Department of Applied Mechanics

Design aspects of high strength steel welded structures improved by high frequency mechanical impact (HFMI) treatment

Halid Can Yıldırım

Aalto University

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Design aspects of high strength steel welded structures improved by high frequency mechanical impact (HFMI) treatment

Halid Can Yıldırım

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Abstract

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Abstract

This doctoral study is concerned with the fatigue strength of welded steel structures which are improved by high frequency mechanical impact (HFMI) treatment. A comprehensive evaluation of 417 HFMI test data obtained from the literature and 24 HFMI fatigue data tested as a part of this work are studied. According to the statistical analyses an S-N slope of five (5) is proposed. A yield strength correction procedure which relates the material yield strength (f_y) to fatigue is presented and verified based on the constant amplitude $R = 0.1$ axial tension fatigue data. The f_y correction method significantly reduced the observed scatter in the data with respect to data without any f_y correction. Fatigue strength evaluations are done based on the nominal stress (NS), the structural hot spot stress (SHSS) and the effective notch stress (ENS) methods. By defining a reference f_y at 355 MPa, an increase in strength of approximately 12.5% for every 200 MPa increase in f_y above the reference f_y is found. For the NS and SHSS systems, this study gives HFMI design recommendations including a five (5) fatigue class increase in strength with respect to the NS and SHSS fatigue classes for the same weld detail in the as-welded condition. In the case of the ENS, a four (4) fatigue class improvement is proposed and verified. For HFMI welds with $f_y > 950$ MPa, the proposals are extended to represent a stepwise increase up to an eight (8) fatigue class improvement for the NS and the SHSS methods whereas the ENS method leads to a seven (7) fatigue class improvement. All the proposed characteristic curves in this study are conservative with respect to available fatigue test data. In the experimental study case, longitudinal non-load carrying high strength steel attachments were considered. Specimens were manufactured by a robot using an identical weld procedure and afterwards they were sent to four different HFMI tool manufacturers for post-weld treatment. All improved specimens were tested using the same variable amplitude loading history. Experimental test results indicate that all of the HFMI-improved welds from the four different HFMI equipment manufacturers satisfied the previously-proposed characteristic S-N line based on both the material f_y and the specimen geometry. In addition, detailed specimen alignment, weld profile and HFMI groove measurements were done for each specimen. Residual stress measurements were performed on some of the specimens using the X-ray diffraction method. While clear differences were observed, the HFMI groove dimensions and the resulting residual stress state following treatment were generally similar. The goal of the round robin study was to verify that a single guidance could be developed for different HFMI technologies.

Keywords high frequency mechanical impact (HFMI), weld toe improvement, fatigue strength improvement, high strength steels, structural hot spot stress, effective notch stress
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Preface

The work on this thesis was carried out at the Department of Applied Mechanics at Aalto University. Support for this work has been partially provided by the LIGHT research programme of the Finnish Metals and Engineering Competence Cluster (FIMECC), the Finnish Funding Agency for Technology and Innovation (TEKES), the Research Foundation of Helsinki University of Technology, and the EU Research Fund for Coal and Steel under grant agreement RFSR-CT-2010-00032 “Improving the fatigue life of high strength steel welded structures by post weld treatments and specific filler material”. I wish to express my gratitude to certain people and instances contributing significantly to the completion of this work.

Firstly, I would like to express my deepest gratitude to my supervisor Gary B. Marquis, Professor of Mechanics of Materials and the Dean of the School of Engineering, for always being supportive and eager to participate in my thesis project. Without his positive and supportive way of guiding my thesis, this journey would never have found its way to completion. His valuable insights on my research, his competence and support in this doctoral process, and his experiences in preparing scientific articles are greatly appreciated.

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I am fortunate to have spent six mounts at KTH-Royal Institute of Technology in such an inspiring and pleasant environment. For this, I want to thank all of my colleagues and friends at KTH. I would like to offer my deepest thanks and appreciation to Zuheir Barsoum, Professor of Lightweight Structures at KTH-Royal Institute of Technology in Sweden, for all the encouragement, foresight and relieving guidance throughout my stay in Stockholm.

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I wish to thank the two peer reviewers of this thesis, Prof. Mohammad Al-Emrani from Chalmers University of Technology in Sweden and Prof. Michael Stoschka from Montanuniversität Leoben in Austria.

I wish to thank Prof. Cetin Morris Sonsino from Fraunhofer Institute for Structural Durability and System Reliability LBF in Germany and Prof. Michael Stoschka from Montanuniversität Leoben in Austria for acting as my opponents.

I would like to thank to my elder brother Ahmet, for his endless support and discussions about my doctoral studies. His advice for my academic life have been useful and effective on my goals.

Finally, I would like to thank my parents, Hatice and Yasin Yıldırım for their unlimited love and support. I would not have completed this study without their belief and trust in me. I always feel their love even though I have been away thousands of kilometres from them for several years.

Helsinki, September 5, 2013,

Halid Can Yıldırım

Contents

List of Publications

This thesis consists of an overview and the following publications which are referred to in the text by the following corresponding Roman numerals.

I Halid Can Yıldırım and Gary B. Marquis. Overview of fatigue data for high frequency mechanical impact treated welded joints. *Welding in the World*, Volume 56, issue 7/8, pages 82-96, 2012.

II Halid Can Yıldırım and Gary B. Marquis. Fatigue strength improvement factors for high strength steel welded joints treated by high frequency mechanical impact. *International Journal of Fatigue*, Volume 44, pages 168-176, 2012.

III Halid Can Yıldırım, Gary B. Marquis and Zuheir Barsoum. Fatigue assessment of High Frequency Mechanical Impact (HFMI)-improved fillet welds by local approaches. *International Journal of Fatigue*, Volume 52, pages 57–67, 2013.

IV Halid Can Yıldırım and Gary B. Marquis. A round robin study of high frequency mechanical impact (HFMI)-treated welded joints subjected to variable amplitude loading. *Welding in the World*, Volume 57, issue 3, pages 437-447, 2013.

Author's Contribution

Publication I: "Overview of fatigue data for high frequency mechanical impact treated welded joints"

The author was the main author of the paper. All the available HFMI data was collected by the author. A comprehensive re-analysis of the published HFMI-treated fatigue data was performed by the author. Gary B. Marquis contributed to the manuscript with valuable comments and suggestions.

This paper was suggested to be published in the *Welding in the World* by the Commission XIII (Fatigue of Welded Components and Structures) of the International Institute of Welding (IIW) during the annual assembly in Chennai, India, 2011.

Publication II: "Fatigue strength improvement factors for high strength steel welded joints treated by high frequency mechanical impact"

The author was the main author of the paper. The author studied several proposals for HFMI welds and derived a novel proposal based on the available fatigue data in the literature. Gary B. Marquis contributed to the manuscript with valuable comments and suggestions.

Publication III: "Fatigue assessment of High Frequency Mechanical Impact (HFMI)-improved fillet welds by local approaches"

The author was the main author of the paper. The author performed all of the finite element analyses for the local stress based fatigue assessment methods and proposed new design rules. Gary B. Marquis and Zuheir Barsoum contributed to the manuscript with valuable comments and suggestions.

Publication IV: "A round robin study of high frequency mechanical impact (HFMI)-treated welded joints subjected to variable amplitude loading"

The author was the main author of the paper. The author had the main responsibility for planning and executing the experiments, analysing the data, and interpreting the results. Weld profile measurements and evaluations of the straightness of specimens were performed by the author. Gary B. Marquis contributed to establishment of the test setup and the manuscript with valuable comments and suggestions.

This paper was suggested to be published in the *Welding in the World* by the Commission XIII (Fatigue of Welded Components and Structures) of the International Institute of Welding (IIW) during the annual assembly in Denver, USA, 2012.

Nomenclature

f_y	Yield strength
$f_{y,o}$	Reference yield strength
FAT	The IIW fatigue class, i.e. the nominal or effective notch stress range in MPa corresponding to 95% survival probability at 2×10^6 cycles to failure (a discrete variable with 10-15% increase in stress between steps)
k_o	Strength magnification factor for high frequency mechanical impact treatment for steel $f_y = f_{y,o}$
k_R	Strength magnification adjustment considering R-ratio
k_y	Strength magnification adjustment considering yield strength
m_1	Slope of the S-N line for stress cycles above the knee point
m_2	Slope of the S-N line for stress cycles below the knee point
R	Stress ratio ($\sigma_{min}/\sigma_{max}$)
n	Number of cycles
N_f	Cycles to failure
ΔS	Nominal stress range
t	Plate thickness of the specimen
α	Yield strength correction coefficient after high frequency mechanical impact
γ	Strength correction coefficient for high frequency mechanical impact
ρ	Radius
σ	Stress
σ_N	Standard deviation in Log(N_f)

subscripts

A	In the as-welded condition
eq	Equivalent value
i	Value for specimen i where $\Delta S_i \geq \Delta S_k$
j	Value for specimen j where $\Delta S_i < \Delta S_k$
k	Characteristic value corresponding to 95% survival probability at 2×10^6 cycles to failure (continuous variable)
H	Following high frequency mechanical impact treatment
f	Effective value
m	Mean value corresponding to 50% survival probability at 2×10^6 cycles to failure

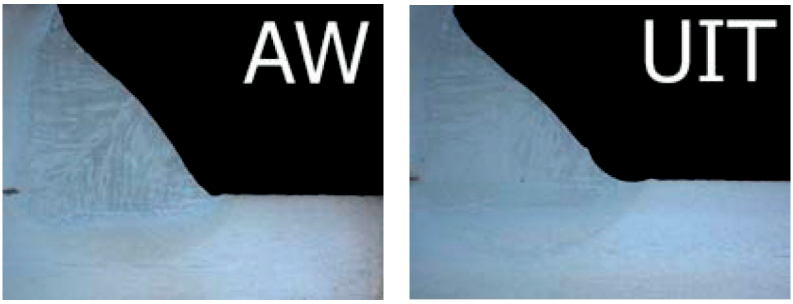
1. Introduction

1.1 Background

Welded steel structures subject to cyclical loading are prone to fatigue failure due to irregular geometries, notches and metallurgical effects which are induced by welding. Thus, fatigue strength of welded structures is lower with respect to their base material. Therefore, more attention should be given to weld detail for design proposals.

Various weld toe treatment methods have been developed in order to improve the fatigue strength of welded structures. Fatigue strength improvement methods may be applied during the welding process, e.g., by weld profile control or using special electrodes which help produce beneficial compressive residual stresses. Alternatively some improvement techniques are performed as separate work operations after the welding, i.e., post-weld. These methods can be divided into two groups: weld profile modification methods, and residual stress modification methods. These improvement methods can be performed either at the initial fabrication stage or under the service loading of components. For the weld profile modification methods, the first aim is to remove or reduce the size of the weld toe flaws which may result in an extended crack initiation phase of the fatigue life. The second aim is to reduce the local stress concentration due to the weld profile by achieving a smooth transition between the plate and the weld face. The most known weld profile modification methods are machining or grinding of weld seam and toe, and re-melting the weld toe by TIG, plasma or laser dressing. For the residual stress modification methods, on the other hand, the aim is to eliminate the high tensile residual stress in the weld toe region and induce compressive residual stresses at the weld toe. Hammer and needle peening are two of the well-known residual stress methods. Detailed information about improvement techniques can be found, for example, in the International Institute of Welding (IIW) best practice guidelines which concern post-weld treatment methods for steel and aluminium structures [1].

In addition to the mentioned improvement techniques, there have been an increasing number of publications dealing with high frequency mechanical impact (HFMI) treatment technologies. The innovation of improving the fatigue strength of welded structures by locally modifying the residual stress state using ultrasonic technology is attributed to scientists and engineers who worked in the former Soviet Union [2] [3]. Today, there are numerous HFMI peening tool manufacturers and service providers, and the number is increasing steadily as the technique has proven to be reliable, effective and user-friendly. While details of the tools differ, the working principal is identical: cylindrical indenters are accelerated against a component or structure with high frequency (>90 Hz). Devices are known by the following names: ultrasonic impact treatment (UIT) , ultrasonic peening (UP), ultrasonic peening treatment (UPT), high frequency impact treatment (HiFIT), pneumatic impact treatment (PIT) and ultrasonic needle peening (UNP), see Publications I, II and III.



(a) Cross-section of a weld toe (b) Cross-section of a treated weld toe

(c) Before treatment (d) After treatment

Figure 1.1. Typical weld toe profile in the as-welded condition and following HFMI treatment, [4] and Publication IV.

The impacted material is highly plastically deformed causing changes in the material microstructure and the local geometry as well as the residual stress state in the region of impact. Figure 1.1 shows cross sections of typical weld profiles in as-welded condition and following HFMI treatment, [4] and Publication IV.

In comparison to traditional peening methods, such as hammer or needle peening, the operation is more user-friendly and the spacing between alternate impacts on the work piece is very small resulting in a finer surface finish. The indenters are high strength steel (HSS) cylinders and manufacturers have customized the effectiveness of their own tools by using indenters with different diameters, tip geometries or multiple indenter configurations. Figure 1.2 shows an example of an HFMI device and several examples of indenter sizes and configurations which are available.

1.2 Objectives and scope

The aim of this doctoral study has been to investigate design aspects of welded steel structures improved by HFMI treatment. More specifically, this study has been addressed to solve the following questions:

- Which S-N slope is more appropriate for HFMI-improved welds?

- Does the degree of fatigue strength improvement for HFMI-treated welds depend on the material yield strength? If yes, can it be analysed considering HFMI-improved welds with different material yield strength?

- Can a single design methodology be defined for numerous HFMI technologies?

- Is it possible to extend existing local stress-based fatigue assessment methods also to HFMI-improved welds?

1.3 Research approach

The research consisted of four main research themes:

(a)

(b)

Figure 1.2. Example of (a) an HFMI device and (b) indenter sizes and configurations [5].

- A comprehensive literature review:
  To collect all HFMI-improved test data available in the literature and to analyse them in order to assess the best-fit S-N slope, the confidence interval of the S-N slope and the observed degree of improvement in fatigue strength.

- Fatigue strength assessment in the nominal stress approach:
  To define a yield strength magnification factor which increases with increasing yield strength, and to propose and to verify design FAT classes for HFMI-improved welds in the nominal stress by considering the influence of yield strength on fatigue strength improvement.

- Fatigue strength assessment in the local stress approaches:
  To apply the existing local stress assessment approaches, and to propose and verify FAT classes for HFMI-improved welds in the structural hot spot stress and the effective notch stress by considering the influence of yield strength on fatigue strength improvement.

- A variable amplitude round robin fatigue test program:
  To perform a round robin test program on specimens improved by several HFMI treatment technologies, and to justify that all the HFMI fatigue data satisfies the previously proposed FAT classes.

1.4 Dissertation structure

The available HFMI fatigue test data in the literature was presented and analysed (Publication I). A yield strength correction method that relates to material yield strength was developed and verified (Publication II). Fatigue design recommendations of HFMI-treated welds in the nominal stress, the structural hot spot stress and the effective notch stress methods were proposed and verified (Publications II and III). A round-robin exercise including different HFMI tool manufacturers was performed (Publication IV).

2. Analysis and experimental methods

2.1 Evaluation of S-N slope of published data

High frequency mechanical impact (HFMI) treatment technique resembles both hammer and needle peening methods from the mechanical point of view. The S-N slope for those treatment methods were given as $m_1 = 3$ by the IIW recommendations [1]. However, the choice of $m_1 = 3$ in the post-weld improvement guideline results in conservative design curves in the high cycle fatigue regime but less conservative or even non-conservative results for lower cycles to failure, i.e., $N = 1 \times 10^4$. Individual experimental studies for HFMI treatments also typically observe that the slope of the best-fit line through the S-N data is typically greater than the $m_1 = 3$ used in the IIW guideline [6] [7] [8] [9] [10]. Therefore, special attention was given to the S-N slope in this study because the assumed S-N slope has a major impact on the measured degree of fatigue strength improvement, and will eventually influence the improvement factors proposed for high strength steels.

The available HFMI fatigue test data was extracted from the literature for the four commonly-used specimen types. The specimen types were longitudinal welds, T-joint, cruciform welds and butt joint. A total of 45 data sets were reviewed with different yield strengths, plate thicknesses and loading types, see Table 2.1. Most of the tests were performed using constant amplitude at $R = 0.1$, but some test data for alternate stress ratios $(-1 \leq R \leq 0.5)$ or variable amplitude loading were also reported. Wherever possible, failure modes other than at the weld toe and run-outs have been excluded. However, failure modes were not reported for all studies.

Table 2.1. Extracted HFMI fatigue test data from Publications I, II and III.

	Loading type	Data points	Stress ratio	Thickness [mm]	Yield strength [MPa]
Longitudinal	Tension	149	0.1...0.5	5...30	267...969
Cruciform	Tension	68	-1...0.5	9.5...20	350...812
Butt	Tension	147	0.1...0.5	5...16	422...786
T-joints	Bending	53	0.1	5...20	420...960

2.2 Fatigue strength improvement as a function of material yield strength

The existing IIW guideline for treatment methods [1] allows up to 25% increased design stress for mild steel (f_y < 355 MPa) and up to 40% increased design stress for steel f_y > 355 MPa. This single division was recommended for hammer and needle peening methods, and it was primarily due to the lack of systematic experimental data for higher strength steels welds. Thus, only one recommendation was proposed for all weld toe improvement methods. However, numerous researchers have observed that the degree of improvement increases with material yield strength even beyond that range. This improvement is even clearer especially for welds treated by one of the mentioned HFMI techniques, see e.g., Maddox [11], Bignonnet [12], Haagensen [13], Refresh Project [14] and Publication I.

In 2009, a design method for HFMI-treated welds was presented based on several research projects in Germany [14]. In that proposal, the S-N curve slope of $m_1 = 5$ was also suggested. The characteristic fatigue strength calculation was defined using the strength magnification adjustments for R-ratio, yield strength and HFMI treatment for steel f_y = $f_{y,o}$, see Eq. 2.1.

$$\Delta S_H = \Delta S_A \times (k_o k_y k_R) \tag{2.1}$$

where the strength magnification factors are given by Eq. 2.2.

$$k_o = \gamma \tag{2.2a}$$

$$k_y = 1 + \alpha(1 - f_{y,o}/f_y) \text{ for } f_{y,o} \leq 690 \text{ MPa} \tag{2.2b}$$

$$k_R = 1.0 \text{ for } R \leq 0.1 \tag{2.2c}$$

In Publication II, several different hypotheses were investigated as a mean of establishing the empirical relationship between material yield strength and fatigue strength for HFMI-treated welds. Only data for axially-loaded test specimens loaded at R = 0.1 loading were considered, and no statement could be made about stress ratio. The yield stress of steel grades varied from 267 to 960 MPa and plate thickness varied from 5 to 30 mm. The best-fit for the available data was found using the empirical relationship with an exponential form, Eq. 2.3, of the strength magnification factor, Eq. 2.4, which increases with material yield strength.

$$\Delta S_H = \Delta S_A \times k_o^{(1/1-k_y)} \tag{2.3}$$

$$k_y = \alpha(\frac{f_y - f_{y,o}}{f_{y,o}}) \tag{2.4}$$

When assessing the available data, it was assumed that:

- the slope of S-N curves for HFMI-improved welds was $m_1 = 5$, Publication I,

- fatigue strength values, ΔS_A , from the IIW recommendations [15] are valid,

- and the best-fit for the data results in the minimum σ_N.

2.3 Stress assessment based on local approaches

Although the yield strength correction method was initially developed for fatigue strength assessments of HFMI-improved welds based on the nominal stress (NS) approach, the method was also suggested for local assessment approaches. Publication III provides an evaluation of published HFMI-treated fillet welds using the local assessment methods like the structural hot spot stress (SHSS) [16] and effective notch stress (ENS) [17] methods as defined by the IIW. When performing the analysis, only axially-loaded test data from longitudinal and cruciform fillet welds subjected to stress ratio R = 0. 1 was considered.

2.3.1 The structural hot spot stress (SHSS) method

The IIW published fatigue design recommendations based on the use of the SHSS which include proposals for design curves expressed in terms of the hot-spot stress range [16]. The structural stress at the hot-spot refers to all stress-increasing effects of a structure, with the exception of the non-linear peak stress occurring at the local notch, e.g., at the weld toe. Two characteristic curves are proposed for as-welded fillet welded joints namely, FAT 90 for load-carrying or FAT 100 for non-load carrying welds [16]. For welds improved by hammer or needle peening, the appropriate SHSS characteristic curve for non-load carrying joints is FAT 125 for mild steel (f_y < 355 MPa) and FAT 140 for higher strength steel (f_y > 355 MPa) with an S-N slope of $m_1 = 3$. For load-carrying joints, the respective characteristic curves are FAT 112 for mild steel and FAT 125 for higher strength steel.

2.3.2 The effective notch stress (ENS) method

In the case of the ENS method, Commision XIII of the IIW developed a guideline concerning fatigue design of welded components based on the ENS approach [17]. The maximum stress at the notch, e.g. weld toe or root, can be idealized by assuming a linear-elastic material behaviour using the finite element method. The actual weld profile at the toe or root that includes all variations of weld shapes is replaced and rounded by a fictitious notch radius in order to avoid arbitrary or infinite stress results. For welds having a plate thickness of over 5 mm, it is proposed that

$$\rho_f = \rho + 1 \text{ mm} \tag{2.5}$$

where ρ is the actual radius of the weld toe and is the effective radius that is implemented to the finite element modelling. For a worst case scenario and for practical applications, the actual radius is usually assumed to be close to zero. Therefore, the ENS approach for the fatigue assessment of as-welded structures is reduced to $\rho_f = 1$ mm at the weld toe or root.

When the stress assessment method is based on the maximum principal stress, FAT 225 is normally considered for all types of as-welded connections [17]. For von Mises stress, FAT 200 is used. Nonetheless, some recent studies have shown that with the ENS approach for welded structures, the FAT 225 S-N line represents less than 95% survival probability, particularly for cruciform and butt welds [18] [19] [20]. Meanwhile, characteristic curves for improved joints have not been defined yet.

2.4 Experimental round robin study

The proposed FAT classes in Publications II and III are based on the available HFMI test data in the literature. The fatigue test data was collected from 46 publications and included treated welds from six different HFMI tool manufacturers. However, none of those studies have included data for identical testing of welded joints treated with several HFMI methods. From the design guideline point of view, proposed FAT values should not be assigned to a particular HFMI treatment technology. Instead, characteristic curves should be valid for welds treated by any of tool manufacturers which have demonstrated the effectiveness of their equipments. Therefore, a round robin study was completed in Publication IV in order to confirm that fatigue test results from the various tool manufacturers satisfy the previously-proposed FAT values. The target of the study was not to compare treatments but to assist in the development of common design proposals.

Nominally identical longitudinal non-load carrying attachments in high strength steel were manufactured at a single location using a single robot and identical weld procedures, see Figure 2.1. The longitudinal gusset had angeled corners in order to accommodate a Barkhausen noise sensor which was attached during fatigue testing. This is a separate study and the results are not reported here. The gusset was double-bevelled along the entire edge to help ensure full penetration. The root of a groove was manually TIG welded from single side without the filler material and it was back gouged from the opposite side. Then, the back gouged side of the root was welded with the filler material. After a single manual weld root pass, a second finishing pass was accomplished using a welding robot and MAG welding.

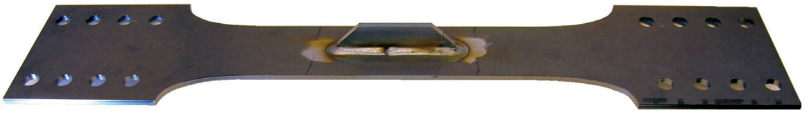
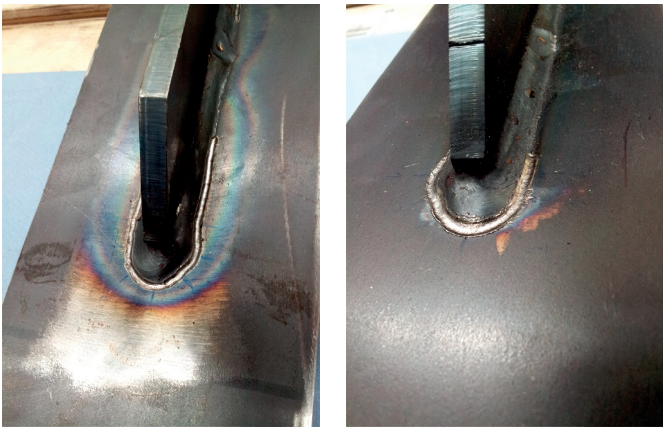


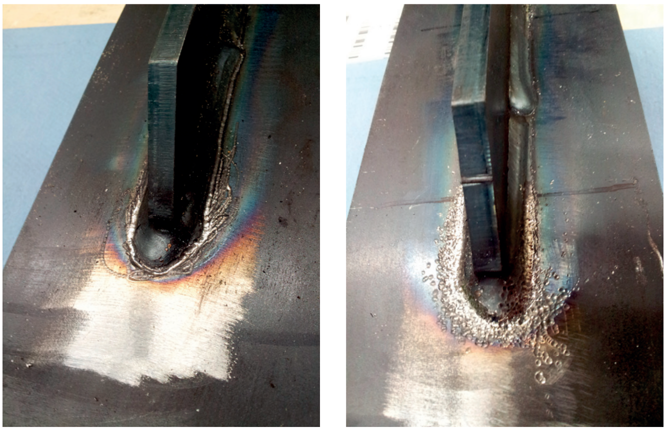
Figure 2.1. Picture of the test specimen

The specimens then randomly distributed to four HFMI equipment manufacturers for treatment. Specific details of the HFMI treatment were left to the equipment manufacturers. These companies were Applied Ultrasonics [21], Integrity Testing Laboratory Inc. [5], Lets Global [22] and Pfeifer [23]. Examples of HFMI-treated specimens following the four alternate treatments are shown in Figure 2.2. Equipment manufacturers are identified by letters A, B, C or D which were randomly assigned to the four companies.

In the case of the test setup which is shown in Figure 2.3, anti-buckling supports were fitted to the specimens to avoid the risk of specimen buckling during the relatively large compressive stress cycles that occurred regularly during variable amplitude loading at R = -1. More details of testing can be found in Publication IV.



(a) Company A (b) Company B



(c) Company C (d) Company D

(e) As-welded

Figure 2.2. Example specimens for as-welded and following HFMI treatment by four equipment manufacturers (Publication IV).

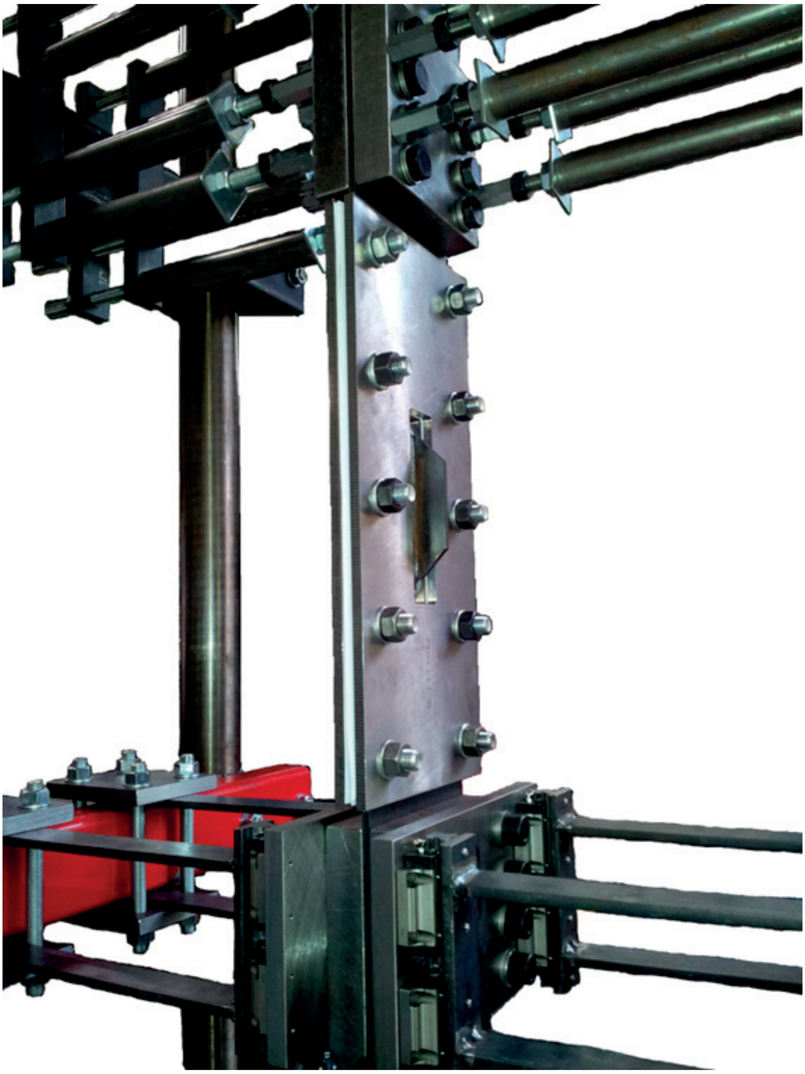


Figure 2.3. Picture of the test setup.

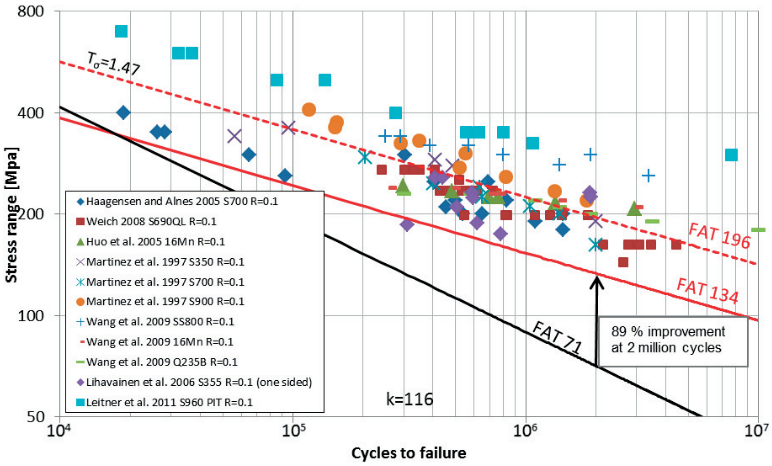
3. Results and discussions

3.1 Evaluated S-N slope of HFMI published data

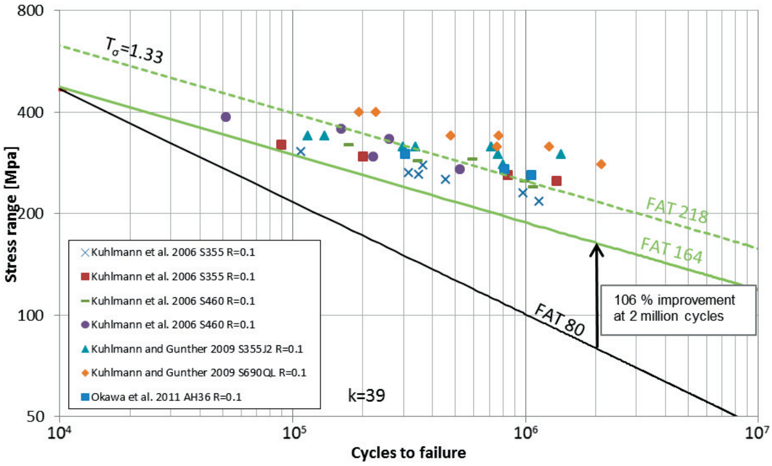
According to slope estimation analysis of overall 414 published data points, an S-N slope $m_1 = 5$ passed through or was below the scatter band for virtually all data sets for all four specimen types (Publication I). Therefore, an S-N slope $m_1 = 5$ was suggested to be used for the available HFMI fatigue data. The slope of $m_1 = 5$ is also a "nice" number. For instance, it has been suggested for plate edges failures in the IIW best practice guideline [15] and for thin and flexible structures under normal stresses caused by bending or axial loading [24].

All the available data obtained at R = 0.1 was statistically analysed. In each case, an S-N slope of $m_1 = 5$ was assumed. Fatigue strength improvement values at $N = 2 \times 10^6$ were calculated and indicated in Figure 3.1 with regression lines. The solid lines in these figures are the characteristic lines whereas the dashed lines are the mean lines of the respective characteristic lines.

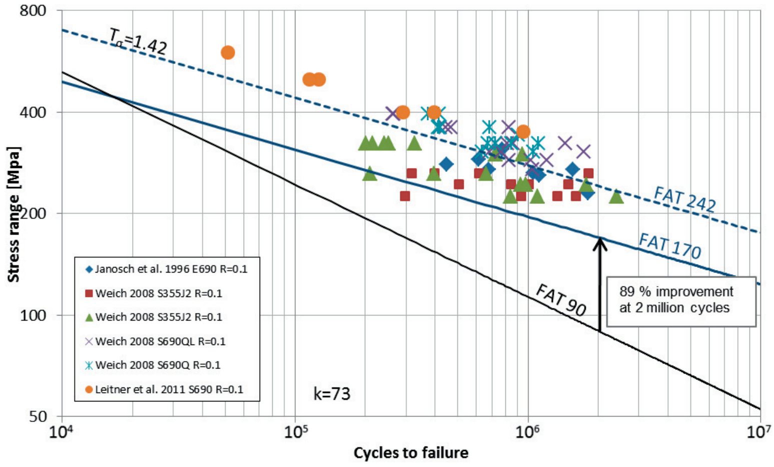
Further quantitative comparisons of HFMI treatment with respect to some of available the hammer-peened data were also done in Publication I for both longitudinal and cruciform welds as well as T-joints. In each of the specimen types, the regression lines from HFMI-treated welds in Figure 3.1 were presented with corresponding to hammer peened data. It was shown that the S-N slope $m_1 = 5$ also tends to follow the trend of the hammer peened data, see Publication I.



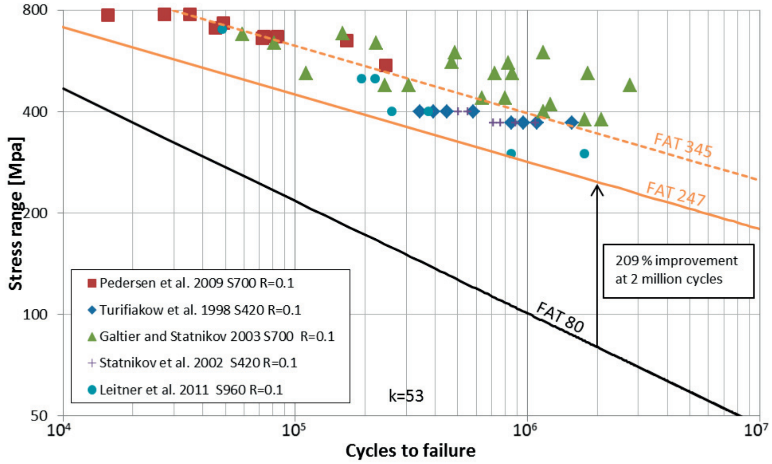
(a) Longitudinal welds



(b) Cruciform welds



(c) Butt joints

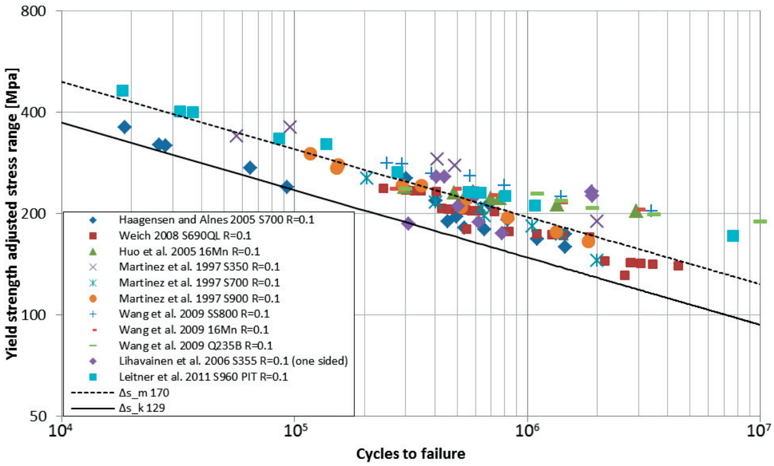


(d) T-joints

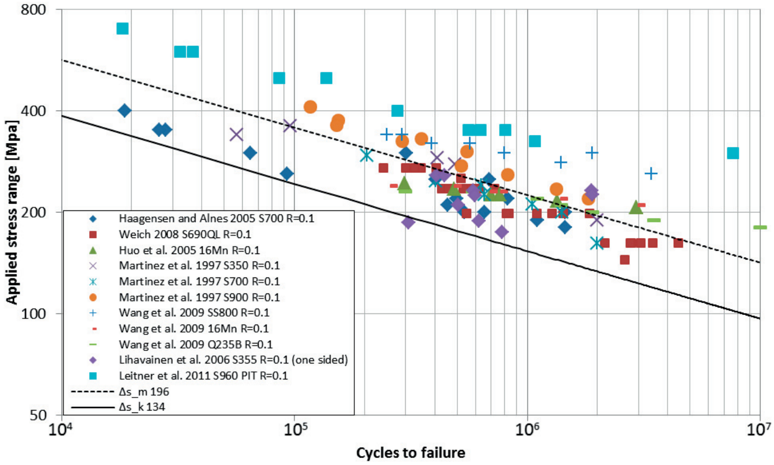
Figure 3.1. Extracted HFMI-treated fatigue data at R = 0.1 from the literature.

3.2 Fatigue strength improvement as a function of material yield strength

In Publications II and III, further evaluations of fatigue data with a yield strength correction method were performed for nominal stress and local stress assessment methods. Only axially-loaded test specimens at R=0.1 were considered. Stress concentration values were calculated using finite element methods as defined in the IIW guidelines for the SHSS [16] and for the ENS [17] approaches.



(a) with f_y correction, α = 0.23



(b) without f_y correction

Figure 3.2. Fatigue data for improved longitudinal welds at R = 0.1.

In Figure 3.2, the evaluation of fatigue data for longitudinal non-load carrying attachments in the NS is shown as an example. Statistically assessed test results of all HFMI-treated welds based on geometries in the NS are shown in Table 3.1. It is clear that the use of f_y correction method results in decreased σ_N and lower ΔS_k and ΔS_m for each specimen type. Lower values of ΔS_k and ΔS_m are to be expected since these values represent the lines for HFMI-treated specimens at the reference f_y = 355 MPa. Without correction (α = 0) the curves are higher since the lines represent a mix of test specimens with a wide variety of yield strengths, mostly f_y > 355 MP. If these were not the case, α=0 curves could be lower. While ΔS_m reduces by 6-16% for the three specimen types, ΔS_k changes by less than 3% due to the significant reduction in σ_N. Similar observations can be made for local stress assessment methods considering the f_y correction method, see Publication III.

Table 3.1. Statistical analysis of HFMI published data in the nominal stress method. Each specimen type is analysed with f_y correction (Eq. 2.3 and Eq. 2.4, α > 0) and without f_y correction (α = 0). S-N slope $m_1 = 5$ was assumed.

Specimen type	total data points	α	ΔS_k [MPa]	ΔS_m [MPa]	σ_N [MPa]
Longitudinal	116	0	134	196	0.415
weld		0.23	129	170	0.302
Cruciform	39	0	164	218	0.307
weld		0.31	166	204	0.156
Butt	73	0	170	242	0.381
joint		0.39	168	204	0.213
All	218	0.27	normalized	values	0.274
joints			1.31	1.69	

For the NS in Table 3.1, there is a small difference between specimen types in the value of α which results in a minimum value for σ_N . The greatest value of α = 0.39 was observed for cruciform welds while the lowest was observed for the longitudinal attachments, α = 0.23. When all experimental results are evaluated as a single data set the value α = 0.27 is found. However, it can be noted that σ_N changes only slowly with α. In practice, the value α = 0.27 means that ΔS_m increases by about 12.5% for every 200 MPa increase in f_y above the reference value of 355 MPa. In the IIW system this is approximately equal to one fatigue class for every 200 MPa increase in f_y. It also indicates a similar decrease in ΔS_m for f_y < 355 MPa.

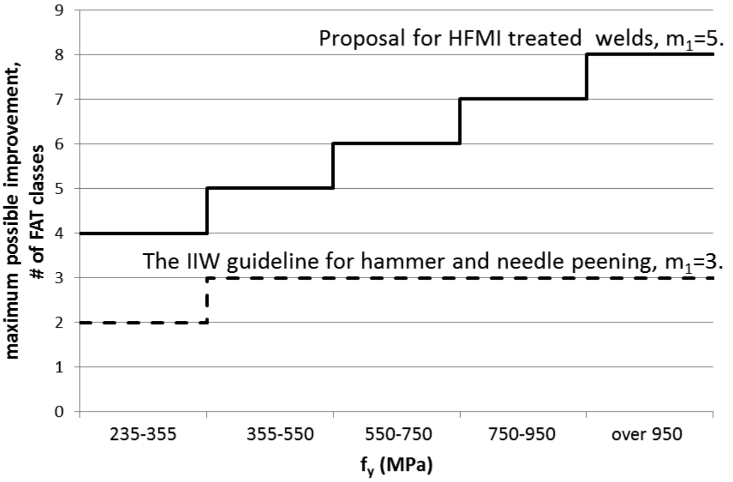
3.2.1 Design proposals for the nominal stress method

After evaluating all test data together based on specimen geometry, design proposals for HFMI welds can now be made. Design methods for the NS, SHSS and ENS methods are shown in Figure 3.3 as a solid line whereas the existing IIW recommendations are presented with dashed lines [1]. The increase in FAT classes for HFMI welds are presented as a function of yield strength using $m_1 = 5$ for all fatigue assessment methods. For the NS and SHSS methods, the IIW gives only one single division at 355 MPa using $m_1 = 3$, whereas characteristic curves in the ENS method for improved joints have not been previously defined.

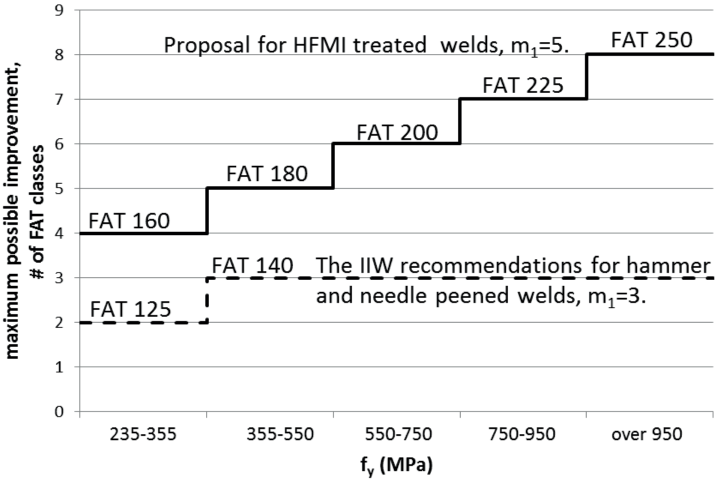
Table 3.2. Existing IIW FAT classes for as-welded and hammer or needle peened welded joints and the proposed FAT classes in the NS system for HFMI-treated joints as a function of f_y.

f_y [MPa]	longitudinal welds	cruciform welds	butt welds
	as-welded, $m_1 = 3$ [15]		
all f_y	71	80	90
	improved by hammer peening, $m_1 = 3$ [1]		
$f_y \leq 355$	90	100	112
$355 < f_y$	100	112	125
	improved by HFMI, $m_1 = 5$		
$235 < f_y \leq 355$	112	125[a]	140[a]
$355 < f_y \leq 550$	125	140	160
$550 < f_y \leq 750$	140	160	180
$750 < f_y \leq 950$	160	180[a]	-
$950 < f_y$	180	-	-

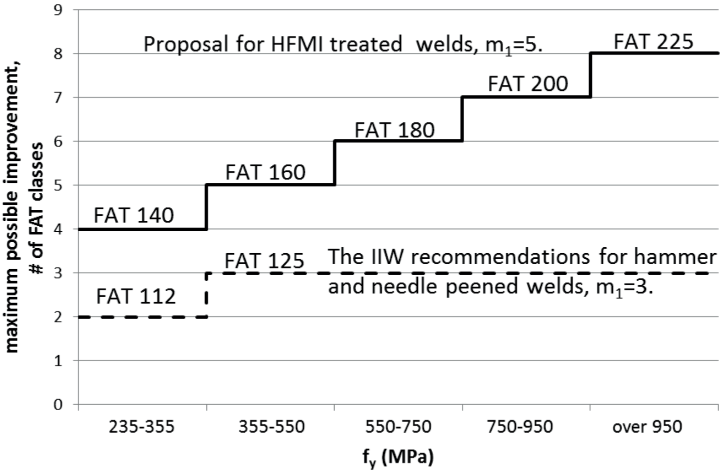
[a] no data available



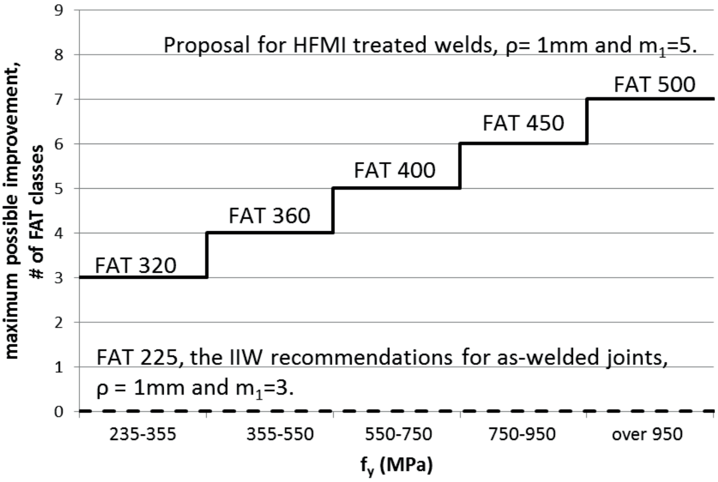
(a) For all joints in the nominal stress method



(b) For non-load-carrying joints in the structural hot spot stress method



(c) For load-carrying joints in the structural hot spot stress method



(d) For all joints in the effective notch stress method

Figure 3.3. Proposed maximum increases in the number of FAT classes as a function of f_y.

In Figure 3.4, the HFMI experimental data for longitudinal welds fabricated from different strength steels in the NS method are plotted based on the proposed FAT classes in Table 3.2 as a solid line. No points in Figure 3.4 fall below the proposed S-N lines. Thus, the target survival probability for the characteristic lines is achieved considering that FAT classes represent discrete steps. Further validations of FAT values for other types of joints in the NS method were presented in Publication II.

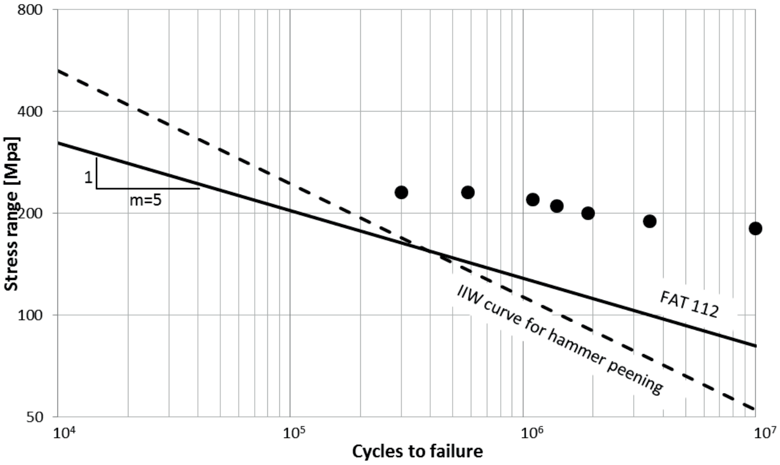
3.2.2 Design proposals for the structural hot spot stress method

The NS method presents a single set of improvement methods with various FAT values depending on the specimen geometry, see Figure 3.3a and Table 3.2. Based on the NS study, a weld detail in $355 < f_y \leq 550$ MPa steel improved by HFMI is expected to have a maximum of five fatigue class improvement with respect to the same detail in the as-welded condition. If the same logic is applied to the SHSS method, the resulting S-N line for non-load-carrying fillet welds would be FAT 180 and for load-carrying fillet welds it would be FAT 160, see Figures 3.3b and c and Table 3.3. Further stepwise increases for every 200 MPa can also be made in the SHSS method depending on yield strength.

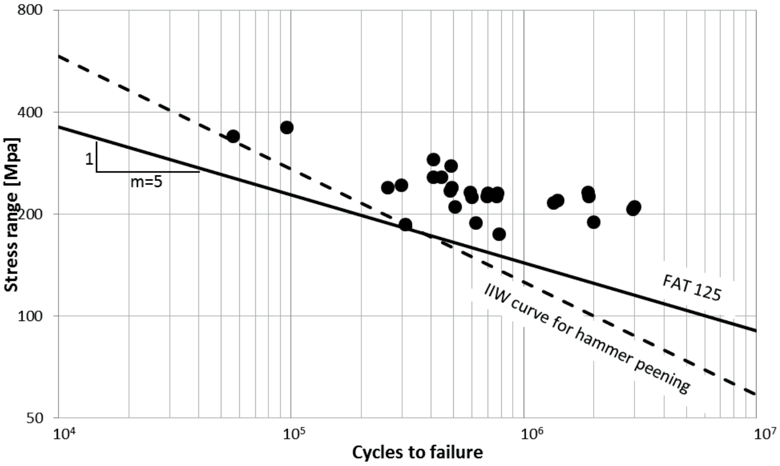
In Figure 3.5, the HFMI experimental data for non-load carrying welds fabricated from different strength steels in the SHSS method are plotted based on the proposed FAT classes in Table 3.3 as a solid line. With the exception of only one data point that appears in Figure 3.5c, the proposed S-N curves are conservative with respect to the experimental results. The design FAT lines are intended to represent 95% survival probability so one point, or even several points, in 116 below the lines might be expected. Results for load-carrying joints in the SHSS method were given in Publication III.

3.2.3 Design proposals for the effective notch stress method

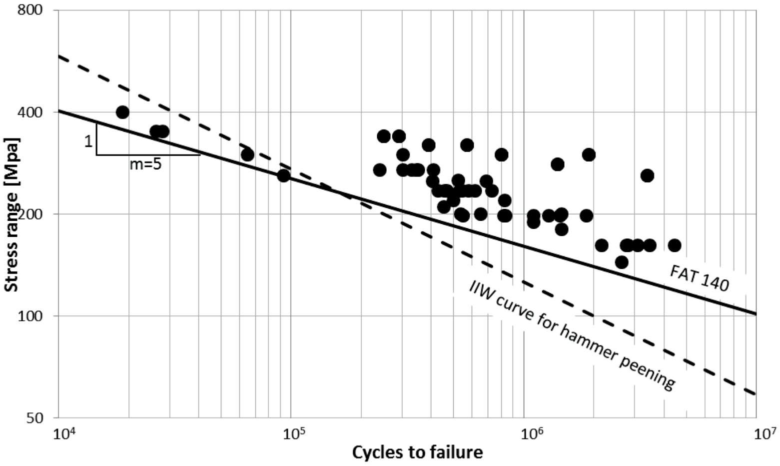
In the case of ENS method, Figure 3.3d and Table 3.3 gives the existing IIW characteristic FAT class for the ENS approach for as-welded joints and the respective proposed FAT classes for HFMI-treated fillet welds. In light of the aforementioned, recent studies have shown that the FAT 225 S-N line may not represent 95% survival probability for joints in the as-welded condition [18][19][20], it was decided that a fatigue class improvement of four (4) would be added for welded details in $355 < f_y \leq$



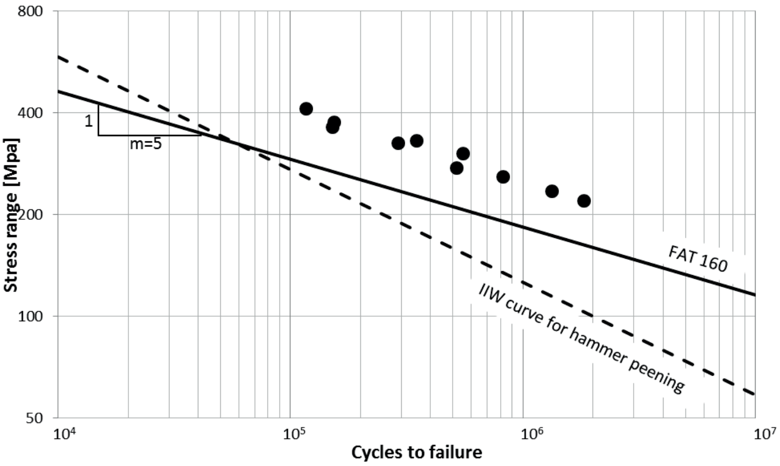
(a) $235 < f_y \leq 355$



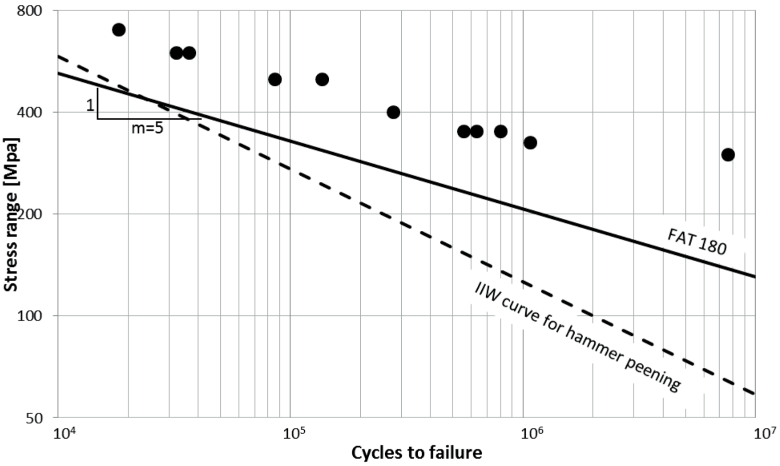
(b) $355 < f_y \leq 550$



(c) $550 < f_y \leq 750$



(d) $750 < f_y \leq 950$



(e) $950 < f_y$

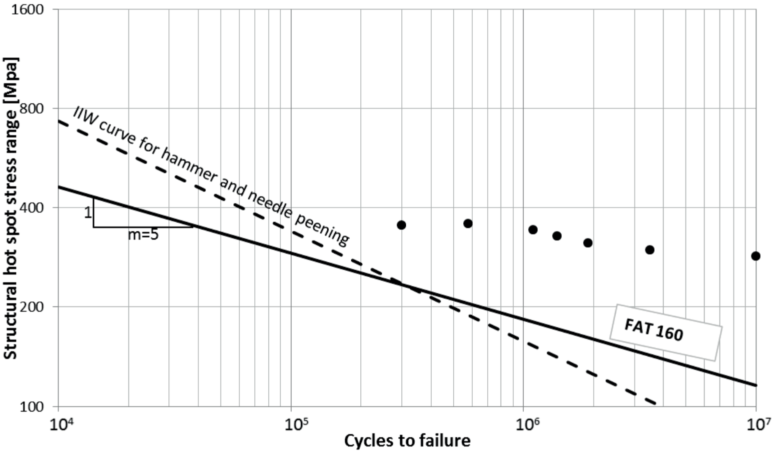
Figure 3.4. Available data for HFMI-treated longitudinal welds shown in relation to the proposed design curves from Table 3.2.

Table 3.3. Existing IIW FAT classes for SHSS and ENS approaches for as-welded and improved joints and the proposed FAT classes for HFMI-treated joints as a function of f_y.

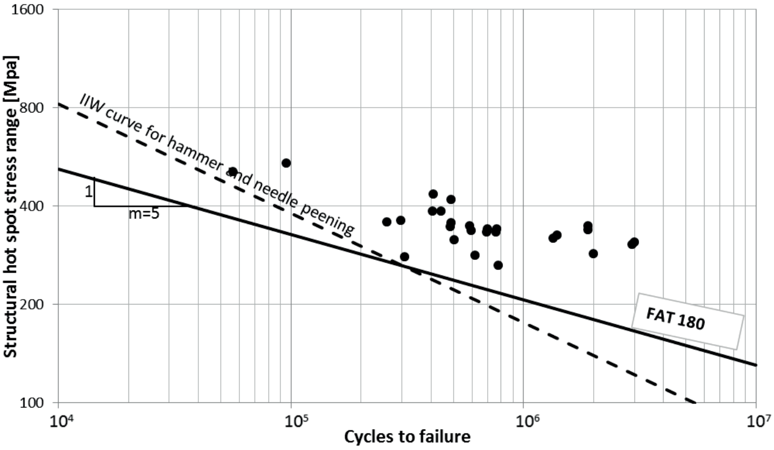
	SHSS		ENS, ρ_f=1 mm
f_y [MPa]	Load-carrying fillet welds	Non-load-carrying fillet welds	For all fillet welds
	as-welded, $m_1 = 3$ [15]		
all f_y	90	100	225[a]
	improved by hammer peening, $m_1 = 3$ [1]		
$f_y \leq 355$	112	125	-[b]
355 < f_y	125	140	-[b]
	improved by HFMI, $m_1 = 5$		
235 < $f_y \leq 355$	140	160	320
355 < $f_y \leq 550$	160	180	360
550 < $f_y \leq 750$	180	200	400
750 < $f_y \leq 950$	200	225	450
950 < f_y	225	250	500

[a] some studies suggest that FAT 200 is a better fit for the experimental data

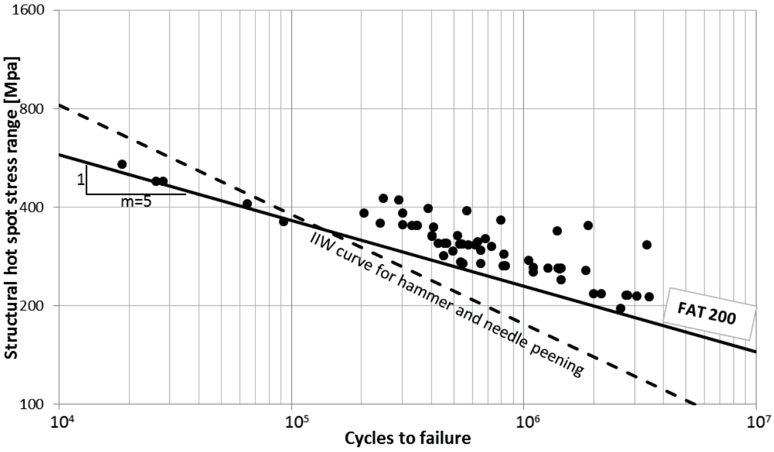
[b] no proposals were ever developed



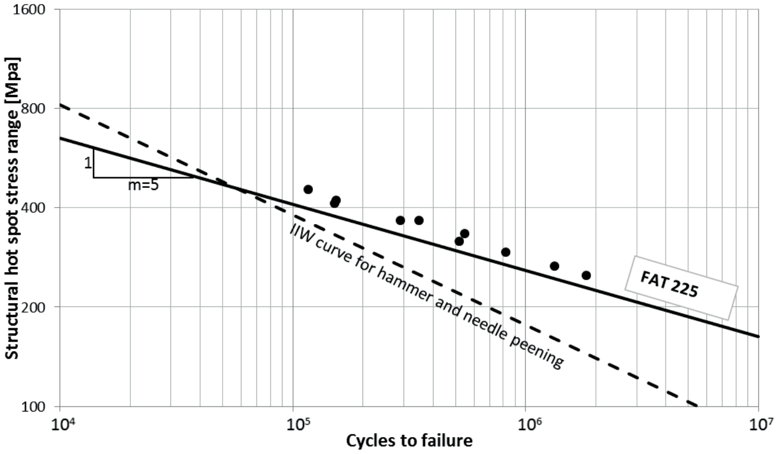
(a) $235 < f_y \leq 355$



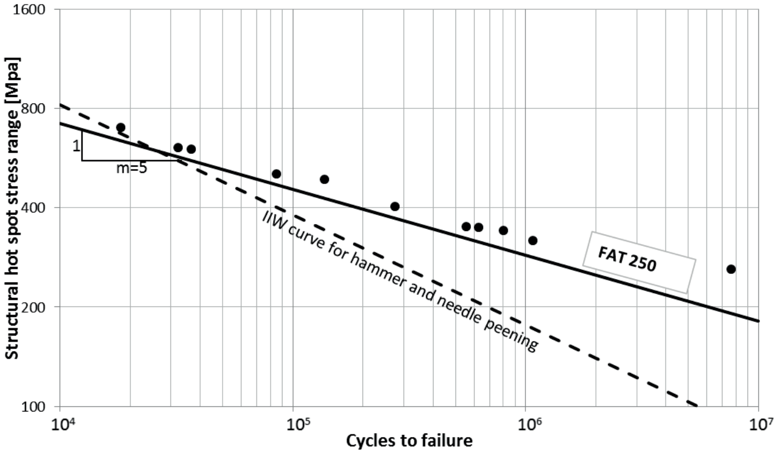
(b) $355 < f_y \leq 550$



(c) $550 < f_y \leq 750$



(d) 750 < $f_y \leq 950$



(e) 950 < f_y

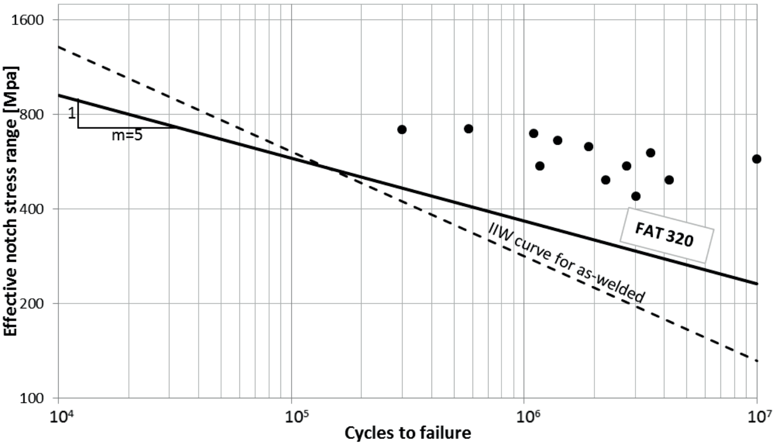
Figure 3.5. Available data for non-load carrying HFMI-treated welds shown in relation to the proposed design curves from Table 3.3.

550 MPa steel. Classes for other f_y are similarly adjusted for the ENS method and S-N curve for an HFMI-improved detail in 355 < $f_y \leq$ 550 MPa steel would be FAT 360. The FAT proposals in SHSS and ENS methods are shown in Table 3.3 and they are defined only for HFMI-treated fillet welds.

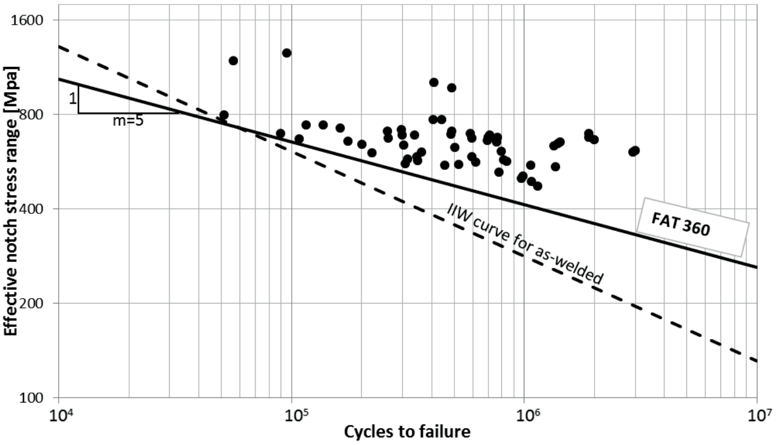
Figure 3.6 shows the experimental data represented as ENS and grouped according to f_y, the proposed characteristic S-N lines from Table 3.3 for HFMI-improved welds and the IIW characteristic curve for as-welded joints. No points in Figure 3.6 fall below the proposed S-N lines. Thus, the target survival probability for the characteristic lines is achieved considering that FAT classes represent discrete steps.

For all fatigue assessment methods, the use of yield strength correction representing one fatigue class (approximately 12.5%) increase in strength for every 200 MPa increase in f_y was verified. In the high cycle regime, the proposed increase in fatigue strength for HFMI-treated high strength steel welds can be significantly greater than that is in the IIW guideline for hammer or needle peened welds. In the low and medium cycle regime, though, the new proposals may even result in lower allowable stresses. For instance, with reference to Figure 3.3a and Table 3.2, for longitudinal welds with 355 < $f_y \leq$ 550 MPa in the NS system, the current study shows a maximum FAT class increase of five (5) while the IIW guideline gives only three (3). However, it should be noted that the current study is based on a recommended S-N slope $m_1 = 5$ while the IIW guideline uses $m_1 = 3$. This means that for $N_f = 3.7 \times 10^5$ cycles, the current proposal actually allows lower ΔS in comparison with the IIW guideline even though the current study proposes an increase of two additional FAT classes. For longitudinal welds with 550 < $f_y \leq$ 750 MPa, the current study proposes a FAT class increase of six (6). This means that the current proposal allows lower ΔS than the IIW guideline for $N_f = 1.8 \times 10^5$ cycles. Even for the greatest yield strength f_y > 950 MPa, the current study proposes an increase of eight (8) FAT classes. In this case, the current proposal allows lower ΔS than the IIW guideline for $N_f < 2.4 \times 10^4$ cycles. Similar observations can be made for the other joint geometries and other assessment methods, see Publications II and III.

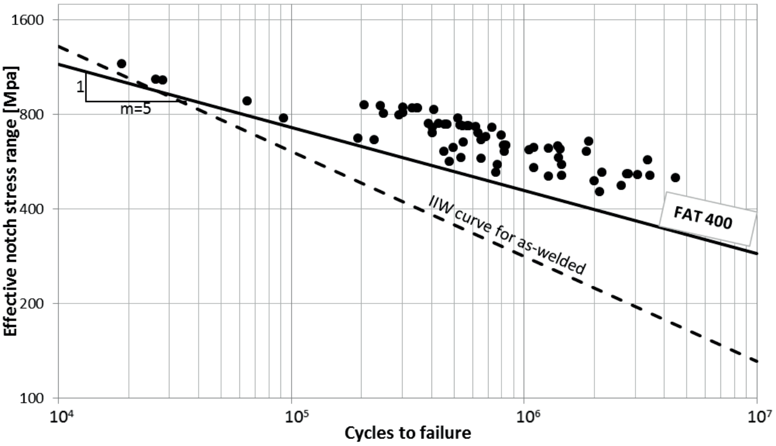
The change in slope of the S-N lines between the as-welded state and following HFMI treatment results in a change in the computed fatigue strength improvement as a function of N. For a low strength steel welded detail it was shown that the S-N lines intersect at about N = 72000 cycles.



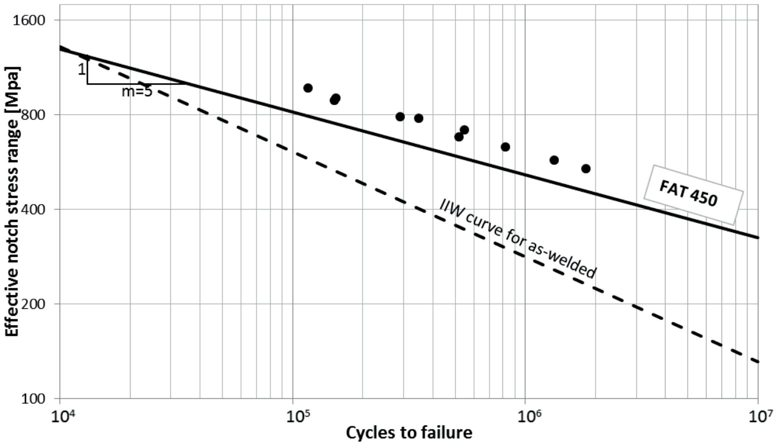
(a) $235 < f_y \leq 355$



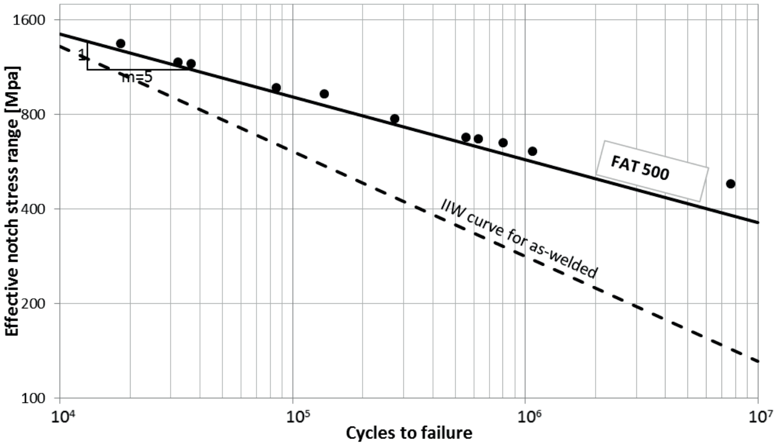
(b) $355 < f_y \leq 550$



(c) $550 < f_y \leq 750$



(d) 750 < $f_y \leq 950$



(e) 950 < f_y

Figure 3.6. Experimental data for HFMI-treated welds based on ENS with ρ_f=1 mm. Proposed characteristic curves from Table 3.3.

For higher strength steels, the computed cycle limits below which HFMI does not provide benefit were given by Marquis et al. [25]. These values are shown in Table 3.4. As can be seen from this table, for steels with yield strength f_y > 750 MPa, it is computed that HFMI would have a beneficial effect even into the low cycle fatigue regime, N < 10000 cycles.

Table 3.4. Computed cycle limit below which HFMI is not expected to result in fatigue strength improvement as a function of f_y [25].

Steel grade [MPa]	N [cycles]
$f_y \leq 355$	72000
355 < $f_y \leq 550$	30000
550 < $f_y \leq 750$	12500
750 < f_y	<10000

3.3 Experimental round robin study

3.3.1 Test results

Six specimens from each equipment manufacturer were fatigue tested using a single test machine and identical loading history. The specimens were fatigue tested under load-controlled axial loading in a hydraulic fatigue testing machine.

Variable amplitude test results for as-welded and HFMI-treated longitudinal non-load carrying attachments are shown graphically in Figure 3.7 with the expected IIW characteristic variable amplitude line (FAT 80) for this specimen and the characteristic line (FAT 160) for HFMI-treated specimens with 550 < $f_y \leq$ 750 MPa. Equivalent stress ranges were calculated using a bi-linear S-N curve assumption for variable amplitude loading as presented by Niemi [26], Eq. 3.1. In this equation, the S-N line was assumed to change slope from m_1 for $N = 1 \times 10^7$ to $m_2 = 2m_1 - 1$ for $N > 1 \times 10^7$. Damage summation of D=1 was assumed since the obtained results could all be covered with this value. According to Publication I, a recommended S-N slope for HFMI-treated welds was $m_1 = 5$ for cycles above ΔS_k. Thus, for HFMI-treated specimens, $m_2 = 9$ was used for $N > 1 \times 10^7$. For this type of specimen geometry, the S-N curve knee point, ΔS_k = 123 MPa, was determined at $N = 1 \times 10^7$ based on HFMI constant amplitude test data available in the literature Publication II. For as-welded case, on the other hand, ΔS_k = 70 MPa was determined at $N = 1 \times 10^7$ based on FAT 80. Slopes $m_1 = 3$ and $m_2 = 5$ were used for as-welded case.

$$\Delta \mathrm{S_{eq}} = \left(\frac{1}{\mathrm{D}} \times \frac{\sum \Delta \mathrm{S_i^{m_1} n_i} + \Delta \mathrm{S_k^{(m_1-m_2)}} \times \sum \Delta \mathrm{S_j^{m_2} n_j}}{\sum \mathrm{n_i} + \sum \mathrm{n_j}}\right)^{\frac{1}{m_1}} \tag{3.1}$$

In Eq. 3.1, n_i is the number of cycles of stress ΔS_i where $\Delta S_i \geq \Delta S_k$ and n_j is the number of cycles of stress ΔS_j where $\Delta S_j < \Delta S_k$.

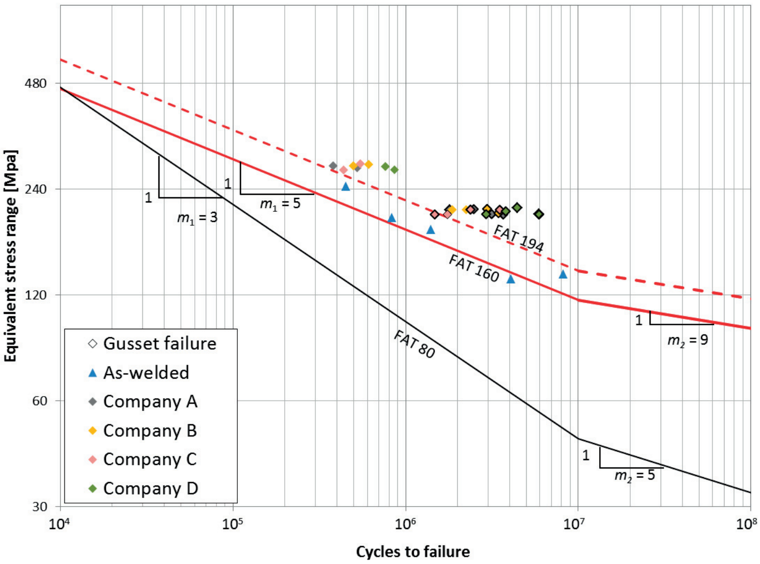


Figure 3.7. Fatigue test results obtained from variable amplitude loading with a previously proposed design line FAT 160 (in red) in the NS method for 550 < $f_y \leq$ 750 MPa by Yıldırım and Marquis (Publication II).

From the fatigue design point of view, it is important to note that all test results for HFMI-treated specimens are well above the proposed S-N line (FAT 160) for this specimen type and material. All data points are also above the expected 50% survival probability of the design curve which is shown as a dashed line. Ideally, the experimental data would be scattered on both sides of this FAT 194 line. Notice that FAT 160 was previously-proposed in Publication II based on a literature study of HFMI-treated longitudinal, cruciform and butt welds subject to R = 0.1 constant amplitude loading. The variable amplitude stress term is presented as an equivalent constant amplitude stress considering a bi-linear S-N curve assumption for variable amplitude loading as presented by Niemi [26]. Therefore, comparison of the influence of variable amplitude loading can be made using Figure 3.7 [27].

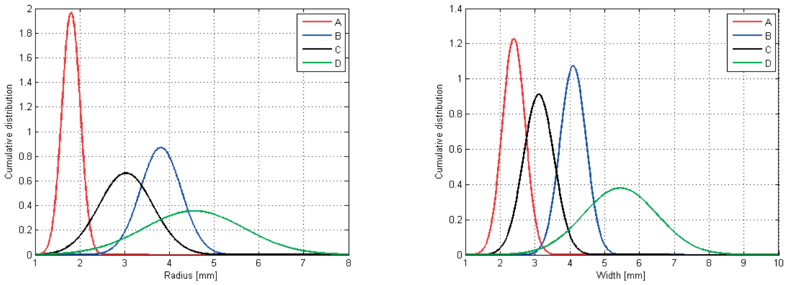
3.3.2 Weld profile and straightness measurements

Weld toe measurements using the silicon replica method were performed at the notch of HFMI-treated welds. Measurements were done at the four weld toes of each specimen taking into account radius, width and depth. Then, full statistical evaluation of radius, width and depth of the obtained HFMI groove was performed using a normal distribution, see Figure 3.8. It should be noted that other distributions were not evaluated for these measurements. The average values for all measurements for each company (A, B, C and D) and the standard deviations are given in Table 3.5. The average values of HFMI groove radius varied from 1.80 mm to 4.55 mm, groove depth varied from 0.16 mm to 0.29 mm, and groove width varied from 2.39 mm to 5.45 mm. It should be noted that the bottom of the HFMI groove is not perfectly spherical and so the radius is not constant for the entire groove. These values are consistent with recommended values for UP treatment as recommended by Kudryatsev [8].

Table 3.5. Average values of HFMI-treated weld measurements for companies A, B, C and D and standard deviations.

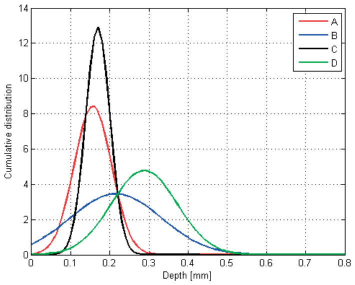
Manufacturer	Radius [mm]		Width [mm]		Depth [mm]	
	mean	SD	mean	SD	mean	SD
A	1.80	0.20	2.39	0.32	0.16	0.05
B	3.81	0.46	4.10	0.37	0.22	0.11
C	3.03	0.60	3.11	0.43	0.17	0.03
D	4.55	1.11	5.45	1.05	0.29	0.08

Angular distortions of the specimens before and after treatment were measured. Measurement values were in all cases small and never exceeded 1° in the as-welded condition. Straightness measurements on all specimens were repeated following HFMI treatment. No measurable change in angular misalignment was found for any of the HFMI treatments. Therefore, HFMI treatments used in this study from four different manufacturers had no influence on the straightness of specimens. All measurements were clearly presented in Publication IV.



(a) Radius

(b) Width



(c) Depth

Figure 3.8. Statistical analysed HFMI weld toe radius, width and depth for several HFMI technologies (A-D). Test specimens are from a round robin study presented in Publication IV.

3.3.3 Residual stress measurements

X-ray diffraction-based residual stress measurements were taken on some specimens both before and after fatigue testing. These were reported in Publication IV. All four weld toes for a specimen were measured before testing. After testing only the two weld toes distant from the point of fatigue fracture could be reliably measured. The measurements include pre-fatigue test measurements for two as-welded and eight HFMI-treated specimens. Further measurements following fatigue testing includes the same two as-welded specimens and six of the eight HFMI-treated specimens. Reported stress values in Publication IV were in the direction longitudinal with respect to the axis of the specimen, i.e., perpendicular to the local weld toes at the stiffener end.

Tensile residual stresses were measured in the case of all as-welded specimens' weld toes whereas compressive residual stress were observed in 31 of the 32 HFMI grooves prior to fatigue testing. In all HFMI welds the measured value moved in the direction of increased tensile stress, i.e., initially compressive residual stresses were significantly less compressive or even slightly positive after variable amplitude fatigue loading. It means that significant compressive residual stress relaxation occurred during fatigue loading. After complete fracture of as-welded specimens, on the other hand, smaller values of tensile residual stresses were measured indicating that some relaxation of stresses during constant amplitude fatigue loading had occurred. In all as-welded cases, though, the residual stresses at the weld toes following fatigue testing were still tensile.

Table 3.6 summarizes the observations made at eight (8) weld toes for each of the four HFMI treatment procedures. Treatment B had the lowest compressive mean value but also the lowest standard deviation while treatment C had the greatest compressive mean value and the greatest standard deviation. Overall there does not seem to be a dramatic difference in the surface residual stresses at the bottom of the HFMI groove between the different treatments.

3.3.4 The effective notch stress approach using actual radius

The IIW recommendations for the notch stress method enables the addition of 1 mm to the actual radius, see Eq. 2.5. In this case, however, the notch stress needs to be assessed against a slightly reduced fatigue class.

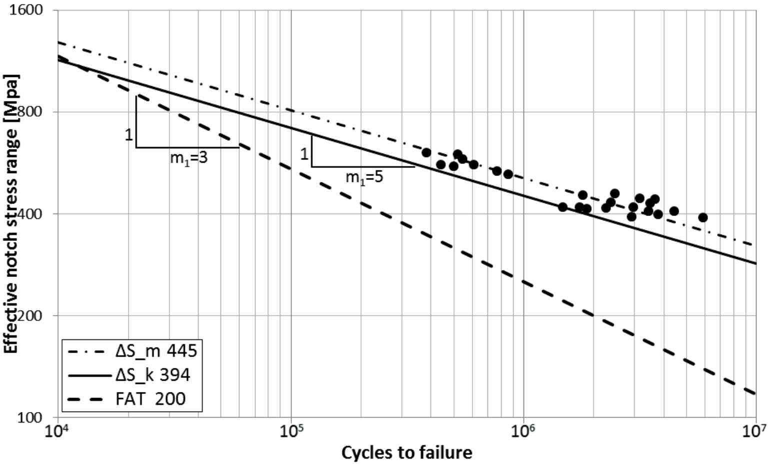
Table 3.6. Mean and standard deviation of the measured residual stresses for the four different HFMI treatments based on data reported in Publication IV.

	Treatment			
residual stress [MPa]	A	B	C	D
mean value for eight (8) weld toes	-243	-206	-277	-239
standard deviation for eight (8) weld toes	92	88	167	131

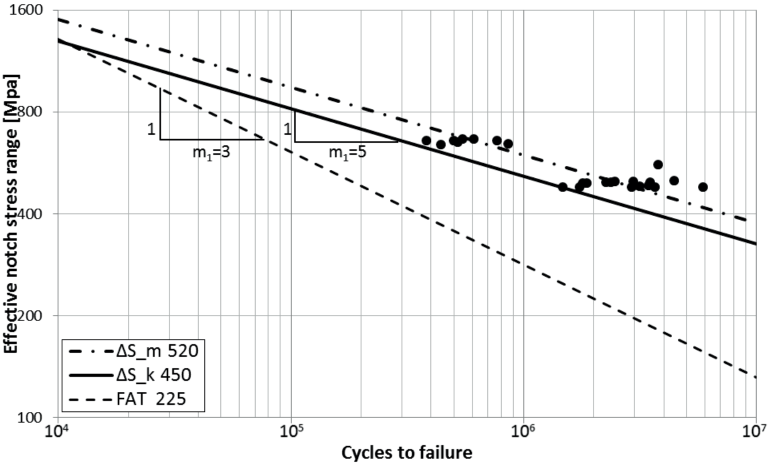
A suitable fatigue class in the IIW system is defined as FAT 200 [17]. This approach has not been established and verified for welds with larger weld toe radius yet, like the HFMI-treated welds. Nevertheless, an evaluation of this approach was necessarily performed for the round robin test data from Publication IV. The average radii values of HFMI-improved welds for each manufacturer from Table 3.5 were used. Stress concentration values were calculated using finite element analyses with the addition of actual average radius values to 1 mm.

Effective notch stress assessment of experimental study considering actual radius is shown in Figure 3.9a. The expected IIW characteristic line, FAT 200, is also shown. It is clear from the figure that both the characteristic curve and S-N slope $m_1 = 3$ are not consistent with the notch stress data. In other words, the IIW curve allows significantly less applied stress in the high cycle region as compared to the regression lines evaluated from fatigue data. Additionally, the characteristic fatigue strength, based on the statistical assessment of experimental fatigue data and stress concentration evaluated using ρ_f = 1 mm, was found to be 450 MPa in Figure 3.9b. The corresponding proposed maximum possible FAT class, FAT 400, in Table 3.3 for fillet welds from steel with 550 < $f_y \leq$ 750 MPa is shown in Figure 3.10. The consistency of these two values and the S-N slope $m_1 = 5$ indicate that the ENS method based on fictitious radius ρ_f = 1 mm is easer to apply compared to the procedure of addition of actual radius to 1 mm.

In literature, the benefits of HFMI treatment technologies are considered to be derived from the introduction of beneficial compressive residual stresses near the weld toe, as well as the achievement of a smooth transition from parent material to weld metal via the establishment of a defined weld groove shape. Since this study is based on available experimental test results, all features which contribute to increased fatigue strength have already been included. With regard to the ENS method, it has been shown in Table 3.5 that the HFMI groove profile following treatment from various HFMI technologies produce different toe radii depths



(a) $\rho_f = \rho + 1$ mm



(b) $\rho_f = 1$ mm

Figure 3.9. Effective notch stress assessment of round robin test results considering (a) actual toe radii and (b) fictitious radius ρ_f = 1 mm.

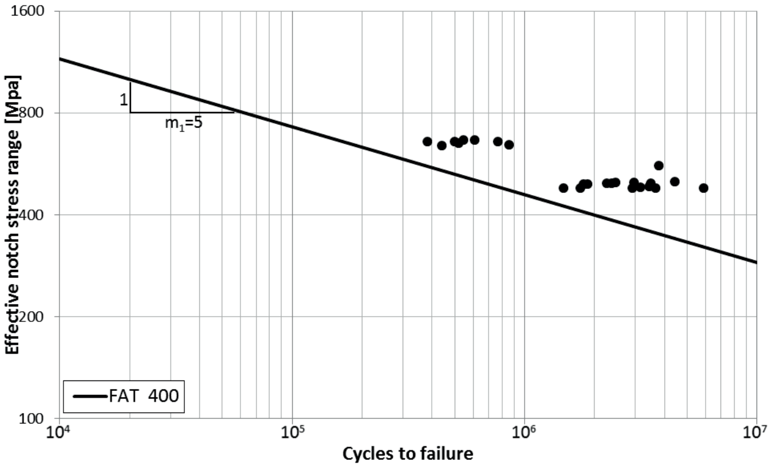


Figure 3.10. Effective notch stress assessment of round robin test results considering fictitious radius ρ_f = 1 mm and proposed FAT value at 550 < $f_y \leq$ 750 MPa from Table 3.3.

and widths. This can be also seen in Figure 3.8 for weld toe measurements of HFMI-treated welds. Instead of measuring each HFMI weld profile and applying distinct radii for each application, the use of ρ_f = 1 mm even for HFMI-improved weld models is a more practical and easier-to-implement solution. End users who regularly resort to the ENS approach frequently have automatic meshing routines which can then be used for an entire structure, including both HFMI-treated welds and non-treated welds.

4. Conclusions

In this dissertation design aspects of welded steel structures improved by high frequency mechanical impact (HFMI) treatment have been studied. HFMI fatigue data points from several treatment technologies were reported, however no attempt has been made to separate the methods or provide any ranking. An appropriate design S-N curve has been suggested to represent the available data. It has been shown that the degree of fatigue strength improvement for HFMI-treated welds depend on the material yield strength. The fatigue strength of HFMI-treated welds with different steel grades has been assessed by considering an empirical relation between the material yield strength and the degree of improvement. A single design methodology for numerous HFMI technologies has been verified by the experimental study. The existing local stress-based fatigue assessment methods have been extended also to include proposals for HFMI-improved welds.

In total, 441 data points for the four specimen types were presented. Most tests have been performed using constant amplitude R = 0.1 axial tension fatigue, but some data for other R-ratios, variable amplitude testing and bending were also reported. Material yield strength varied from 267 MPa over 900 MPa and plate thickness varied from 5 mm to 30 mm.

More specificity the following conclusions are highlighted:

1. An S-N slope of $m_1 = 5$ fit well with the available HFMI-treated fatigue data. Thus, all of the following conclusions were based on an assumed S-N slope of $m_1 = 5$ and fatigue strength improvements were defined at $N_f = 2 \times 10^6$.

2. An increase in fatigue strength with the material yield strength was found. A yield strength correction method was proposed and verified.

HFMI-treated welds with different yield strength were analysed together by the correction method. Approximately 12.5% increase in strength for every 200 MPa increase in f_y above $f_{y,o}$ was found. This correction significantly reduced the observed scatter in the data with respect to data without any yield strength correction.

3. Fatigue classes for the NS, SHSS and ENS systems which represent the fatigue strength of HFMI-improved joints at $N_f = 2 \times 10^6$ cycles and assume an S-N slope $m_1 = 5$ were proposed and verified with the available data.

4. For the NS and the SHSS method, a five (5) fatigue class improvement with respect to the same weld detail in the as-welded condition was proposed and verified for welds with 355 < $f_y \leq$ 550 MPa. For the ENS method, a four (4) fatigue class improvement was proposed and verified.

5. For the ENS method, instead of measuring each HFMI weld profile and applying distinct radii for each application, the use of ρ_f = 1 mm even for HFMI-improved weld models could be a more practical and easier-to-implement solution.

6. The proposed characteristic curves were found to be conservative with respect to more than 95% of the available fatigue test data.

7. According to the experimental round robin study, all of the HFMI-improved welds from the four different HFMI equipment manufacturers satisfied the previously-proposed characteristic S-N line.

8. Based on the X-ray diffraction measurements of round robin test specimens, residual stress states following the treatment were generally similar even though the HFMI groove dimensions were different. Furthermore, significant compressive residual stress relaxation did occur during fatigue testing.

9. Welded specimens treated by HFMI methods tend to have slightly greater fatigue strength than do specimens treated with traditional hammer peening.

10. Results of the study are valuable and promising for the usage of the HFMI improvement techniques.

In the future, more data obtained at stress ratios other than R = 0.1, for variable amplitude testing are needed. More HFMI data for different type of specimens with yield strength greater than 750 MPa should be studied. Studies on large structures improved by HFMI treatment method are encouraged. The fracture mechanics approach should also be applied for HFMI-treated welds. More specific considerations should be given when assessing specimens with low stress concentration values. Also, more studies on residual stress stability during loading for treated welds should be encouraged. Attention must also be given to defining quality assurance procedures for HFMI-treated welds. Extensive literature review on other improvement techniques, e.g. TIG dressing or burr grinding, should be performed. When reporting test results, researchers are encouraged to explicitly provide the experimental data points and to clearly define the observed failure location for each test.

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In the past decade, high frequency mechanical impact (HFMI) has significantly developed as a reliable, effective and user-friendly method for post-weld fatigue strength improvement technique for welded structures. This doctoral study presents one approach to fatigue assessment for HFMI-improved joints. A yield strength correction procedure which relates with the material yield strength is presented and verified based on the constant amplitude R = 0.1 axial tension fatigue data. Stress analysis methods based on the nominal stress, the structural hot spot stress and the effective notch stress are all discussed. All the proposed design recommendations in this study are conservative with respect to available fatigue test data. Experimental test results indicate that all of the HFMI-improved welds from the four HFMI equipment manufacturers satisfy the proposed characteristic S-N line which is based on both the material yield strength and the specimen geometry.

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