of the load level and therefore result in a slope similar to the slope of the as welded state. For the S460TM the assumption arises that due to plastification a residual stress relaxation may occur, so that the beneficial influence of the improvement methods is limited for higher upper load levels. This may lead to the flatter SN-curves.

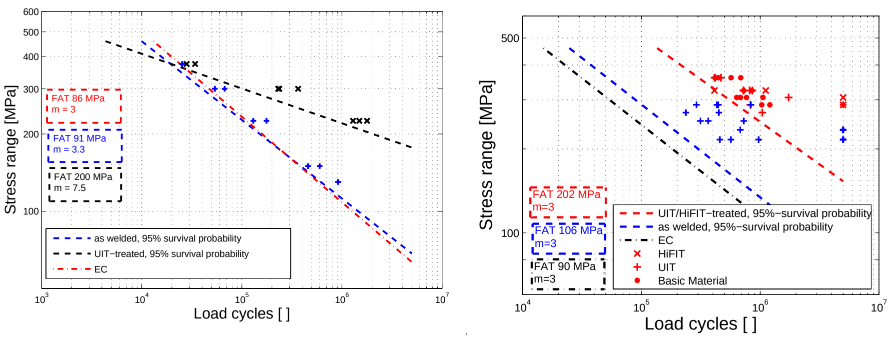

Figure 3. Experimentally derived SN-curves for butt welds S460TM (left) and S690Q (right)

4 DESIGN

4.1 Adaptation of existing design rules

In order to consider the beneficial effect of the peening methods in the design of structures different approaches can be used. Of course the experimentally derived SN-curves for tested details can be used and the design can be based on the nominal stress approach. For different details for which no tests are available an approach would be to derive fixed improvement factors. This approach is already manifested in the IIW recommendations for postweld treated details (5). Improvement factors which shift the SN-curves parallel to higher strengths are given depending on the improvement method. High frequency peening methods are not especially named. For hammer peened welds a factor of 1.6 for steel grade higher than 355 MPa and a factor of 1.3 for lower grade steel are proposed. The maximum FAT class is limited to 125 respectively to 112 for lower grade steel. As a first approach the given data for hammer peened details are applied to the tested butt welds. For both steel grades this results in a FAT class of 142, but has to be reduced to the maximum allowed class of 125. The experimentally derived SN-curves are compared to the IIW-recommendated curves assuming a slope of m=3 and also of m=5 in order to account for the change of the slope due to the treatment. For the S460TM specimens an SN-curve with a slope of m=3 underestimates the improvement for low stress ranges but overestimates the fatigue strength for higher stress ranges due to the small gradient of the experimental SN-curve. Regarding the results for the S460TM butt welds the assumption of a FAT-class of 125 is conservative up to a stress range of 300 MPa. Applying a slope of m=5 to the improved FAT-classes both assumptions show conservative results. The fatigue life is underestimated 4 to 8 times depending on the load level. Regarding the results for the S690Q butt welds the assumption of the IIW recommendations with a slope of m=3 are conservative for the experimental derived SN curves with free calculated slopes of 3 (Fig. 4). It is obvious that the assumed slope has a significant influence on the correctness of the fatigue life assumption.

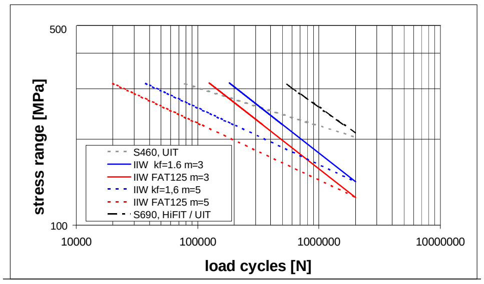

Figure 4. Calculated SN-curves respecting IIW improvement factors

As shown above besides the nominal stress approach local approaches based on finite element calculations can be used to compute the fatigue life. In this case the notch stress approach is used respecting the measured weld toe radius after the treatment assuming a FAT class of 225. An averaged weld toe radius after the treatment of r=2.5mm is applied and leads to a notch factor of 1.9. Based on a slope of m=3 and a slope of m=5 the load cycles are calculated and plotted versus the nominal stress. Fig. 5 left (slope m=5) and right (slope m=3) present a comparison between the calculated SN-curves and the experimental results. Fig. 5 shows that the calculated SN-curve with a slope of m=3 is very conservative for the S690Q UIT and HiFIT treated specimens. Due to the flatter slope of the S460TM treated welded details the fatigue strength is calculated assuming a slope of m=5. This leads to very conservative results (see Fig. 5).

As discussed already in chapter 3 the beneficial effect of the high frequency peening methods is not only based on the geometrical effect but also on the introduction of residual stresses and an increase of the surface hardness. Therefore, this effect also has to be respected in the simulation. The compressive residual stresses are calculated by simulating the peening process assuming elastic plastic material behaviour. In a second step the fatigue loading is applied. Usually mean stresses are not considered in the design of fatigue loaded welded details in order to respect that during welding tensile stresses are induced so that even under compressive loading tensile effective stresses might occur. As the peening methods induce defined compressive residual stresses a consideration of mean stresses in the treated zone seems to be acceptable. In this case the mean stresses result from the superposition of the residual stresses and the load stresses assuming that no stress relaxation occurs.

Due to the minor influence of compressive stresses on the fatigue strength the EUROCODE (2) proposes to consider only 60% of compressive stresses for unwelded or stress relieved details. This approach is adopted to the HiFIT-/UIT-treated case considering the FAT-class 225 as local fatigue strength for the calculated notch stresses (see Fig. 5). The calculated load cycles are plotted versus the nominal stress range. The slope of this calculated SN-curves differs from the slope used for the FAT class 225 because in this concept for each load level only 60 % of the compressive stresses are considered. The results very well fit for the S460TM details. The results for the S690Q details fit very well the experimentally determined SN-curve of the HiFIT/UIT-treated specimens.

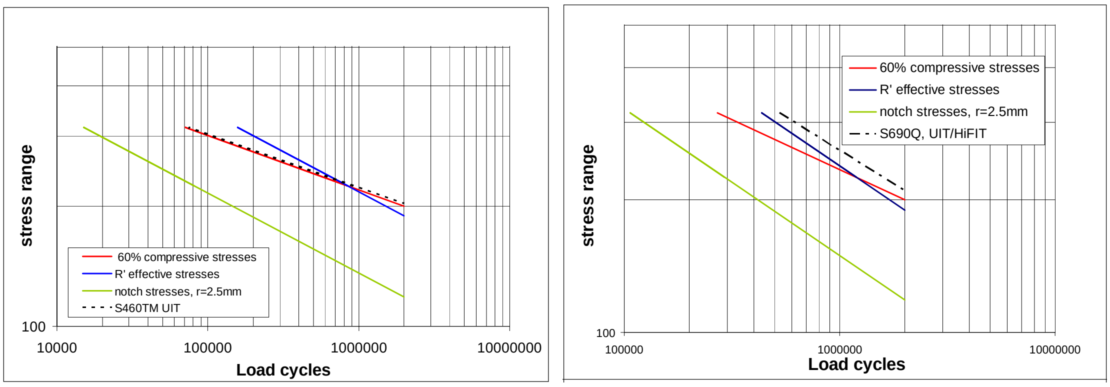

Figure 5: Calculated SN-curves based on notch stresses and experiment, butt weld S460TM m=5 (left), butt weld S690Q m=3(right)

Alternatively the concept of the IIW recommendations (6) which respect the mean stresses by regarding the applied stress ratio are analyzed. For base material as well details with negligible residual stresses it is recommended to apply the following improvement factors:

$f(R) = 1.6$ for $R < -1$ (1)

$f(R) = -0.4 \times R + 1.2$ for $-1 \leq R \leq 0.5$ (2)

$f(R) = 1.6$ for $R > 0.5$ (3)

In the experiments a stress range of R=0.1 has been applied. Up to an upper nominal load stresses of 350 MPa the effective stress range for the effective notch stresses R’ at the weld toe is smaller than -1 so that an improvement factor of 1.6 can be applied to the FAT class 225 for the local fatigue strength. The results also very well match the experimentally determined results for the S690 Q, being slightly less conservative as the results calculated based on the Eurocode (Fig. 5). The fatigue strength of the S460TM estimated with a slope of m=5 is overestimated for load stress ranges higher than 225 MPa due to the very flat slope of the experimentally derived SN-curve (Fig. 5).

4.2 Local approach

Another approach has been in general described by Nitschke-Pagel and Wohlfahrt (10) for post weld treated welds. Here, the effects of the treatment are respected by increasing the material resistance. The compressive residual stresses as well as the increase of the surface hardness are respected by improvement factors which are applied to the general endurance limit, resulting in a local fatigue endurance limit. The general formula is given underneath:

$$R_D^{RS,HV,R_t} = R_W^{O} + h \cdot \Delta HV - m \cdot \sigma^{RS} - t \cdot \Delta R_t \quad (4)$$

In this formula the surface roughness is included besides the influence of the hardness and residual stresses. The influence factor for the residual stresses has to take into account the residual stress sensitivity of the material. This sensitivity strongly depends on the material properties. Consulting the Goodman correlation (4) for the influence of mean stresses on the fatigue strength:

$$R_D^{m} = R_W^{O} - \left(1 - \sigma_m / R_m\right) \quad (5)$$

R_D^{m} local fatigue strength respecting mean stresses

σ_m mean stress

The factor m for the mean stress influence can be assumed as

$$m = R_W{}^{O} / R_m \tag{6}$$

The ultimate strength R_m depends on the measured surface hardness can be calculated as follows:

$$R_m = 3.29 \cdot HV - 47 \tag{7}$$

Using this approximation the material the effect of the treatment on the ultimate strength due to surface hardening on the mean stress sensitivity can be respected. The influence of the residual stresses is considered in the same way as mean stresses would be. This assumption can only be made in case no stress relaxations occurs during fatigue loading. Due to pure tensile fatigue loading nearly constant compressive residual stresses can be assumed for this load case because no material nonlinearities due to the addition of compressive load and residual stresses can occur. Own experimental results prove this for test specimens treated with the HiFIT method. In other cases a possible residual stress reduction during loading has to be considered.

Scholtes (13) also describes the influence of edge layer hardening on steel with different initial surface hardness. The positive effect of a certain increase of the surface hardness is higher for material with lower initial hardness. A correlation between the surface hardness and the endurance strength of welded details has to be investigated more detailed.

In this study the local fatigue strength concept is applied to the experimental results. An endurance limit of 166 MPa for the FAT class 225 is included into the calculations. First the experimentally determined residual stresses at the surface are respected. The following minimum transverse residual stresses could be found after the treatment: S460 TM UIT: -200 MPa, S690Q HiFIT/ UIT: -380 MPa. This leads to local endurance limits of S460 TM UIT: 210 MPa, S690Q HiFIT / UIT: 222 MPa. Extending this approach into the finite fatigue life with a slope of m=3 local for the S690 fatigue strengths S690Q HiFIT / UIT: 301 MPa are derived. The assumption of flatter SN-curves would lead to smaller fatigue strengths. Due to the experimentally investigated flatter SN-curves for UIT treated of S460TM butt welds, which have also been published by Dürr (3) for this steel grade, the fatigue strength for this detail is calculated with a slope of m=5, resulting in a fatigue strength of 252 MPa. The resulting SN-curve compared to the nominal stresses are plotted in Fig. 6.

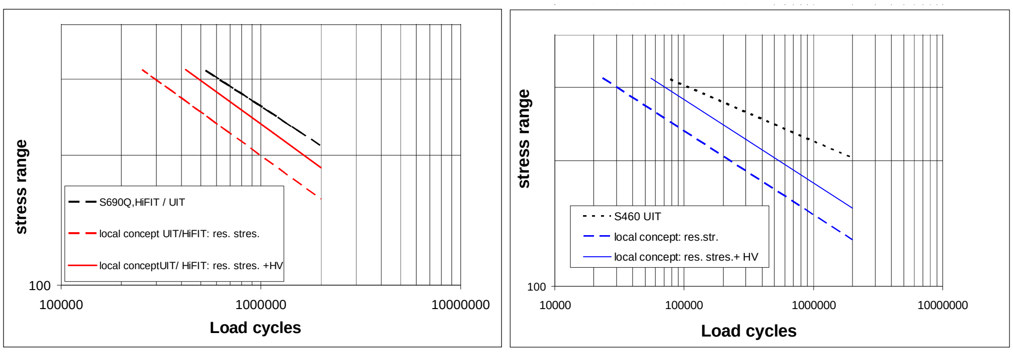

Figure 6. Calculated SN-curve based on the local fatigue strength

It can be seen that this approach is still a very conservative estimation, underestimating the fatigue strength by 20 to 30 % for the S690Q and of 50% for the S460TM.
In order to realistically respect for the increased material resistance due to the surface hardening an improvement factor has to be derived as Nitschke and Wohlfahrt (10) already proposed.
In both cases the surface hardness is increased by 100 HV 0.1. First approaches are made in order to improve the fatigue life assumptions considering the hardness effect. In these cases an increase of the local endurance strength of 40 MPa leads to very good results (Fig. 6). Further investigations have to analyze the residual stress relaxation behaviour for different steel grades and load levels. Above that the influence of the surface hardening has to be scientifically studied.

5 CONCLUSION

It can be concluded that high frequency peening methods can highly increase the fatigue strength of welded structures. Their beneficial effect is based on a geometrical improvement as well as on material mechanical effects, which lead to higher material resistance. Different design approaches are presented. It is shown that the IIW recommendations given for hammer peened joints which parallel shift the SN-curves to higher strength lead to conservative results in case the correct slope is considered. Especially for steel grade S460 a slope of m=3 would lead to uncertain assumptions for high stress ranges. The notch stress approach leads to very conservative results in case only the geometric effect is considered. Including the residual stresses and weighting the minor influence of the compressive stresses on the fatigue like the EC and IIW recommendations propose for base material and details with negligible residual stresses also lead to very realistic fatigue life estimation in case of adapted slope.
The local concept which has been generally proposed by Scholtes (13) and Nitschke-Pagel, Wohlfahrt (10) allows to consider the influence of the increase of the surface hardness as well as the residual stresses on the fatigue resistance. The influence of the surface hardness has to be analysed more detailed.

The investigations show that a realistic approach for the slope of the defined SN-curves is of major importance for reasonable fatigue life estimation.

6 REFERENCES:

1. X. Cheng, J. Fisher, B. Yen, Z. Ma, Proceedings of IABSE Symposium: Metropolitan Habitats and Infrastructure 2004, Shanghai, China, 2004.
2. DIN EUROCODE 3: Design of Steel Structures. Part 1.9: Fatigue Strength of Steel Structures. prEN 19993-1-9-2005. German Version, Beuth Verlag GmbH, Berlin, 2006.
3. A. Dürr, Zur Ermüdungsfestigkeit von Schweißkonstruktionen aus höherfesten Baustählen bei Anwendung von Nachbehandlungsverfahren, Ph.D thesis, Fakultät Bau- und Umweltingenieurwissenschaften, University Stuttgart, Germany, 2006.
4. J. Goodman, Mechanics Applied to Engineering, Long Man, Green & Co. London, Great Britain, 1899
5. P. J. Haagensen, S. J.Maddox, IIW Recommendations on Post Weld Improvement of Steel and Aluminium Structures, IIW Document XIII-1815-00, 2006.
6. Hobbacher, A.: Recommendations for the Fatigue Design of Welded Joints and Components, IIW/IIS, IIW Document XII-1965-03 / XV-1127-03, 2006.
7. U. Kuhlmann, J. Bergmann, A. Dürr, R. Thumser, Effizienter Stahlbau aus höherfesten Stählen unter Ermüdungsbeanspruchung, AiF-Forschungsvorhaben, Forschungsbericht P 620, Forschungsvereinigung Stahlanwendung, 2006.
8. V.-M. Lihavainen, A novel approach for assessing the fatigue strength of ultrasonic impact treated welded structures Ph.D. thesis, Lappeenranta University Technology, Finland, 2006.
9. H. Neuber, Über die Berücksichtigung der Spannungskonzentration bei Festigkeitsberechnungen, Konstruktion im Maschinen-, Apparate- und Gerätebau, (7), 1968 pp. 245-251.
10. T. Nitschke-Pagel, H. Wohlfahrt, Zeitschrift für Metallkunde, Vol. 97, 12, 2006, pp. 1697-1705
11. R. Olivier, G. Köttgen,T. Seeger, Schweißverbindungen I, Heft 143, Forschungskuratorium Maschinenbau (FKM), Frankfurt, 1989.
12. S. Roy, Experimental and Analytical Evaluation of Enhancement in Fatigue Resistance of Welded Details Subjected to Post-Weld Ultrasonic Impact Treatment, Ph.D.-thesis, Department of Civil and Environrnental Engineering, Lehigh University, USA, 2006“
13. B. Scholtes, Eigenspannungen in mechanisch randschichtverformten Werkstoffzuständen, Ursachen, Ermittlung und Bewertung, DGM Informationsgesellschaft mbH, Oberursel, Germany, 1991.
14. Seeger, T.; Heuler, P., Ermüdungsverhalten metallischer Werkstoffe, Deutsche Gesellschaft für Metallkunde, Ed., Munz, D. , 1985, S. 213-235.
15. T. Ummenhofer, I. Weich, and T. Nitschke-Pagel, , IIW Document XIII-2085-05, 2005.
16. T. Ummenhofer, I. C. Weich and T. N. Nitschke-Pagel (2006):, The Proceedings of the 16th International Offshore and Polar Engineering Conference, Vol. IV, pp. 98-105, San Francisco, California, USA.