CHALMERS

Post weld treatment

Implementation on bridges with special focus on HFMI

POJA SHAMS HAKIMI
MOHAMMAD AL-EMRANI

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014
Report 2014:8

REPORT 2014:8

Post weld treatment

Implementation on bridges with special focus on HFMI

POJA SHAMS HAKIMI

MOHAMMAD AL-EMRANI

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014

Post weld treatment
Implementation on bridges with special focus on HFMI

POJA SHAMS HAKIMI
MOHAMMAD AL-EMRANI

Report 2014:8

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber *Structures*
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Post weld treatment of a laboratory test specimen. Adapted from M. Heshmati, "Fatigue Life Assessment of Bridge Details Using Finite Element Method" 2012

Chalmers reproservice
Göteborg, Sweden 2014

Post weld treatment

Implementation on bridges with special focus on HFMI

POJA SHAMS HAKIMI
MOHAMMAD AL-EMRANI
Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
Chalmers University of Technology

ABSTRACT

Post weld treatment is a measure of fatigue enhancement of steel and aluminum structures and is today a common procedure in many industries due to the substantial improvements that is gained by it. In the bridge industry, steel and composite bridges have lost competitiveness in recent years due to high requirements on the fatigue design, resulting in more use of material. Although, experiences regarding post weld treatment have not come as far in this industry, studies indicate that large savings with more than 20% material reduction can be achieved for a bridge. This combined with the fact that higher material grades increase fatigue performance after treatment, yields considerable economic advantages and positive effects on the bridges life cycle costs, not to forget the environmental benefits.

Herein, examples of nine new and old bridges that have been subjected to post weld treatment are presented, together with international studies regarding fatigue improvement assessment and procedure and quality control recommendations. Furthermore, studies of modeling this technology by finite elements are presented to show the extent of knowledge that exists within this filed, including residual stress simulations, simulations of the post weld treatment and fatigue simulations by different methods. This is of importance for making parameter studies and gain more experience prior to bridge application.

Key words: bridges, fatigue, enhancement, post weld treatment, HFMI, finite element modelling

Svetsefterbehandling
Implementering på broar med fokus på HFMI

POJA SHAMS HAKIMI
MOHAMMAD AL-EMRANI
Institutionen för bygg- och miljöteknik
Avdelningen för Konstruktionsteknik
Stål- och träbyggnad
Chalmers tekniska högskola

SAMMANFATTNING

Svetsefterbehandling är ett sätt att förbättra utmattningsegenskaperna hos stål- och aluminiumkonstruktioner och är idag en vanlig metod i många industrier tack vare den markanta förbättringen som erhålls. Inom broindustrin har stål- och samverkansbroar tappat konkurrenskraft de senaste åren på grund av höga krav på utmattningsdimensioneringen, vilket resulterat i mer materialanvändning. Fastän erfarenheten av svetsefterbehandling inte kommit lika långt i denna industri visar studier på att stora besparingar med mer än 20 % materialreduktion kan uppnås för en bro. I kombination med det faktum att högre materialhållfasthet kan öka utmattningshållfastheten efter svetsefterbehandling fås betydliga ekonomiska fördelar både i byggskedet och ur ett livscykelperspektiv samt inte minst fördelar för miljön.

I denna rapport presenteras exempel på nio nya och gamla broar som har blivit svetsefterbehandlade samt internationella studier rörande rekommendationer för utvärdering av förbättring i utmattningshållfasthet och process och kvalitetssäkring. Dessutom presenteras studier som berör modellering av svetsefterbehandling med finita element för att sammanfatta kunskapen som finns inom området. Dessa inkluderar simulering av egenspänningar, svetsefterbehandlingens effekter samt utmattningsbeteendet. Detta är av vikt för att utföra parameterstudier inför tillämpning på broar.

Nyckelord: broar, utmattning, förbättring, svetsefterbehandling, HFMI, finita element

Contents

Preface

This study was performed between May and September of 2014 as collaboration between Chalmers University of Technology and ELU Konsult AB, and was financed by the Swedish Road Administration. It was performed to present the state-of-the-art in the field of post weld treatment for fatigue enhancement, to promote the application of this technology on Swedish bridges. The following persons are greatly appreciated for their contributions to this report:

- Peter Gerster, PITEC GmbH
- Michael Neher, PFEIFER GmbH
- Yuri Kudryavtsev, SINTES
- Alain Nussbaumer, Federal Institute of Technology in Lausanne (EPFL)
- Martin Leitner, Montanuniversität Leoben
- Scott Walbridge, University of Waterloo
- Zuheir Barsoum, Kungliga Tekniska Högskolan (KTH)
- Mohsen Heshmati, Chalmers University of Technology (CTH)
- Farshid Zamiri Akhlaghi, Chalmers University of Technology (CTH)

1 Introduction

As a preliminary study requested by the Swedish Road Administration under the project "Competitive Steel & Composite Bridges", this report is intended to present a state-of-the-art regarding post weld treatment (PWT) implementation on bridges. Special focus is put on the ***High Frequency Mechanical Impact (HFMI)*** treatment techniques. Studies conducted at Chalmers University of Technology show that significant improvement of fatigue life can be achieved by PWT of bridge details prone to fatigue failure [1]. This can in some cases lead to material savings with more than 20% [2].

1.1 Background

Fatigue enhancement procedures are today used in a variety of applications in many different industries. Some examples are crane [3][4][5], wind power [5][6], offshore [7][8], aircraft, spacecraft and the automotive industries [9]. With such procedures, the automotive industry has been able to substantially reduce material consumption in their products in recent years. This has led to reduced fuel consumption, increased power output and higher safety, among other benefits [9]. During the last seven years, PWT has become an accepted method for life extension of existing offshore structures. Thanks to the progress in understanding the performance of different treatment procedures and the development of quality assurance methods, the use of PWT techniques for fatigue life enhancement of welded details is now common practice in this field [7].

In the bridge industry, the progress of fatigue enhancement procedures has not come as far. In many cases for steel and composite bridges, failure due to some limited number of fatigue-sensitive details is the decisive factor in design, resulting in higher material usage than otherwise necessary in ultimate or serviceability limit states. This has led to reduced competitiveness for these bridges. With implementation of fatigue enhancement methods such as PWT on a few details in steel bridges, substantial material savings can be achieved. In combination with use of high strength steel, this can result in considerable weight reduction and economic advantages. Many studies show that the fatigue strength of welded steel details can become at least 1.3-1.6 times stronger by PW-treating the weld toe, removing flaws and impurities that were introduced during welding. Moreover, the PWT also results in a smoother geometry in the transition between weld and steel plate, reducing stress concentrations. These effects together increase the number of load cycles necessary to reach fatigue failure since a high number of load cycles can be endured during the crack initiation phase. In non-treated welds, the initiation phase is negligible, thus, fatigue loading almost directly gives rise to crack propagation.

1.2 Objectives

The aim of this report is to give an overview of different post weld treatment techniques and set a base for further research regarding implementation of such techniques on bridges. Deeper focus is put on HFMI treatments. Mainly three questions are answered:

- What international studies have been made regarding PWT, and are there relevant fatigue tests and design rules/recommendations available?
- Are there examples of PWT applications in the bridge industry?

Are there any examples of FE-modeling of PWT-effects and can they give reliable predictions?

2 Post weld treatment

In this section, a compilation of relevant information and studies are presented, both generally for different post weld treatment techniques, and more specifically for the HFMI methods. HFMI treatments include several different high frequency peening techniques and equipment, such as ultrasonic impact treatment (UIT), ultrasonic peening (UP), high-frequency impact treatment (HiFIT), etc. Common for all of these techniques is that indenters of high strength steel are used to impact the steel material at the weld toe region with high frequency. In general, all post weld treatment techniques enhance the fatigue strength through two main mechanisms:

1. Smother transition in the area of weld toe
2. Removal of weld defects in the weld toe from which fatigue cracking takes place in as-welded details (undercut)

These mechanisms contribute to reduced stress concentrations and a positive shift of fatigue strength properties towards those of plain, non-welded details, see Figure 1. The crack initiation phase becomes longer and leads to fatigue strength improvement. Thanks to a longer crack initiation phase, increase of steel grade also improves fatigue strength in PW-treated welded details [10].

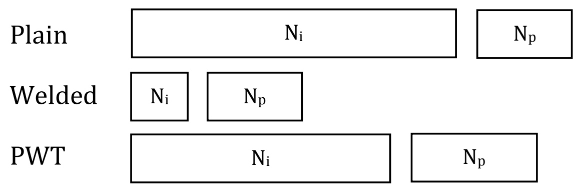

Figure 1. Schematic illustration of fatigue life of steel details. Ni = Number of cycles for crack initiation. Np = N cycles for crack propagation to failure. Adapted from [2].

Some PWT techniques, such as HFMI, give additional advantages by altering the residual stress state around the weld toe area. In as-welded details, the weld toe area usually experiences considerable tensile stresses [4], which are unfavorable with respect to fatigue. Altering the residual stresses into more favorable compressive stresses can thus lead to higher fatigue strength. Based on the discussed effects, PWT methods can be divided into two groups. Group 1 – “Stress Concentration Factor (SCF) reducing” and Group 2 – “Residual stress altering”.

The benefits gained from residual stress altering PWTs of the weld toe can be substantial, especially in combination with high material strengths, however, the induced compressive residual stresses might decrease or completely get relaxed under certain loading conditions. Awareness of this is important and more on this subject is discussed in section 2.3. Furthermore, it is emphasized that weld toe treatment is irrelevant for details in which the fatigue strength is governed by failure in the weld root.

2.1 Comparison of different methods

Four different weld profiles are illustrated in Figure 2. The first is an as-welded specimen (AW) and the other three are specimens treated with different PWT techniques; Burr grinding (BG), ultrasonic impact treatment (UIT) and TIG dressing (TIG).

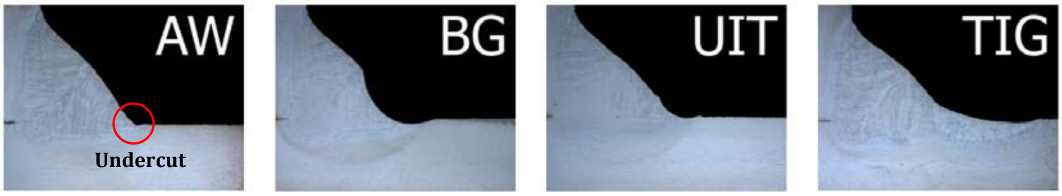

Figure 2. The as-welded (AW) weld profile with the undercut defect and the weld profiles after treatment with burr grinding, ultrasonic impact treatment and TIG dressing, respectively. Adapted from [4].

BG and TIG primarily enhance fatigue performance by making the transition between weld and base plate more continues, reducing stress concentration (Group 1). These methods also remove weld toe flaws and impurities, such as the devastating undercut from which cracks normally propagate under fatigue loading. With BG, the material is mechanically ground away while with TIG, the weld toe is re-melted. UIT mainly enhances fatigue performance by inducing compressive residual stresses through cold working with high frequency impacts (Group 2). Also in this case, stress concentrations are reduced and weld defects removed. Figure 3 illustrates typical examples of tools used for these PWTs.

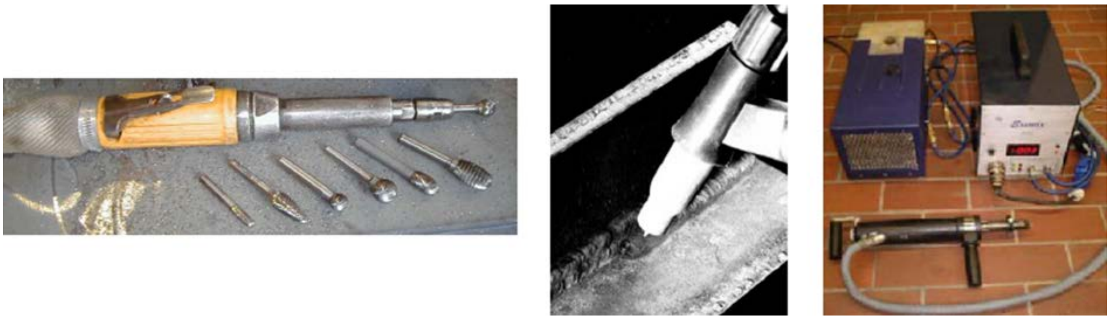

Figure 3. Burr grinding (left), TIG dressing(middle) and UIT (right) tools [4][11].

These techniques were compared in a study by Pedersen et al [4]. The study aimed at finding the most suitable PWT method for mass production in the mobile lifting equipment and crane industry, where high strength steel (HSS) is a common choice of material and a low weight is of importance. In these structures, medium cycle fatigue with high stress ranges is decisive for the failure. The results of the study are presented in Table 1. It was concluded that high strength steel can be used advantageously for medium cycle fatigue when PWT is executed. For a fatigue life of 100.000 cycles, the improvements were practically identical for all methods and for a fatigue life of 2 million cycles, UIT gave the highest improvement and BG, a considerably lower improvement in comparison.

Table 1. Comparison of different PWT methods [4]. MC = Medium cycle (100.000), HC = High cycle (2 million).

Method	Improvement		Comments
Burr grinding	MC: +31%	HC: +49%	Slow process. Not applicable on thin plates.
TIG dressing	MC: +38%	HC: +70%	Smoothest transition from weld to plate. Significantly faster than BG. Flexible with regard to Start/Stop. Considerable variation of TIG dressed profile along the weld length.
Ultrasonic impact treatment	MC: +33%	HC: +78%	By far the fastest technique. More time consuming at Start/Stops. Easy to apply. Little force input needed => comfortable => better results

TIG dressing was identified as the most suitable PWT for this application due to the large improvements in medium cycle fatigue, availability of equipment and flexibility of the process. In the case of lifting cranes, where a few highly stressed welded details are decisive for the whole structures capacity, post treating a weld of 500mm resulted in a light weight and durable design.

Tominaga et al [3] also carried out comparisons in their study, regarding repair of crane runway girders. These structures carry the cranes and work similarly to bridges. The effectiveness of fatigue improvement of UIT was compared to grinding by small and large scale fatigue testing of 400MPa mild steel details. According to Tominaga et al, UIT gave an improvement of three fatigue classes (corresponding to 8 fold life increase) compared to one fatigue class for grinding, in accordance with the fatigue classification system of the Japanese Society of Steel Construction. UIT was also found to be more efficient from operational aspects, compared to grinding and hammer peening. Hammer peening is similar to UIT, but is an older method with much lower frequency impacts.

The Technical Committee 6, under the organization “European Convention for Constructional Steelwork”, also discusses various advantages of different PWT methods. In general PWT gives most efficient results for detail categories between FAT 36 – 80, and negligible effects on categories equal to or above FAT 90. Treatment methods belonging to Group 1 (SCF reducing) yield an improvement with a factor of 1.3 in stress range. While methods in Group 2 (residual stress altering) yield an improvement of 1.3 – 1.6, depending on the applied stress ratio, maximum stress, weld detail and choice of method. HFMI is considered to possibly yield even higher improvement especially in the case when high strength steel is used.

2.2 International recommendations

Fatigue enhancement with PWT is basically not covered in international codes, with some limited exceptions, according to Nussbaumer [12]. However, recommendations do exist. For HFMI treatment, recommendations are currently under development, see section 2.3.

The International Institute of Welding (IIW) gives recommendations regarding four different PWT techniques; burr grinding, TIG dressing, hammer peening and needle peening [11]. The recommendations are intended for both new structures and for fatigue life extension of existing ones. The IIW recommendations address issues as equipment, procedures, inspections and quality control and also improvement assessment. The improvement assessments are made by means of S-N curves, which were derived from laboratory experiments conducted on post weld treated specimens. The scope of the recommendations is restricted to steel plate thicknesses between 6 to 50mm and for steel grades up to 900MPa. Moreover, for the peening improvement methods, which rely on compressive residual stresses that are vulnerable to high compressive loading, the maximum stresses must not exceed 80% of yield stress and stress ratios must be smaller than R = 0.5.

In the following, examples of IIW recommendations are presented for burr grinding and hammer peening. For corresponding recommendations for the other PWTs, it is referred to [11]. However S-N curves applying for all PWT improvements are presented in Figure 5.

The extent of weld preparation that is necessary varies depending on the PTW applied. For burr grinding, de-slagging and wire brushing of the weld is enough. Regarding burr grinding equipment, specific requirements are given by the IIW for the rotation speed of the burr, which should be between 15 000 and 40 000rpm in case of pneumatic, hydraulic or electric grinders. For air-driven grinders, a pressure of 5 to 7 bars is recommended. Diameter of the burr should be scaled relative to the plate thickness (t), where burrs with diameters between 10 to 25mm should be used on plates with thicknesses between 10 to 50mm.

For the procedure of burr grinding, recommendations are given considering the angle of the tool, treatment length and groove depth, see Figure 4. Groove radius should not be less than 0,25t. No trace of the original weld toe should remain and no scratches should exist in the groove, parallel to its length direction. These properties of the groove should be measured and visually inspected in bright light with magnifying glass.

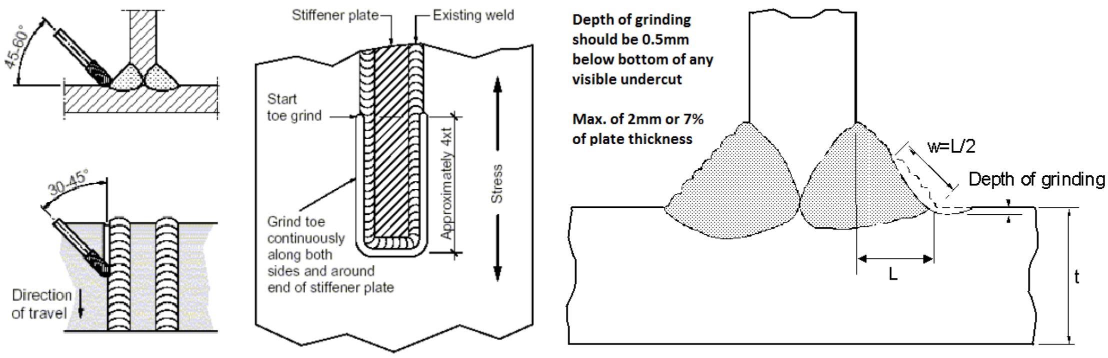

Figure 4. Procedure recommendations of IIW for burr grinding [11].

For hammer peening, traces of oxide, scale, spatter and other materials must be removed from the loaded plate adjacent to the weld as well as the weld cap. This is done by de-slagging and wire brushing, or alternatively by grinding. Peaky or severely convex welds can cause defects that result in worsening of the fatigue performance when impacted. Thus, preparation in form of light grinding is advised to gain a normal shape.

When residual stress altering PWTs such as hammer peening is applied, the degree of fatigue improvement is benefited if the treated detail is subjected to tension during treatment. Conversely, a state of compression during treatment lessens the improvement. The hammer peening equipment used in most research investigations fulfil following specifications; these are therefore recommended. A suitable device has piston diameter between 15 to 30mm, runs with an air pressure of 5 to 7 bars and has a frequency between 25 and 100Hz. The device weight varies between 1.0 to 3.5kg and the impact energy delivered, between 5 and 15 Joule. The indenter which impacts the material should have a hemispherical shape with a radius of 3 to 9mm. It must continuously be verified that the indenter is not worn out.

When performing hammer peening treatment, the positioning of the indenter is important. Both the weld material and the base plate on either side of the weld toe need to be deformed. The tool should be held at a 45° angle to the base plate and preferably 90° to the direction of travel. A groove depth of at least 0.3mm should be reached for structural steels of less than 600MPa and after four passes. Normally, a depth of 0.5mm is achieved. It is recommended to combine the use of small and large indenter diameters to increases the likelihood of the weld toe actually receiving treatment. To assure that these criteria are fulfilled, qualitative inspection should be performed to ensure a uniform groove with smooth finish, without any trace of the original weld toe. With visual inspection, crack-like flaws can be detected and the overall treatment should be compared to reference specimens with well executed treatments.

If all requirements are satisfied, improvement assessment can be carried out with the help of the following design S-N curves, see Figure 5. Values within parenthesis regard fatigue class (FAT) before treatment. The curves basically give an improvement of two FAT classes for BG and TIG, corresponding to a factor of around 2.0 on fatigue life, and for the peening techniques an improvement of three FAT classes, which gives a factor of around 2.8 on fatigue life. Though, reduction expressions must be used for plate thicknesses (t) exceeding 25mm, since the S-N curves are derived for this reference thickness, see equation (1) [11]. As can be noted, for low cycles, no improvement is achieved greater than the curve for parent material, FAT 160. A change of slope from m=3 to 5 occurs at 10 million cycles for variable amplitude loading. For the peening treatments, IIW gives further restrictions on the applied stresses. The higher S-N curves can only be used if compressive loads are lower than $0.25f_y$. When stress ratios of $R \geq 0$ are applied, the curves must be used in conjunction with maximum stresses instead of stress ranges.

$$f(t) = \left(\frac{25}{t_{eff}}\right)^{0.2}, \tag{1}$$

$t_{eff} = 0.5L \ for \ L/t \ \leq 2$ and

$t_{eff} = t \ for \ L/t \ > 2$

Det Norske Veritas (DNV) [13] also gives recommendations of PWT improvements, by means of factors on fatigue life, see Table 2. Treatments included are grinding, TIG dressing and hammer peening. For steel with the yield strength e.g. 340MPa, an increase of fatigue life with a factor of 3.4 is attained for grinding and TIG dressing, and a factor of 3.74 for hammer peening. Comparing to recommendations of IIW, DNV gives substantially longer fatigue lives. It is noted that the difference in improvement between BG/TIG and hammer peening is lesser according to DNV. In recommendations from NORSOK [14], it is mentioned that in some cases, larger improvements can be achieved compared to what is given by DNV. It is also mentioned that for existing structures, the fatigue damage at the weld toe can be reset to zero by using grinding and/or hammer peening.

Table 2. Improvement on fatigue life by different methods according to DNV [13].

Improvement method	*Minimum specified yield strength*	*Increase in fatigue life (factor on life)* 1)
Grinding	Less than 350 MPa	$0.01f_y$
	Higher than 350 MPa	3.5
TIG dressing	Less than 350 MPa	$0.01f_y$
	Higher than 350 MPa	3.5
Hammer peening 3)	Less than 350 MPa	$0.011f_y$
	Higher than 350 MPa	4.0

1) The maximum S-N class that can be claimed by weld improvement is C1 or C depending on NDE and quality assurance for execution ~~see Table A-5 in Appendix A.~~

2) f_y = characteristic yield strength for the actual material.

3) The improvement effect is dependent on tool used and workmanship. Therefore, if the fabricator is without experience with respect to hammer peening, it is recommended to perform fatigue testing of relevant detail (with and without hammer peening) before a factor on improvement is decided.

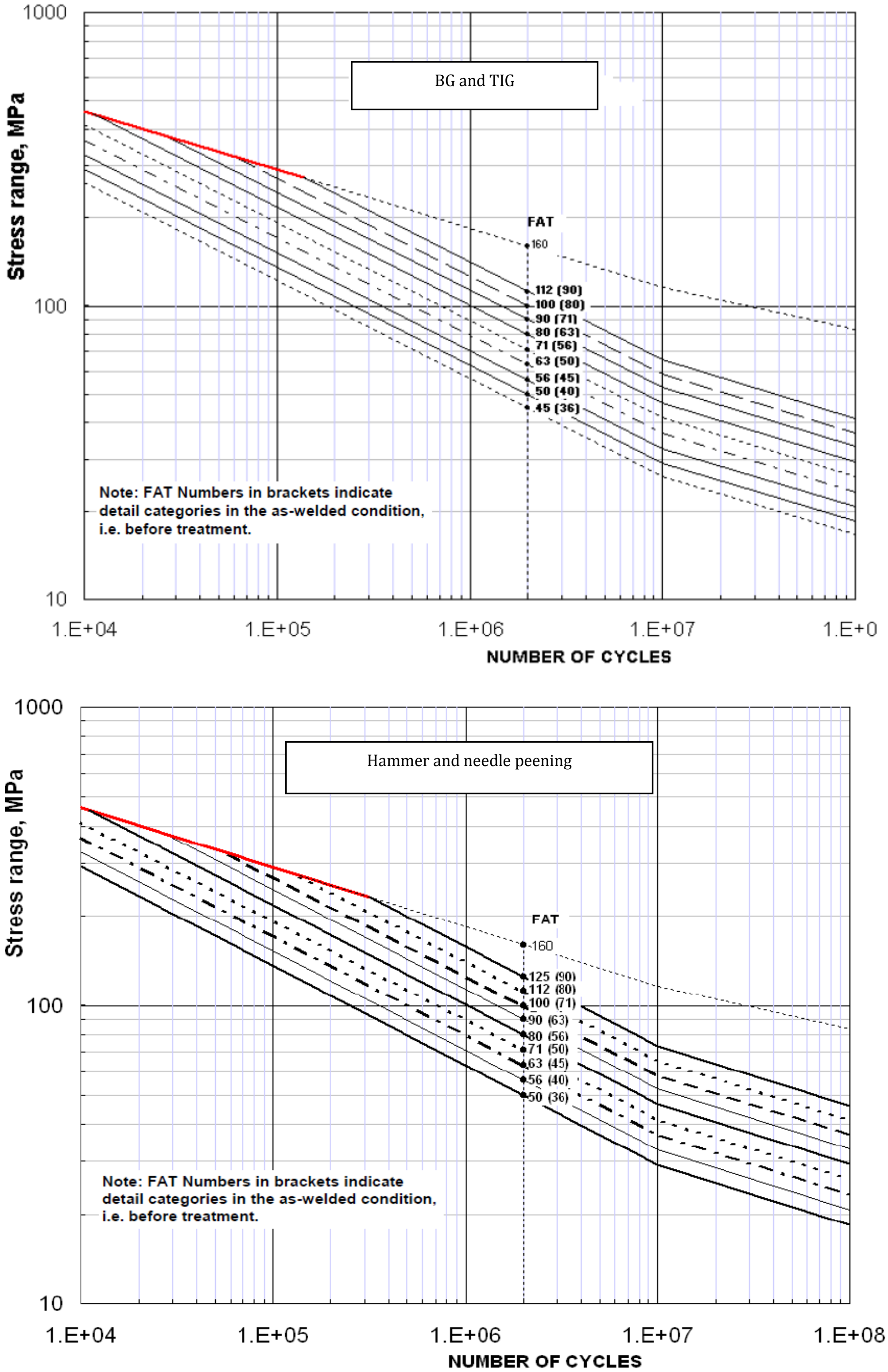

Figure 5. Design nominal stress S-N curves for improvement by BG/TIG and Hammer/Needle peening [11].

2.3 High Frequency Mechanical Impact treatment

High Frequency Mechanical Impact treatment belongs to the category of residual stress altering methods and is similar to hammer and needle peening. The major difference is that greater quality results are achieved due to the higher frequency, giving smaller spacing between impacts and resulting in better fatigue improvement. Figure 6 shows examples of indenter types used in HFMI treatment. As was mentioned before, recommendations and guidelines are currently under development for this PWT method. Bellow, a way of predicting the improvement is presented followed by procedure and quality assurance guidelines.

Figure 6. Example of indenter size and configurations. Photo courtesy of Integrity Testing Laboratory (ITL) and Structural Integrity Technologies Inc. (SINTEC) [10].

2.3.1 Improvement assessment guidelines

Marquis et al [10] performed a study and presented a design proposal for HFMI-improved weld details, taking into account the benefits of increased steel grades. The proposal applies for HFMI, independent of what equipment used. Decisive criteria that reduce the degree of improvement are identified as plate thickness and weld size effects and loading effects, such as stress ratio and variable amplitude loading. It is proposed that in a general case, HFMI treating details with steel qualities ≤ 355MPa can increase the fatigue strength with four fatigue (FAT) classes, see Figure 7. This can be compared to methods like burr grinding or TIG dressing which give an increase of two FAT classes for the same material quality [10]. Though, the improvements are only allowed on details with fatigue classes of FAT 50 to FAT 90. The reason is that other fatigue classes apply for details which are either non-welded, have a failure mode other than the weld toe, or are already improved, e.g. ground flushed butt welds.

The design proposal includes three stress assessment approaches, which are nominal stress, structural hot-spot stress (SHSS) and effective notch stress (ENS) approaches. Nominal stress approach is the most commonly used approach in engineering practice today, and usually the method referred to when speaking of FAT classes. For each type of assessment approach, appropriate S-N curves are developed with a slope of m=5 in the region $1 \times 10^4 < N < 1 \times 10^7$ and m´=9 for $N > 1 \times 10^7$.

For nominal stress approach, which is a global non-detailed stress assessment method, effects of discontinuities are disregarded by the designer and only the average stress in the cross section is used. Since the design methodology for nominal stress approach is detail-specific, the stress concentrations are accounted for by the corresponding FAT classes. In Figure 7, characteristic S-N curves for HFMI-improved details are presented [10]. For comparison, an S-N curve for as-welded FAT 90 is also presented. It is noted that for low cycles, the as-welded curve gives better fatigue resistance than the corresponding HFMI curve. Thus, no improvement is gained in that region.

Marquis et al suggest utilization of material strength as an increasing influence on the HFMI improvement. Finer steps for the material strength effect is proposed compared to recommendations of IIW for needle and hammer peening [10]. Instead of just increasing the FAT class once for materials above 355MPa, it is suggested to increase it once for every 200MPa of rise in material strength, see Figure 8. In best case scenario with no reductions due to thickness and size effects or due to loading effects, this suggestion leads to an increase of eight FAT classes with HSS of > 950MPa.

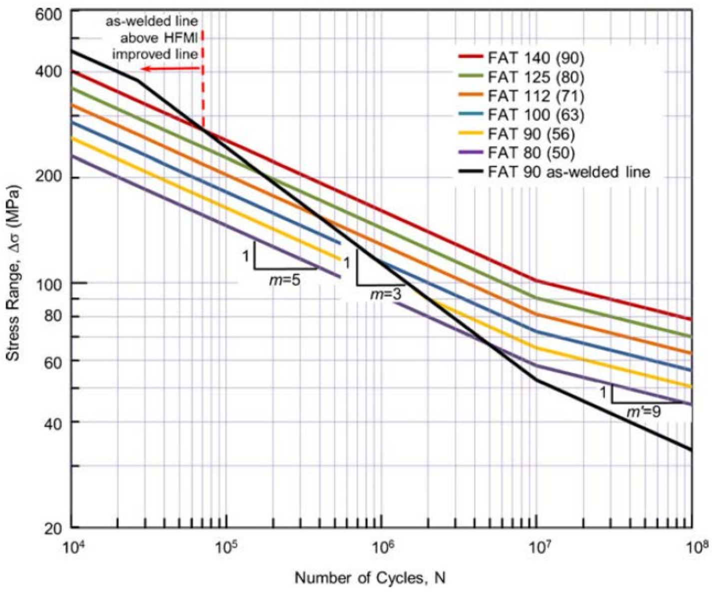

Figure 7. Characteristic nominal stress S-N curves for HFMI-improved welded joints for $f_y \leq 355MPa$. Values in parenthesis represent the FAT class of the joint in the as-welded condition [10].

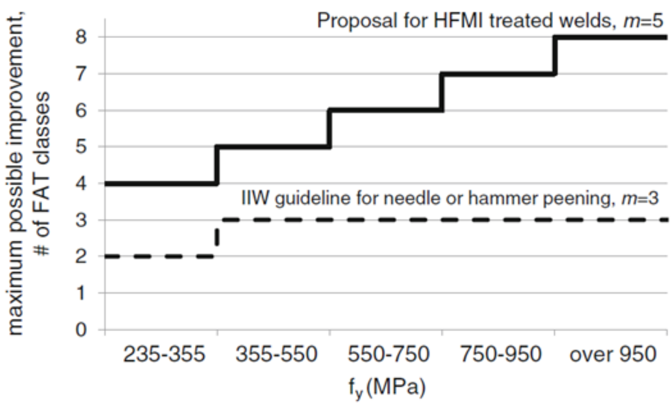

Figure 8. Proposed maximum increase in the number of FAT classes as a function of f_y [10].

SHSS assessment aims to find the case-specific stress concentrations by thorough modeling of the welded structure or detail. This approach is a semi global/local stress assessment method. Naturally, this leads to completely different stress values compared to nominal stress approach, thus also different S-N curves should be used. The ENS approach strives to come around stress singularities at geometrical discontinuities (notches) by modeling them with a notch of 1mm radius so that more realistic stresses are attained. In this case, the assessment requires detailed local modeling and dense finite element meshing. Improvements according to these assessment methods are presented in Table 3. For SHSS, two distinctions are made regarding fatigue detail categories; load carrying and non-load carrying fillet welds. IIW recommendations for hammer and needle peening are also included.

Table 3. FAT classes of HFMI improvement for structural hot-spot stress and effective notch stress [10].

Structural hop-spot stress

f_y (MPa)	Load-carrying fillet welds FAT	Non-load-carrying fillet welds FAT
As-welded, m=3		
All f_y	90	100
Improved by hammer or needle peening, m=3		
$f_y \leq 355$	112	125
$355 < f_y$	125	140
Improved by HFMI, m=5		
$f_y \leq 355$	140	160
$355 < f_y \leq 550$	160	180
$550 < f_y \leq 750$	180	200
$750 < f_y \leq 950$	200	225
$f_y > 950$	225	250

Effective notsch stress

f_y (MPa)	Effective notch stress characteristic curve modelled using ρ_f=1 mm
All f_y	As-welded, m=3 225
Improved by HFMI, m=5	
$235 < f_y \leq 355$	320
$355 < f_y \leq 550$	360
$550 < f_y \leq 750$	400
$750 < f_y \leq 950$	450
$950 < f_y$	500

After the identification of fatigue strength improvement, corrections shall be made regarding the weld size and thickness of the plate, reducing the fatigue strength for the thicker plates used. The same expression given by the IIW is suggested, equation (1). Thickness correction does however not apply for the ENS approach, since the thickness effect already is considered in the stress analysis.

Loading effects shall be regarded by limiting the maximum stresses to 80% of yield stress and stress ratios R ≤ 0.5, in accordance with IIW [11]. Reduction of improvement must be made for stress ratios between 0.1 and 0.5, see equation (2). These recommendations consider the stability of the compressive residual stresses, which may become unstable when loaded closely to the yield strength of the material. Studies indicate strong beneficial influence of material yield strength on the stability of the compressive residual stresses. The stability may also be negatively affected by large stress cycles from variable amplitude loading.

$$k_r = 1.075 - 0.75R \qquad (2)$$

The design procedure presented assumes that no improvement is achieved with HFMI treatment for very low cycle fatigue; see the red arrow in Figure 7. For instance, the improvement applicability for low strength steel (≤ 355MPa) starts at 72.000 cycles. Similarly for HSS (> 750MPa), the improvement applies at 10.000 cycles and above. Moreover, the study is applicable for plate thicknesses within the range of 5 to 50mm and for steel qualities between 235 to 960MPa

2.3.2 Procedure and quality assurance

Marquis and Barsoum [15] give an overview of procedure and quality aspects to consider, when assuring that full improvement is achieved after treatment. The proposal consists of general guidelines based on discussions, presentations and experimental evidence published within the Commission XIII of the IIW. In contrast to the case of design guidelines, for procedure and quality assurance, the method of HFMI treatment is pertinent. Since there are many varieties of HFMI tools and technologies available and increasing with time, specific recommendations are not given.

Even though HFMI treatments are regarded as user-friendly, the necessity for the operator to get training and understanding of the nature of PWT is discussed by Marquis and Barsoum [15]. The importance of using procedure specification documents is stressed out. Such documents should be used in similar manner as welding procedure specifications, for each weld in a structure. These can be customized and developed specifically for different types of equipment. An example of such specification (Table 4) is developed by Lopez Martinez and Haagensen [16].

In rare cases, implementation of HFMI treatment can by itself introduce crack-like flaws or other defects if executed incorrectly. It is important to note that PWT is not a measure to implement for compensation of insufficient weld quality or poorly performed detailing. If the quality or condition of the weld is not good enough, HFMI treatment can even result in worse fatigue resistance than as-welded details. This can for instance occur due to inappropriate choice of indenter diameter, or excessive concavity of the weld, see Figure 9. This can likewise happen if the weld toe is treated severely. To ensure that each treatment actually results in the improvement predicted by calculations, some quality criteria must be fulfilled. These can be grouped into qualitative and quantitative criteria.

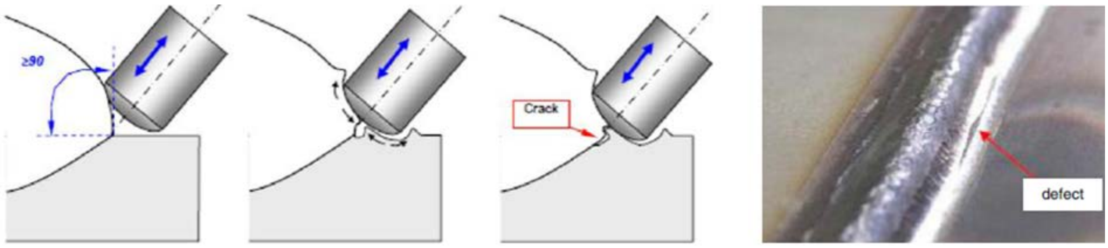

Figure 9. HFMI treatment can results in worse fatigue strength than for as-welded condition. To the right, a photography of an HFMI groove is shown where cracking occurred due to inappropriate treatment [15].

2.3.2.1 Qualitative criteria

The quality of the groove can be visually examined with magnifying glass and surface illumination of at least 350 lx. The groove depth is a good indicator of the level of treatment. The groove and its surface should be smooth, shiny, continuous and as homogenous as possible, see Figure 10a. I.e. no longitudinal lines from the original fusion line (Figure 10b) or transverse lines from individual impacts (Figure 10c) should be visible. These would lead to stress concentrations and eventually crack. If stops in the treatment cannot be avoided, the procedure should restart at least from 10mm behind the stop position.

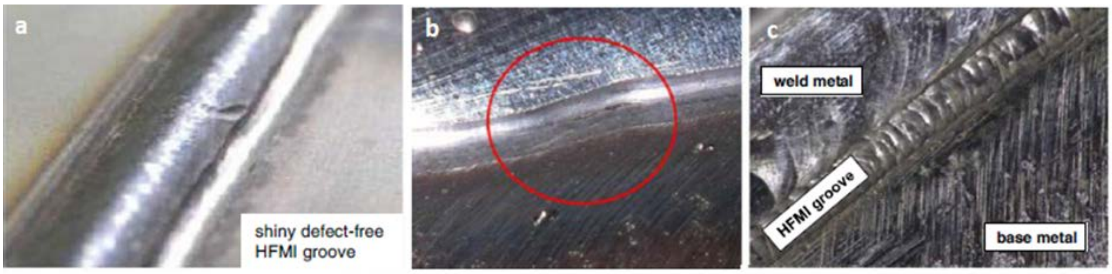

Figure 10. a) Defect-free groove, b) thin longitudinal crack, c) transverse ripples from individual impacts [15].

Table 4. Procedure specification suggested for ultrasonic peening, by Lopez Martinez and Haagensen [16].

LETS-Engineering BV				
Ultrasonic Peening Procedure Specification				
Welding Specification		**Weld joint identification**		
Parent plate		Type		
Thickness		Location		
Filler metal		Identification		
Consumables		UPPS-Number		
Welding Proc Nr		Rev.		
Equipment		Date		
Make and Model		**Photo of treated welded joint**		
Power [kW]				
Tip diam. [mm]				
Weight [kg]				
Impact frequency				
Impact amplitude				
Ultrasonic freq.				
Treatment data				
Position				
Work angle side				
Work angle ahead				
Travel speed				
Number of passes				
Treated length				
Time of treatment				
Tool changes				
Cause				
Operator				
Name				
Experience [hrs]				
Treated length		**Remarks**		
Date of treatment				
Inspection				
Visual				
Photo				
Measurement				
Equipment				
Results				
Toe radius [mm]				
Weld angle [deg]				
Groovedepth[mm]				
Groovewidth[mm]				
Approvals				
	Contractor	**Client**	**Survey Autho.**	
Name				
Date				
Responsible				
Signature				

2.3.2.2 Quantitative criteria

As mentioned before, groove depth is an important quantity. The groove geometry will differ from case to case, depending on material strength and indenter used, but should optimally be within 0.2-0.6mm in depth and 3-6mm in width. The width should be centered about the position of the original fusion line and not vary more than 25% in each direction, see Figure 11. Working speed, maximum and minimum number of passes, angles of the impact from indenter and pressure input by the operator are all important parameters that need attention. But they are specific for the equipment used and should therefore be specified in procedure specification documents.

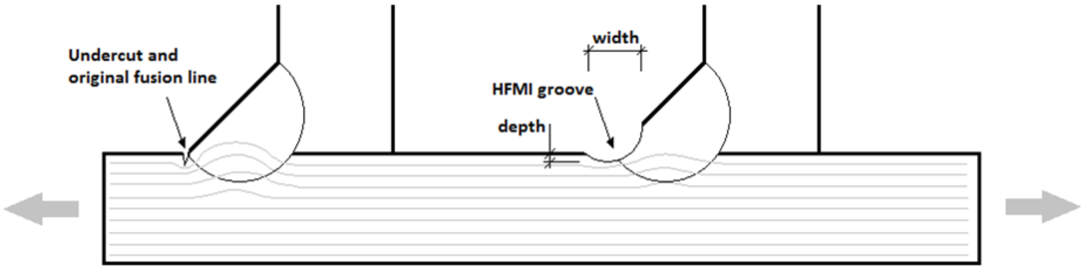

Figure 11. Illustration of the weld before treatment and the HFMI groove.

Furthermore, weld preparation is necessary. It should consist of careful processing of the weld cap and parent material adjacent to it so that no trace of oxide, scale, spatter or other materials are left. The weld profile needs to be evaluated according to ISO 5817 requirements for quality level B, including undercuts, excessive overfill, excessive concavity and overlaps. If significant dead-load is present, giving raise to tensile stresses in the area intended to be treated, it is recommended to implement the HFMI treatment after the structure is put in place and the dead-load applied. Otherwise, tension from the dead-load can partially neutralize the favorable compressive residual stresses from the treatment. Finally, heat treatment and hot-dip galvanizing should be avoided on HFMI-treated structures since they may reduce the induced compressive residual stresses. There is currently no method to evaluate these effects.

2.3.2.3 Consequences of treatment variation

Tehrani Yekta et al [17] investigated the UIT technique by conducting fatigue tests with systematic variations in treatment quality. Six test groups were created (A-F). Group A consisted of as-welded specimens. Groups B, C and D consisted of specimens under-treated by reduced intensity, under-treated by increased speed and over-treated by reduced speed, respectively. These specimens were treated by a robotic arm in order to eliminate variations induced by operator. Groups E and F contained specimens treated properly, either by the robot (E) or manually (F). Three different stress ranges and two different loading conditions were studied, thus, totally six tests per group.

The proper treatment speed was considered being 10mm/s and the intensity measure of the impacts, equal to 27-29µm. For group B, under-treatment was represented by intensity reduction to 18µm. For group C, it was represented by treatment speed increase to 20mm/s. For group D, over-treatment was simulated by a speed decrease to 1mm/s, over-exaggerating unintended severe treatment. Four passes of treatment were applied on the weld toes of all treated specimens. The first with an angle of 45° to the main plate, the second with a deviation of 15° in one direction, the third, 15° deviation in the other direction, and the fourth, with 45° again. The first load condition (LC1) was CAFL of ratio R=0.1 for stress ranges 200, 225 and 250MPa. The second load condition (LC2) was CAFL for the same stress ranges and ratio as LC1, but with under-loads (compressive loads with higher stress ranges) as the first ten cycles of a repeated 1000-cycle history. The under-load cycles had a ratio of R=-1 and a magnitude corresponding to a factor 2.2 on the normal stress ranges; i.e. 440, 500 and 556MPa. Results from this load condition were represented by equivalent stress ranges with Miner’s sum, assuming m=3.0, which gave a slightly increased value compared to the ranges of LC1, see Figure 13d.

After treating all specimens, the following observations could be made, see Figure 12. For group B which received reduced-intensity treatment, the original weld toe line was still visible after four passes. In case of group C with increased treatment speed, traces of individual impacts and different passes were well-distinguishable. Over-treatment (group D) was characterized by significant amount of flaking. For both properly treated groups (groups E and F), the groove became uniform and smooth, although traces of different passes and impacts were better avoided by manual treatment.

The results from testing are presented in Figure 13. In the as-welded case, a slope of 3.54 could be observed with a linear regression line of those data points. Considering all UIT-treated specimens indifferent of group, a slope of m=5.00 was gained. This corresponds exactly to recommendations and observations from other studies, see [10][18]. Proper and improper treatments yielded slopes of m=6.41 and m=4.63, respectively, when looked at separately.

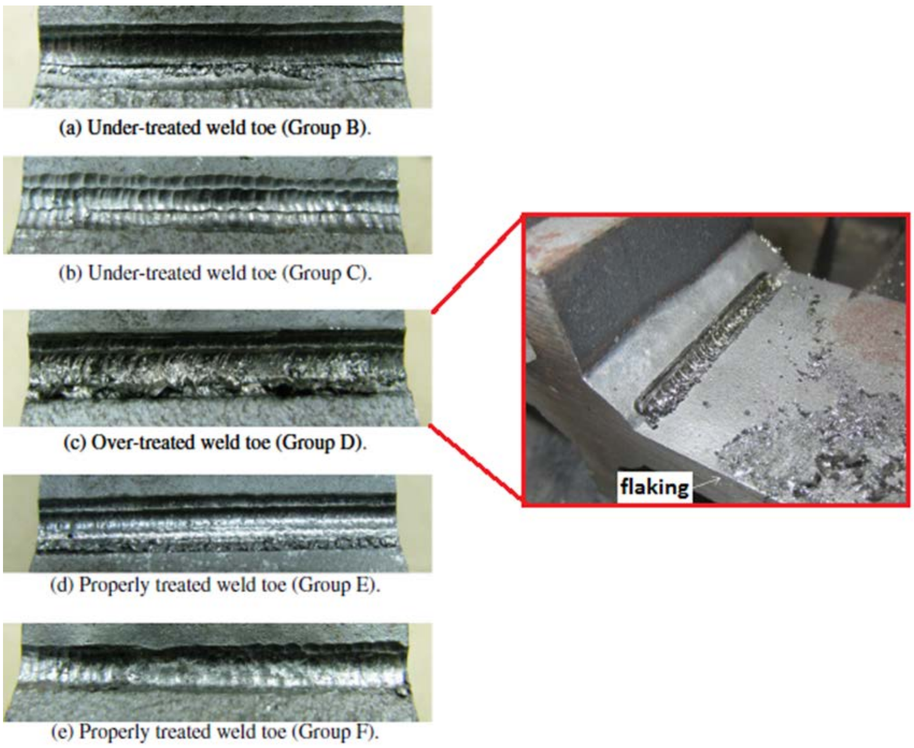

Figure 12. Treatment results for different test groups. Obvious flaking in case of over-treatment was observed. Adapted from [17].

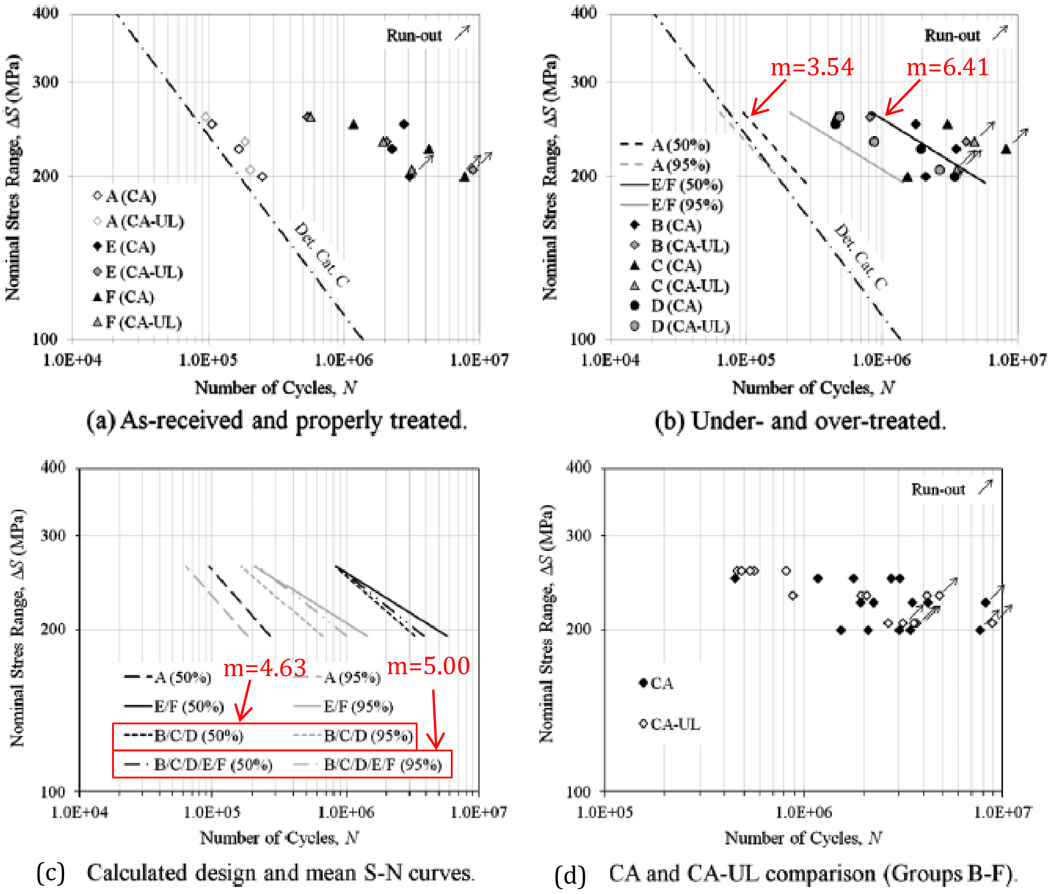

Figure 13. S-N curves from Tehrani Yekta et al [17].

It was observed that a high degree of improvement was achieved, whether or not the treatment was done properly and independent of load condition. This led to the conclusion that the UIT process is robust, allowing for certain amount of variation within the ranges investigated. From Figure 13d, it was confirmed that UIT is sensitive to under-loads with high stress ranges, decreasing in sensitivity as stress ranges get lower.

2.3.3 Overview of fatigue test data with HFMI

This section is designated for compilation of relevant fatigue tests already carried out, partly to get an overview of applicable cases for bridges and partly to identify shortages.

2.3.3.1 Constant Amplitude Fatigue Loading (CAFL)

Yildirim and Marquis [18] collected fatigue test data from published laboratory tests of HFMI-treated specimens. Four types of details were distinguished in a pool of 414 samples. Longitudinal welds, T-joints, transverse attachments and but joint welds. The sample pool differed with respect to plate thicknesses, steel grades and HFMI method implemented. Common for the samples were that all of them had small thicknesses (≤ 30mm), typically a stress ratio equal to 0.1, and were loaded under CAFL. The specifications of the tests are presented in Table 5. Some of the conclusions were that an S-N curve slope of m = 5 fit the data well, that the HFMI-treated specimens had slightly better fatigue strength than hammer peened details and that the reduction method for higher stress ratios than R=0.1, according to equation (2), seemed suitable for HFMI-treated details.

Table 5. Specifications of test samples (constant amplitude axial loading) [18].

Steel type	f_y [MPa]	f_u [MPa]	R	Method	Plate thickness [mm]	Best-fit, m	k
Longitudinal welds							
S700	700	750	0.1	UP+UIT	8	5.5	16
S690QL	786	870	0.1	UIT	16	4.5	16
S690QL	786	870	0.1	HiFIT	16	4	15
16Mn	390	590	0.1	UP/UPT	8	14	6
S350	398	503	0.1	UP/UPT	12	5.3	5
S700	780	850	0.1	UP/UPT	12	3.9	7
S900	900	1010	0.1	TIG+UP	12	4.48	10
SS800	700	830	0.1	UP/UPT	8	9.4	8
16Mn	390	591	0.1	UP/UPT	8	15.8	6
Q235B	267	435.5	0.1	UP/UPT	8	11.7	7
S355	355	600	0.1	UIT	8	3.71	10
S355J2	390	545	0.5	UIT	30	2.97	7
S960	969	1104	-1	UIT	6	4.81	11
S700	700	750	-1	UIT	8	4.24	5
SBHS500	572	661	< 0.5	UIT	12	5.37	10
SBHS500	572	661	0.5	UIT	12	3.83	12
SBHS500	572	661	> 0.5	UIT	12	3.09	11
S960	960	980	0.1	PIT	5	6	11
T-joint welds							
S420	420	490	0.1	UIT	20	11.70	8
S700	700	750	0.1	UIT	6	6.9	10
S700	700	800	0.1	UIT	6	4	21
S420	420	490	0.1	UIT	20	7.5	7
S960	960	980	0.1	PIT	5	3.65	7
Transverse attachments							
S355J2	398.3	537.2	0.1	UIT	12	6.6	7
S355J2	398.3	537.2	0.1	UIT	12	11.1	4
S460ML	503.5	553.4	0.1	UIT	12	5.27	5
S460ML	503.5	553.4	0.1	UIT	12	6.09	5
S690QL	812.8	870.8	0.5	UIT	12	7.22	6
S260	260	465	0.0	UIT	20	9.55	9
S355J2	477	556	0.1	PIT	12	11.6	8
S690QL	781	827	0.1	PIT	12	6.5	7
AH36	392	520	0.1	UIT	20	8.9	3
AH36	392	520	0.1	UIT	20	6.25	3
AH36	392	520	0.5	UIT	20	8.38	3
AH36	392	520	-1	UIT	20	18	3
Butt joint welds							
S355J2	422	524	0.1	UIT	16	7	14
S355J2	422	524	0.1	HiFIT	16	4.2	18
S690QL	786	870	0.1	UIT	16	4.5	18
S690QL	786	870	0.1	HiFIT	16	3.36	12
S355J2	422	524	0.5	UIT	16	8.9	15
S355J2	422	524	0.5	HiFIT	16	9	11
S690QL	786	870	0.5	UIT	16	5	10
S690QL	786	870	0.5	HiFIT	16	5	12
E690	763	836	0.1	UP	9.5	3.74	8
S960	960	980	0.1	PIT	5	7.78	7

UP = Ultrasonic Peening, **UIT** = Ultrasonic Impact Treatment, **UPT** = Ultrasonic Peening Treatment, **HiFIT** = High Frequency Impact Treatment, **TIG** = TIG dressing, **PIT** = Pneumatic Impact Treatment, **R** = stress ratio, **k** = number of samples

For clarification of specifics, it is referred to [18]

2.3.3.2 Variable Amplitude Fatigue Loading (VAFL)

Yildirim and Marquis [19] also performed a round robin study in which they examined effects of variable amplitude fatigue loading (VAFL) on HFMI-treated specimens, and simultaneously verified that satisfactory fatigue improvement is gained indifferent of which equipment manufacturer chosen. Each manufacturer used different HFMI techniques; HiFIT, UP, UPT and UIT. Four manufacturers were chosen and distinguished by letters, A-D. Examples of their treatments are shown in Figure 14. No specification was made on which treatment that was associated to which manufacturer.

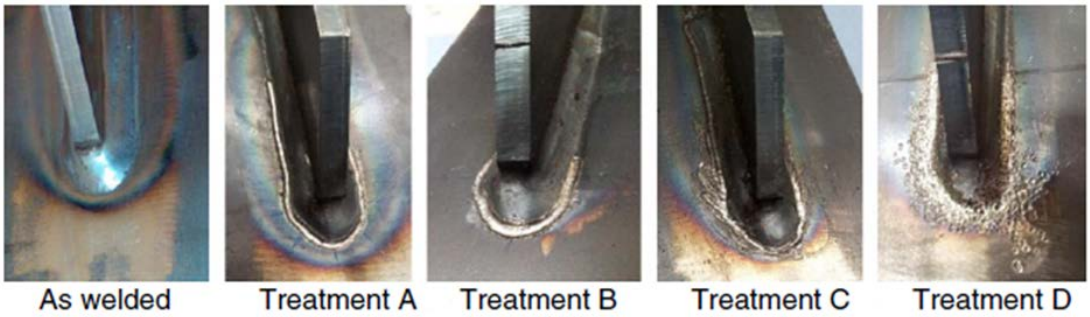

Figure 14. Examples of test specimens as-welded and following HFMI treated by four equipment manufacturers [19].

The same type of detail was selected for all tests; non-load-carrying attachments, accurately welded by machine together with 8mm steel plates of grade S700, see Figure 15. 24 HFMI-treated specimens (six from each manufacturer) were tested under VAFL. The applied load had a stress ratio of R = -1 and contained 14 different amplitudes, representing the load spectrum. Four specimens from each manufacturer were subjected to maximum nominal stresses of 375MPa and two of them to 480MPa. The whole load spectrum was scaled up to achieve the higher maximum stresses.

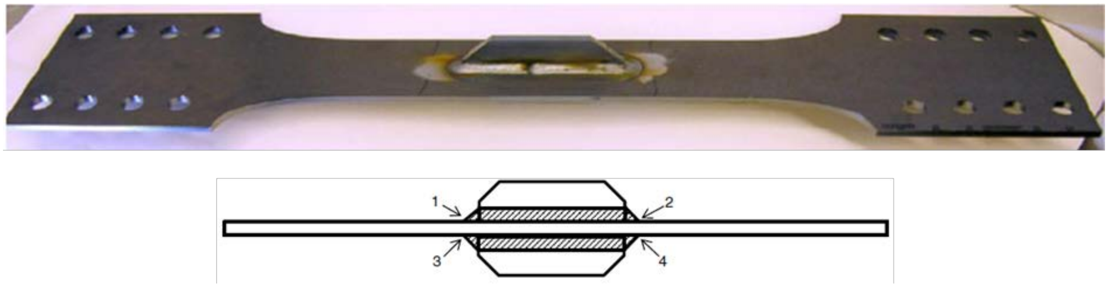

Figure 15. Illustration of the "non-load carrying longitudinal attachment" test specimen used in the study and the weld toes. Adapted from [19].

All eight specimens that were subjected to high stresses failed from the weld toe while 14 out of 16 of those subjected to low stresses failed from the weld root (or gusset, as referred to by the authors). The remaining two failed from the weld toe. The results were represented with equivalent stress ranges and put into an S-N diagram, see Figure 16. The nominal stress fatigue class was identified to FAT 80, before treatment. For the treated detail, a fatigue class of 160 was predicted. All test data points for treated specimens got situated above this S-N curve. Even though this curve originally was derived based on constant amplitude loading with a stress ratio of R = 0.1, it was possible to implement it on this study [19].

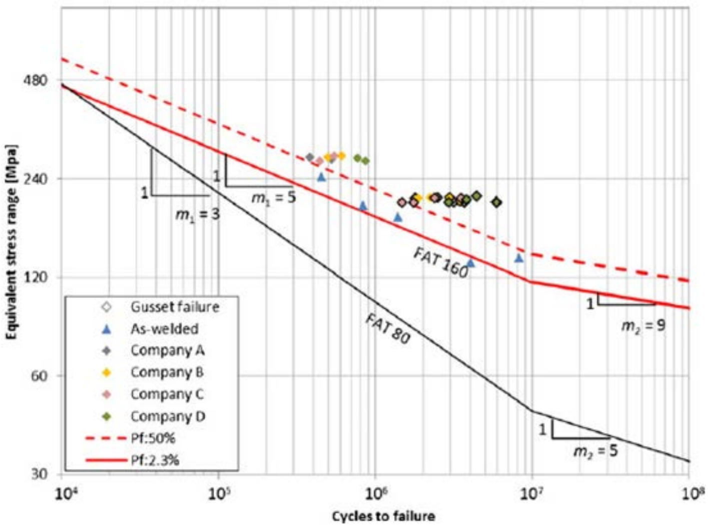

Figure 16. Fatigue test results obtained from variable amplitude loading [19].

In addition, the residual stress states of eight of the specimens above were measured before and after fatigue loading, by X-ray diffraction technique. Two as-welded details were also investigated, though loaded under CAFL. The measured data varied greatly and it was noted that this measuring technique is highly sensitive to the position of measurement point. Nevertheless, a clear overall picture was given which showed obvious relaxation of the internal residual stresses after loading, see Table 6. Measurements were taken from each weld toe at the end of the attachments, see Figure 15.

Table 6. Residual stress measurements (in MPa). As-welded speciemens were loaded under CAFL and HFMI specimens under VAFL. Values within paranthesis are the measured standard deviations [19].

Specimen			Before test: weld toe number				After test: weld toe number			
State	#	ΔS_{max}	1	2	3	4	1	2	3	4
AW	17	281	238 (76)	552 (116)	185 (18)	269 (16)	–	80.7 (18)	–	44.1 (19)
	20	281	465 (74)	279 (49)	226 (13)	369 (14)	299 (29)	–	118 (9)	–
HFMI treated	11/D	960	−306 (12)	−303 (13)	−384 (24)	−419 (60)	–	−165 (10)	–	−149 (10)
	12/D	750	−104 (55)	−138 (50)	−75 (105)	−181 (87)	–	–	–	–
	23/C	750	52 (30)	−325 (33)	−330 (18)	−150 (38)	–	–	–	–
	27/A	960	−329 (24)	−399 (31)	−91 (22)	−207 (21)	22 (9)	–	−11 (18)	–
	28/A	750	−253 (25)	−228 (63)	−247 (29)	−186 (24)	−139 (23)	–	−66 (15)	–
	36/C	960	−457 (37)	−354 (36)	−218 (80)	−430 (35)	–	46 (10)	–	−121 (10)
	38/B	960	−238 (56)	−197 (28)	−364 (38)	−174 (92)	–	62 (23)	–	0 (25)
	40/B	750	−191 (35)	−53 (20)	−172 (32)	−259 (50)	–	48 (19)	–	−179 (43)

Table 7 presents an overview of studies investigating the effects of VAFL on HFMI-treated specimens. The details consist of non-load carrying longitudinal attachments in all tests. More on effects of VAFL and residual stress relaxation is found in [20][21][22].

Table 7. Specifications of test samples (variable amplitude axial loading). k = number of specimens.

Ref.	Steel type	R	Method	Plate thickness [mm]	k
[19]	S700	-1	HiFIT/UP/UPT/UIT	8	24
[23]	16Mn	0.1	UPT	8	7
[24]	S700	-1	UIT	8	6
[24]	S960	-1	UIT/UP	6	3
[25]	S690QL	-1	Not specified (HFMI)	10	1
[25]	S700MC	-1	Not specified (HFMI)	10	1

2.3.4 HFMI application on bridges

One of the most important aspects to consider in the application of HFMI on bridges is the fact that bridges usually have much larger plate thicknesses in comparison to the fatigue test data presented in section 2.3.3. The thickness affects the fatigue resistance of a plate for several reasons, which are mostly accounted for in the fatigue calculations. But, the least studied thickness effect concerns the depth of which the compressive residual stresses from HFMI treatment provide decreased crack propagation rate, and how this relates to the whole thickness and influences fatigue life. Very few experiments have been conducted to examine HFMI treatment on plates thicker than 15mm [3].

Three application examples of HFMI on new bridges are presented in this section (1. Schenkendorfstrasse, 2. Bridge over Autobahn and 3. Cable car bridge) followed by six examples of HFMI application for repair of existing bridges (4. Ruhrstrom Bridge, 5. Ohio River Bridge, 6. Bridge in Ukraine, 7. Gschnitztal Bridge, 8. George N. Wade Memorial Bridge, 9. Burignon Bridge). The extent of information found about the treatments on these bridges varied highly. Some were found in published papers and some by e-mail exchanges with different HFMI manufacturers.

The Schenkendorfstrasse Bridge in Munich [5] was completed 2009, on which HiFIT was considered during early design stage. This construction is a cable-stayed bridge with two interconnected decks, hanging from a pylon with three cable pairs, Figure 17. One of the decks is designated for tram traffic and the other for pedestrian traffic. The pylon itself is anchored partly towards the southern end-support, and partly westbound perpendicular to the bridge length. In order to meet the strict requirement of 100 years fatigue life for the heavy cyclic tram loads, this bridge relies on the applied HiFIT treatment of a limited number of details in the superstructure, near its northern end, see Figure 18. The treated details mainly consist of the welded flange/web connections of the main girders near the bridge end, connections between cross beams and main girders and connections to the supports. In Figure 19, the construction phase is illustrated.

Figure 17. Schenkendorfstrasse Bridge in Munich, from southern end (left) [26] and from east (right) [27].

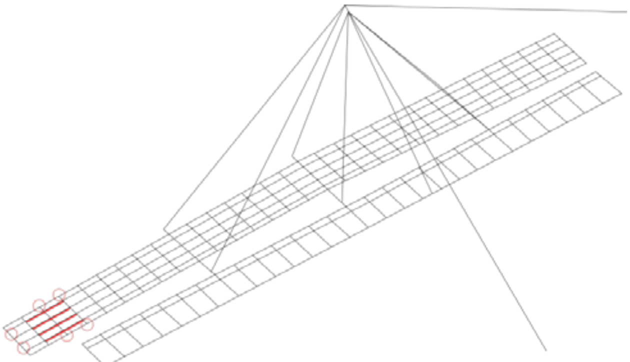

Figure 18. Overview of treated details in the Schenkendorfstrasse Bridge, adapted from [28].

Figure 19. HiFIT treatment in construction phase of the Schenkendorfstrasse Bridge [28].

Over the Autobahn (A73) between Suhl-Lichtenfels in Germany spans a 100m long tubular truss bridge. This unique bridge is the first of its kind in Germany, since the nodes are welded together instead of, as usual for tubular bridges, being pre-cast as one unit. The bridge is made of steel S355 and was designed based on UIT fatigue enhancement of 32 of the highest stressed nodes [29]. More information on this bridge is found in [30] and [31].

Figure 20. UIT-treated bridge over the Autobahn (A73) between Suhl and Lichtenfels [30].

Based on previous positive experience of PIT treatment of tubular guideways in Oakland (California) Airport, this fatigue enhancement technique was also used in design for cable car guideways of tubular frame girders in Las Vegas, USA [32]. The fatigue requirements for such structures are stricter when over-bridging roads and motorways, according to American codes. Therefore, PIT treatment was used to meet these requirements without changing the original design. Laboratory tests conducted at the University of Stuttgart and the University of Seattle (WA) showed an increase of fatigue life with a factor of 4.5 after PIT was implemented.

Figure 21. Tubular guideways for cable cars in Las Vegas [32].

Figure 22. Laboratory tests conducted for the cable car guideways in USA [29].

The Ruhrstrom Bridge is located in Mülheim-Duisburg in Germany [28]. It has been in operation since 1971 and consists of parallel bridges with chains of identical simply supported steel superstructures, carrying railways across the Ruhr-river and meadows nearby, see Figure 23. The main girders and end cross beams are made of steel S355, while the rest of structure mainly is made of steel S235. In connection with an inspection of the bridge, cracks of 20mm were found in the main girders at the welded joints to transverse stiffeners. Attempts of preventing further crack growth was made by drilling, but cracking still continued to a length of 45mm whereafter drilling was performed again with enlarged holes and the allowed train speed was reduced. The damages were explained to be due to the design principle where the frequency of the dynamic lateral loads from the trains happened to fall in the spectrum of the bridges natural frequency in that direction. Extensive improvements were performed on the bridge, both in transverse direction by crossbars connected with bolts, and in longitudinal direction to alter the dynamic behavior of the bridge. For the non-damaged transverse stiffeners, HiFIT treatment was used to prevent future damage and it was proven to be an easy and simple process [28].

Figure 23. Ruhrstrom Bridge treated with HiFIT [28].

The next example regards the use of UP as a measure of weld rehabilitation of one of the Ohio River Bridges in USA [33], see Figure 24. The concerns regarding the fatigue life of this 30 year old bridge arose when a similar bridge with approximately the same age failed in one of its spans due to fatigue cracking in welded elements. Since no fatigue macro-cracks were found in the bridge to be refurbished, thousands of welded details with a total weld length of 500m were treated with UP and the fatigue performance was enhanced [34].

Figure 24. UP-treated bridge over the Ohio River, USA [34][35].

A railway bridge over the Dnepr River in Ukraine was also treated with UP after a fatigue crack of approximately 1 meter was detected during a regular inspection [34], Figure 25. The crack was situated between the web and the upper flange, and was repaired by re-welding. After reparation, UP was implemented to prevent fatigue cracking in the new weld.

Figure 25. UP-treated bridge in Ukraine [34].

Here follows an example regarding HFMI treatment on the 674m long Gschnitztal Bridge in Austria [36] over which the Brenner Autobahn passes, see Figure 26. There has continuously been a large increase of traffic during the years, especially of heavy trucks, on this route which is why this bridge was widened from two to three lanes in each direction, in 1986. The steel structure was nevertheless kept unchanged, with exception of some minor reinforcing measures [37]. Fatigue cracking occurred at the welded transitions between transverse stiffeners and the main girders. Based on positive and convincing results from fatigue testing in laboratory, the cracks were repaired and the details improved with PIT treatment in 2009. In the lab, shown in Figure 27, an as welded specimen was subjected to cyclic loading of 200MPa at stress ratio R=0.1. Cracking started after 568 000 cycles on one side of a welded plate. The loading was stopped and the crack repaired by re-welding followed by PIT treatment of the new welds. Subsequently, the loading was continued to 2 368 000 cycles (568 000 + 1 800 000) till new cracking occurred on the other side, which was not repaired nor treated. Figure 28 shows some of the treated details on the bridge. As can be seen, both weld toes of the fillet welds were treated and at corners, concave indenters were used.

Figure 26.The Gschnitztal Bridge treated with PIT [36].

Figure 27. Test specimen loaded in laboratory [38].

Figure 28. PIT-treated details on the Gschnitztal Bridge [38].

According to the company SONATS [39], the bridge in Figure 29 which is located in Pennsylvania-USA was UIT-treated at longitudinal web stiffeners and gusset plate terminations, and also walkway connection plate attachments to floor beams. The author identified this construction to be the George N. Wade Memorial Bridge.

Figure 29. UIT treatment on the George N. Wade Memorial Bridge [39][40].

The Burignon Bridge is an 18m long railway bridge, situated in Chardonne in Switzerland, close to Lake Geneva, Figure 30. In 2010, K-seams along the bridge were HFMI-treated, according to Neher [41].

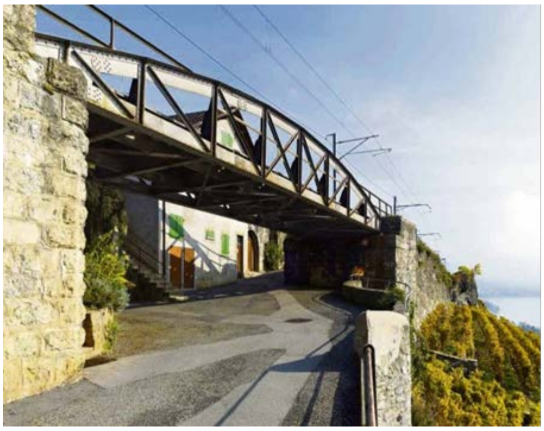

Figure 30. The Burignon Bridge treated with HFMI [43].

3 FE-modeling of HFMI-treated welded details

To model the behavior of HFMI-treated welded details, three different phenomena need to be described; the state of residual stresses from welding, the induced residual stresses from HFMI treatment and the fatigue behavior including crack initiation and propagation. There are alternative ways of conducting these simulations. Some examples of the methods used in the field are presented below.

3.1 Modeling of welding

Barsoum [45] has focused on modeling of residual stresses in welded structures and their effects on the fatigue behavior of welded joints. The consideration of initial residual stresses due to welding in the context of fatigue resistance is of high relevance. The tensile residual stresses are often in the magnitude of the materials yield strength, unfavorable for the fatigue resistance and contribute to increased crack growth rate. The effects of increased tensile residual stresses on the S-N curve are schematically described below, see Figure 31. These stresses both lower the curve and steepen its slope.

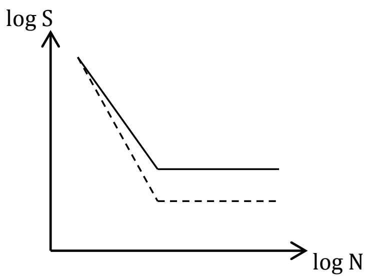

Figure 31. Schematic illustration of the effects of increased tensile residual stresses. Adapted from [45].

To model the residual stress field from welding with the help of FE simulation, it is realized that some simplifications are necessary in order to obtain reasonable computation times, yet maintaining good accuracy [45]. Therefore, 2D FE models were used by Barsoum. A constant heat input was assumed across the weld filler section and the heat input was calibrated either by comparison to experimental data, where available, or by adjustments to accomplish reasonable molten zone size and geometries of the heat distribution from the weld.

Furthermore, the material properties of the weld filler, the heat affected zone and the base metal were assumed to be the same. Steel properties are highly dependent on the temperature, often varying non-linearly. Such properties are thermal conductivity, specific heat, yield stress and thermal expansion coefficient. For some of these properties, describing the exact behavior is not necessary to attain correct residual stresses, which is why they were simplified where appropriate. These assumptions were incorporated in FE simulations and compared to measurements from experiments, see Figure 32. It was concluded that the simulations yielded good agreement with reality [45].

Many researchers have put efforts into understanding residual stresses from welding through FEA. Therefore the knowledge of modeling them is well-developed and today considered a standard procedure [46][47][48][49].

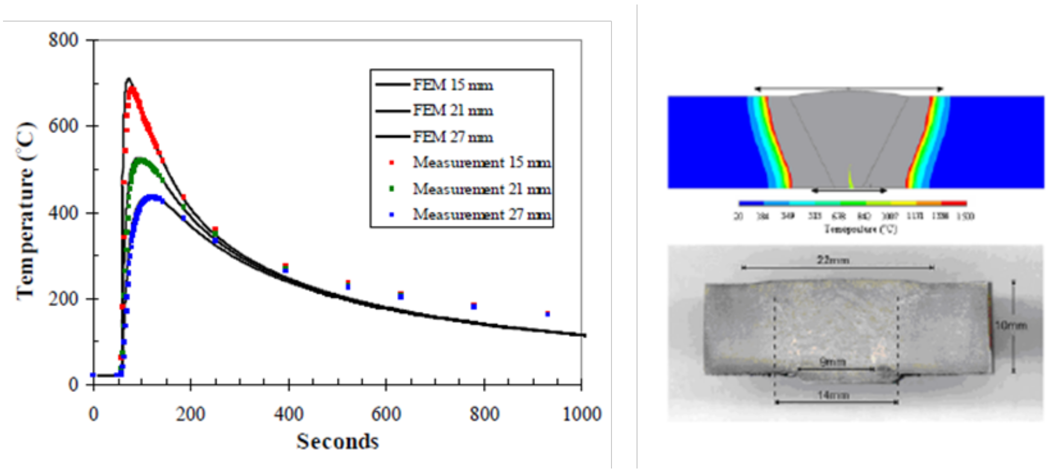

Figure 32. Temperature results from FE simulation of a but-weld compared to measurements from experiments [45]. Results and measurements were taken from distances 15, 21, and 27 mm from the weld.

3.2 Modeling of HFMI treatment

Baptista et al [50] made FE analyses to simulate the hammer peening PWT technique. This technique is essentially the same as HFMI, though, differing in the frequency at which the indenter impacts the material.

They modeled the hammer peening indenter as an elastic material and the impact load was made fully dynamic, capturing the realistic behavior of the impacts, see Figure 33. Moreover, they used non-linear elasto-plastic material properties including kinematic hardening for the plate to be treated, and contact conditions that allowed separation after impact in the normal direction. A friction coefficient of 0.5 was used for the tangential direction.

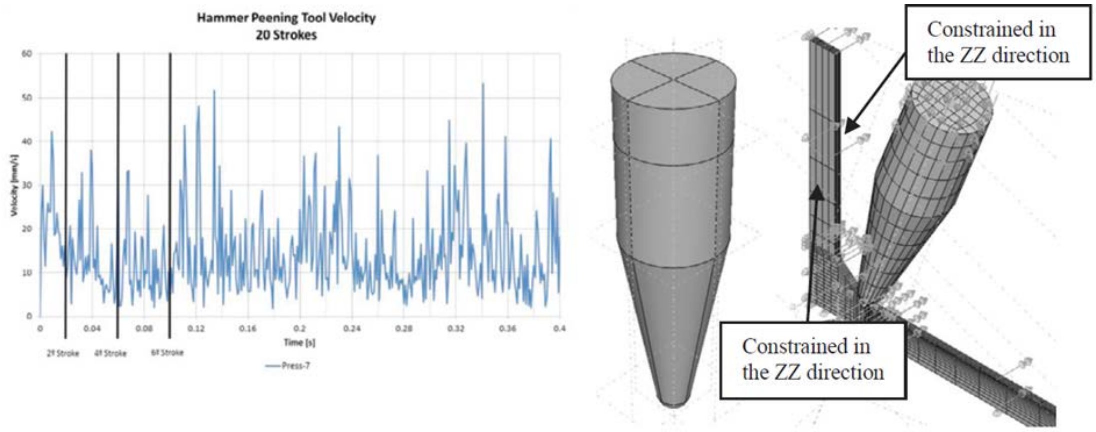

Figure 33. Hammer peening tool velocity variation during operation and the FE model visualization [50].

Residual stress results obtained from simulations were compared to test results, measured with X-ray diffraction and pointed towards satisfying agreement, with 13% difference in longitudinal direction and 7% difference in transversal. More research in this field is found in [51][52][53][54].

3.3 Modeling of fatigue

Fatigue modeling of welded joints can be made on the basis of Linear Elastic Fracture Mechanics (LEFM). Fracture mechanics is a well-established way of modeling crack propagation in materials and it was first introduced during the World War I, by engineer A.A. Griffith.

In linear elasticity theory, a geometric discontinuity such as a crack tip, will give rise to stress concentrations approaching infinity. In LEFM, this problem is handled by viewing it from a thermodynamic aspect, where the relationship between the elastic energy stored in the loaded material, and the energy required to create two new surfaces in a crack, will give the appropriate behavior of the crack propagation. This approach is dependent on an initial crack length, thus not capable of describing the crack initiation phase, essential for simulation of PW-treated details. Therefore, it is necessary to simulate the crack initiation phase, or by other means calculate the number of cycles for crack initiation. Bellow follows some studies performed in order to appropriately capture fatigue behavior with numerical simulations.

3.3.1 Prediction with initiation phase modeling

In the context of weld toe failure, the initiation occurs from the surface and is dependent on the surface roughness. The crack initiation phase is a highly microstructural phenomenon, thus, exhibiting a very different behavior in comparison to the crack propagation phase. For instance, the cracking direction in the initiation phase is shear driven and stochastic in an early stage, dependent on the individual orthotropic crystal grain orientations. After micro-crack coalescence, the crack direction becomes 45° to the load direction as increasing in length. While in the propagation phase, the direction is perpendicular to the global principal tensile stresses.

The basics of the crack initiation process can in short words be described as micro-crack development through occurrence of slip bands in grains. Slip bands arise as planes in the crystalline structure within grains due to movement of dislocations as a result of loading. Micro-cracks develop through these slip bands and coalesce with other cracks from grains nearby into a dense area. From this area, larger cracks start to develop, to later become perpendicular to the principal tensile stresses and fall into the propagation phase.

Jezernik et al [55] strived to improve the existing numerical Tanaka-Mura model for crack initiation in order to better resemble fatigue behavior, especially for High Cycle Fatigue (HCF). Two deficiencies were identified in this model. The first was that only slip bands in separate grains were considered, therefore not simulating any coalescing features. The second was that only the average shear force across the grain were considered for nucleation of micro-cracks, which especially in case of HCF does not yield satisfactory results.

Three improvements were suggested, and used to simulate fatigue strength of a plain steel plate with a circular hole in the middle and compare to experiments. The first improvement was to permit several parallel slip band positions in the same grain instead of only one going through the center. The second, a method to connect adjacent micro-cracks into one longer crack, allowing different micro-cracks to coalesce. The third, to allow segmented micro-cracking through the grain instead of just one cracking step through the whole grain, and usage of more accurate shear stresses compared to the average stress over the grain.

Results obtained from the simulations are presented in Table 8 and comparisons to experiment results are shown in Figure 34. For the crack propagation phase, LEFM was used with Paris law. The crack growth parameters C = $6x10^{-9}$ MPa$\sqrt{m}$ and m=3 were used. The length and direction of the crack obtained from the initiation phase was used as an initial crack for the propagation simulation. As is observed in Figure 34, the initiation phase plays a key role in these specimens, especially as the stress ranges decrease. It was concluded that the simulations yielded reasonably good results compared to experiments, although further investigations were proposed. The modeling of the initiation phase is a vast and complicated research topic. In the following references, more studies are available [56][57][58].

Table 8. Initiation and propagation results from simulation [55].

Load Level (MPa)	600	550	500	485
Initiation cycles	216 000	485 000	1 480 000	∞
Propagation cycles	28 000	35 000	44 000	/
Total cycles	244 000	520 000	1 542 000	∞

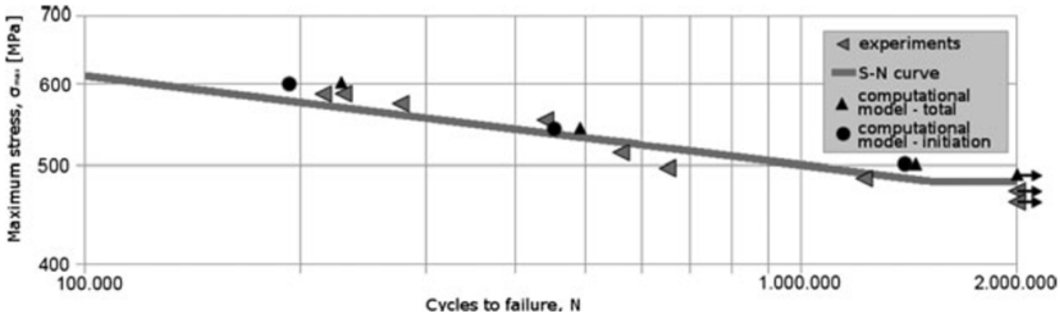

Figure 34. Simulation results compared to experiment results and derived S-N curve [55].

3.3.2 Prediction with other models

It is known, that residual stress based PWT techniques, such as hammer peening, needle peening and HFMI treatments, retard the crack growth rate in the areas where compressive residual stresses are introduced. These effects can be taken into account by introducing stress fields into the LEFM models. However, these stresses can be relaxed, particularly when the structure is subjected to compressive loads and periodic compressive overloads. Moreover, it is suspected that the use of linear material models when assessing residual stress based PWT techniques gives over-optimistic improvement predictions.

Walbridge [59] developed a strain-based fracture mechanic model to predict the whole fatigue life of peened details, based on the same numerical integrations performed in LEFM, but with several modifications. These account for non-linear materials, stress relaxation, crack closure and short crack behavior. The predictions made by this strain-based model were compared to both experiments and results from LEFM simulations. The model was able to predict improvements both under CAFL and VAFL with periodic overloads, accurately. Little difference was gained compared to LEFM simulations for low stress levels. However, for high stress levels and negative stress ratios with compressive overloads, the fatigue lives from this model were shorter in comparison to those of LEFM, as was suspected. Furthermore, it was concluded that the magnitude of the overloads had an important role in reducing the degree of improvement, while that initial crack properties had little influence for most CAFL conditions. The greatest influence of initial crack properties were observed for high stress ranges and ratios [59]. More on fatigue prediction models is found in the following references; [60][61][62][63][64][65][66][67].

4 Discussion and summary

Post weld treatment is a more or less well established method for fatigue enhancement, depending on industry. In offshore industry, it has become a common method, while for the bridge industry, experiences have not come as far. Even though there are some examples of PWT implementations on bridges, the need of further research in this field is necessary and the potential benefits from it are substantial. This has been emphasized in most of the research found.

Among all improvement techniques, HFMI, which is a peening method, seems to be the most promising. This, due to the high potential increase in fatigue strength it imposes and better qualities that can be achieved compared to other peening methods. A study of treatment quality variation concluded that UIT is a robust method, yielding significant improvements even if pronounced over/under-treatment is achieved. Although basically no international codes cover improvements with PWT, recommendations have been established and for HFMI, guidelines are being developed both regarding improvement assessment and procedure and quality assurance.

The guidelines are based on experimental data, mainly coming from relatively thin plates (<30mm) and CAFL with stress ratios equal to R=0.1. Few samples of yield strengths less than 355MPa are present. The number of different thicknesses and yield strengths in the sample pool presented in Table 5 is illustrated in Figure 35. Thick plate sizes and material yield strengths equal to or less than 355MPa are common and of high importance when implementing HFMI on bridges.

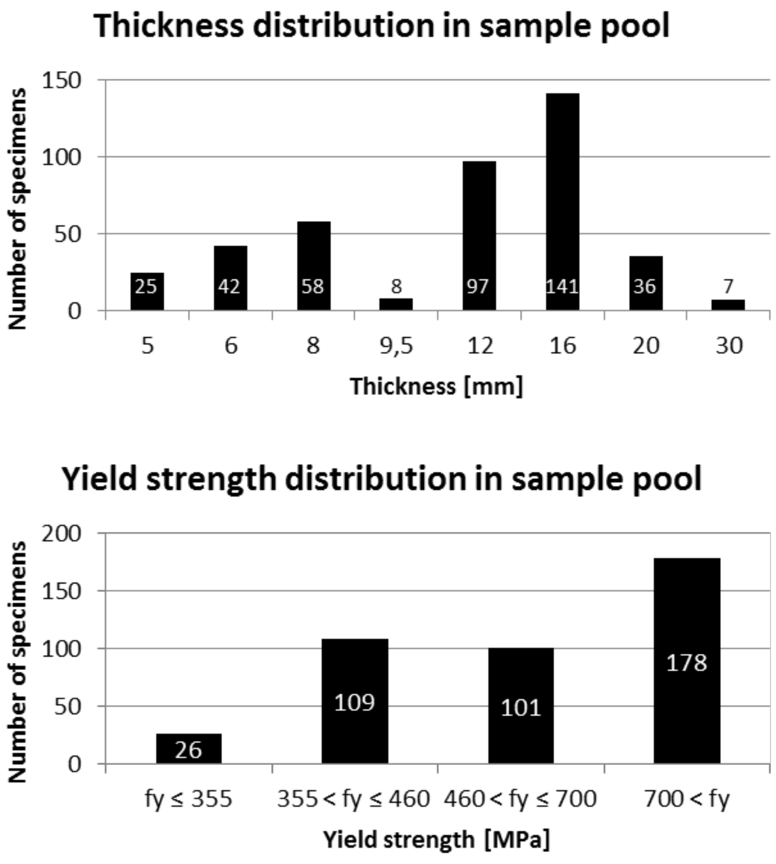

Figure 35. Thickness and yield strength distribution for data from Table 5 (CAFL).

VAFL can either be simulated by its actual variations in the structural detail, or with constant blocks of loads with different amplitudes, derived from e.g. Rainflow or Reservoir methods. Whichever is used in testing, the fact that they can decrease the magnitude and benefits of the compressive residual stresses from HFMI is known, especially at overloads where stresses get close to the material yield strength. The steel grade has a very important effect with regard to relaxation of the stresses induced by HFMI. In the study presented for VAFL in 2.3.3, residual stresses were measured before and after loading [19]. Although obvious residual stress relaxation was observed, the improvement prediction gave correct results with substantial increase in fatigue strength anyway, however, quantification of the relaxation and possible differences between ways of modeling VAFL need more investigation.

Since fatigue testing is a costly procedure, the idea of modeling fatigue behavior by FEM with respect to HFMI treatment has been raised. To do this, one need to account for the crack initiation and propagation phases, taking into consideration the internal residual stresses from welding and HFMI. With the help of FEA, the effects of the parameters of importance for bridges can then be evaluated; for instance, different thicknesses and different compressive residual stresses and geometries from HFMI, resembling variation of treatment quality.

Two promising studies are presented in 3.3.1 and 3.3.2 that predict fatigue life in different ways and yield satisfactory results. However, the study performed in 3.3.1 was only made on plain steel with a discontinuity in form of a hole. Implementing this method on a welded detail improved by HFMI does imply some challenges. For instance, welding a detail dramatically changes the microstructural properties in the material affected by the heat. Usually, analyzing the fatigue of a welded detail basically includes modeling crack propagation with LEFM. But when the weld toe is HFMI-treated, the initiation phase must now also be regarded, having to account for the microstructural change due to welding. Then also, the question arises whether if HFMI in itself also changes the microstructure of the steel significantly or not, aside from geometry and residual stresses, and how this can be accounted for. Due to the complexity described in connection with initiation phase modeling, it is considered that simpler fatigue life predictions, for instance by means of strain-based fracture mechanics are more feasible when analyzing HFMI-improved details.

Since fatigue failure occurs with a relatively large variation, one cannot draw conclusions regarding the adequacy of the FE simulations in a manner of strict quantitative comparison to experiment results. The orders of magnitudes are of more interest and evaluation of data points in S-N curves give a better understanding of the adequacy of the FE models. Further research is needed to investigate special cases and cover circumstances for bridges.

Examples of nine bridges, including railway, tram & pedestrian, cable car and roadway bridges could be found where HFMI treatment had been used. The information available varied between the bridges, but was generally quite scarce.

References

[1] M. Heshmati, “Fatigue Life Assessment of Bridge Details Using Finite Element Method”, 2012.

[2] A. Mosiello and K. Kostakakis, “The benefits of Post Weld Treatment for cost efficient and sustainable bridge design,” 2013.

[3] T. Tominaga, K. Matsuoka, Y. Sato, and T. Suzuki, “Fatigue Improvement of Weld Repaired Crane Runway Girder by Ultrasonic Impact Treatment,” *Weld. World*, vol. 52, no. 11–12, pp. 50–62, Nov. 2008.

[4] M. M. Pedersen, O. Ø. stergaard Mouritsen, M. R. Hansen, J. G. n Andersen, and J. Wenderby, “Comparison of Post-Weld Treatment of High-Strength Steel Welded Joints in Medium Cycle Fatigue,” *Weld. World*, vol. 54, no. 7–8, pp. R208–R217, Jan. 2013.

[5] T. Ummenhofer and I. Weich, “REFRESH – Lebensdauerverlängerung bestehender und neuer geschweiß ter Stahlkonstruktionen,” *Stahlbau*, vol. 75, no. 7, pp. 605–607, Jul. 2006.

[6] T. Ummenhofer, I. Weich, and T. Nitschke-Pagel, “Extension of life time of welded fatigue loaded structures,” in *Wind Energy*, Springer, 2007, pp. 297–300.

[7] L. L. Martinez, Z. Barsoum, and A. Paradowska, “State-of-the-Art: Fatigue Life Extension of Offshore Installations,” pp. 9–20, Jul. 2012.

[8] L. L. Martinez, “Fatigue Life Extension of Offshore Structures by Ultrasonic Peening,” in *ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering*, 2011, pp. 473–479.

[9] L. Wagner, *Shot Peening*. John Wiley & Sons, 2006.

[10] G. B. Marquis, E. Mikkola, H. C. Yildirim, and Z. Barsoum, “Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed fatigue assessment guidelines,” *Weld. World*, vol. 57, no. 6, pp. 803–822, Nov. 2013.

[11] P. J. Haagensen and S. J. Maddox, “IIW Recommendations on post weld improvement of steel and aluminum structures. IIW Doc. XIII-2200r1-07, 2008.–Tig dressing,” *Collab. Test Program Improv. Tech.*, 1995.

[12] A. Nussbaumer, “Course on fatigue and fracture mechanics: influence of residual stresses and post-welding improvement methods,” p. 13, 2009.

[13] Det Norske Veritas, “FATIGUE DESIGN OF OFFSHORE STEEL STRUCTURES,” no. April, 2010.

[14] NORSOK Standard, N006, “Assessment of structural integrity for existing offshore load-bearing structures,” no. March, pp. 20–21, 2009.

[15] G. Marquis and Z. Barsoum, “Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed procedures and quality assurance guidelines,” *Weld. World*, vol. 58, no. 1, pp. 19–28, Jan. 2014.

[16] L. L. Martinez and P. J. Haagensen, “LIFE EXTENSION of CLASS F and CLASS F2 DETAILS USING ULTRASONIC PEENING,” *Int. Inst. Weld.*, pp. 1–9.

[17] R. Tehrani Yekta, K. Ghahremani, and S. Walbridge, “Effect of quality control parameter variations on the fatigue performance of ultrasonic impact treated welds,” *Int. J. Fatigue*, vol. 55, pp. 245–256, Oct. 2013.

[18] H. C. Yildirim and G. B. Marquis, “OVERVIEW OF FATIGUE DATA FOR HIGH FREQUENCY MECHANICAL IMPACT TREATED WELDED JOINTS OVERVIEW OF FATIGUE DATA FOR HIGH FREQUENCY MECHANICAL IMPACT TREATED WELDED JOINTS.”

[19] H. C. Yildirim and G. B. Marquis, “A round robin study of high-frequency mechanical impact (HFMI)-treated welded joints subjected to variable amplitude loading,” *Weld. World*, pp. 437–447, Mar. 2013.

[20] K. Ghahremani and S. Walbridge, “Fatigue testing and analysis of peened highway bridge welds under in-service variable amplitude loading conditions,” *Int. J. Fatigue*, vol. 33, no. 3, pp. 300–312, Mar. 2011.

[21] E. Mikkola, M. Doré, and M. Khurshid, “Fatigue Strength of HFMI Treated Structures Under High R-ratio and Variable Amplitude Loading,” *Procedia Eng.*, vol. 66, pp. 161–170, 2013.

[22] R. C. McCLUNG, “A literature survey on the stability and significance of residual stresses during fatigue,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 30, no. 3, pp. 173–205, Mar. 2007.

[23] L. Huo, “Investigation of the fatigue behaviour of the welded joints treated by TIG dressing and ultrasonic peening under variable-amplitude load,” *Int. J. Fatigue*, vol. 27, no. 1, pp. 95–101, Jan. 2005.

[24] G. Marquis and T. Björk, “Variable amplitude fatigue strength of improved HSS welds,” *Int. Inst. Weld. IIW Doc. XIII-2224-08*, 2008.
[25] M. Khurshid, Z. Barsoum, and G. Marquis, “Behavior of Compressive Residual Stresses in High Strength Steel Welds Induced by High Frequency Mechanical Impact Treatment,” *J. Press. Vessel Technol.*, vol. 136, no. 4, p. 041404, Apr. 2014.
[26] VERKEHRSWELTEN, “Schenkendorfstrasse.” [Online]. Available: http://verkehrswelten.wordpress.com/2011/08/30/munchen-das-tramalphabet-von-m-bis-r-3-3/. [Accessed: 03-Jul-2014].
[27] WIKIMEDIA COMMONS, “Schenkendorfstrasse.” [Online]. Available: http://commons.wikimedia.org/wiki/File:Schenkendorfstrasse_vs_Strassenbahnbruecke.jpg. [Accessed: 25-Jun-2014].
[28] M. Smida, B. Senk, and V. Strähuber, “Versuche und Anwendung hochfrequenter Hämmerverfahren als Schweißnahtnachbehandlung,” *Stahlbau*, vol. 78, no. 9, pp. 650–661, Sep. 2009.
[29] P. Gerster, “PIT treatment examples.” .
[30] “BW 67-1 - A graceful and innovative bridge over the A73.” SSF Ingenieure.
[31] Ö. Bucak, “Weitgespannte. stählerne Straßenbrücke über die BAB A73 / „Brücke Suhl Lichtenfels“.” .
[32] P. Gerster, F. Schäfers, and M. Leitner, “Pneumatic Impact Treatment (PIT) - Application and Quality Assurance.” XIII-WG2-138-13.
[33] T. Proulx, Ed., “Fatigue Improvement of Welded Elements by Ultrasonic Impact Treatment,” in *Experimental and Applied Mechanics, Volume 6*, New York, NY: Springer New York, 2011.
[34] Y. Kudryavtsev, J. Kleiman, A. Lugovskoy, L. Lobanov, V. Knysh, O. Voitenko, and G. Prokopenko, “Rehabilitation and Repair of Welded Elements and Structures by Ultrasonic Peening,” *Weld. World*, vol. 51, no. 7–8, pp. 47–53, Jul. 2007.
[35] “Ohio River Bridge.” [Online]. Available: http://kyinbridges.com/galleries/photos-videos/.
[36] P. Gerster, “Praktische Anwendungen der PIT-Technologie,” *Stahlbau*, vol. 78, no. 9, pp. 680–683, 2009.
[37] G. Haid, “A13 Brenner Motorway - Refurbishment of the corrosion protection on the Gschnitztal bridge,” *World PORR 1622013*, 2013.
[38] P. Gerster, “PIT treatment of the Gschnitztal Bridge.” 2009.
[39] “Flyer_UIT_Bridges_letter.pdf.” [Online]. Available: http://www.sonats-et.com/download.php?table=NDQ%3D&file=cGllY2Vqb2ludGVOVkgxQUkucGRm.
[40] “George N. Wade Memorial Bridge.” [Online]. Available: http://www.dywidag.com.br/referencias/details/article/george-n-wade-memorial-bridge-usa.html. [Accessed: 01-Jul-2014].
[41] Michael Neher, “Re: HFMI applications - E-mail conversation,” 04-Jul-2014.
[42] A. Nussbaumer and D. Imhof, “On the practical use of weld improvement methods,” *Prog. Struct. Eng. Mater.*, vol. 3, no. 1, pp. 95–105, 2001.
[43] S. Giampetruzzi, “Pont de Burignong.” [Online]. Available: http://www.leregional.ch/N29440/lifting-de-choc-pour-pont-centenaire.html.
[44] “Zürich-Wipkingen Bridge.” [Online]. Available: http://www.mkag.ch/mkag/services/references/all/page/5/. [Accessed: 01-Jul-2014].
[45] Z. Barsoum, “Residual stress analysis and fatigue assessment of welded steel structures,” 2008.
[46] Z. Barsoum and I. Barsoum, “Residual stress effects on fatigue life of welded structures using LEFM,” *Eng. Fail. Anal.*, vol. 16, no. 1, pp. 449–467, Jan. 2009.
[47] Z. Barsoum and A. Lundbäck, “Simplified FE welding simulation of fillet welds – 3D effects on the formation residual stresses,” *Eng. Fail. Anal.*, vol. 16, no. 7, pp. 2281–2289, Oct. 2009.
[48] T.-L. Teng, C.-P. Fung, P.-H. Chang, and W.-C. Yang, “Analysis of residual stresses and distortions in T-joint fillet welds,” *Int. J. Press. Vessels Pip.*, vol. 78, no. 8, pp. 523–538, Aug. 2001.
[49] A. Yaghi, T. H. Hyde, A. A. Becker, W. Sun, and J. A. Williams, “Residual stress simulation in thin and thick-walled stainless steel pipe welds including pipe diameter effects,” *Int. J. Press. Vessels Pip.*, vol. 83, no. 11–12, pp. 864–874, Nov. 2006.
[50] R. Baptista, V. Infante, and C. Branco, “Fully Dynamic Numerical Simulation of the Hammer Peening Fatigue Life Improvement Technique,” *Procedia Eng.*, vol. 10, pp. 1943–1948, 2011.
[51] M. Rahman, A. Hütter, and N. Enzinger, “Influencing Welding Residual Stresses of HSS by Pneumatic Impact Treatment (PIT),” 2009.

[52] V. Infante, C. M. Branco, R. Baptista, and E. Gomes, “A residual stresses and fracture mechanics analysis of welded joints repaired by hammer peening,” in *8th Portuguese conference on fracture*, 2002.
[53] R. Jackson, I. Chusoipin, and I. Green, “A Finite Element Study of the Residual Stress and Deformation in Hemispherical Contacts,” *J. Tribol.*, vol. 127, no. 3, pp. 484–493, Jun. 2005.
[54] L. Hacini, N. V. Lê, and P. Bocher, “Evaluation of Residual Stresses Induced by Robotized Hammer Peening by the Contour Method,” *Exp. Mech.*, vol. 49, no. 6, pp. 775–783, Dec. 2009.
[55] N. Jezernik, J. Kramberger, T. Lassen, and S. Glodež, “Numerical modelling of fatigue crack initiation and growth of martensitic steels,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 33, no. 11, pp. 714–723, Nov. 2010.
[56] Y. Li, V. Aubin, C. Rey, and P. Bompard, “Microstructural modeling of fatigue crack initiation in austenitic steel 304L,” *Procedia Eng.*, vol. 31, pp. 541–549, Jan. 2012.
[57] C. Przybyla, R. Prasannavenkatesan, N. Salajegheh, and D. L. McDowell, “Microstructure-sensitive modeling of high cycle fatigue,” *Int. J. Fatigue*, vol. 32, no. 3, pp. 512–525, Mar. 2010.
[58] Q. Y. Wang, C. Bathias, N. Kawagoishi, and Q. Chen, “Effect of inclusion on subsurface crack initiation and gigacycle fatigue strength,” *Int. J. Fatigue*, vol. 24, no. 12, pp. 1269–1274, 2002.
[59] S. Walbridge, “Fatigue analysis of post-weld fatigue improvement treatments using a strain-based fracture mechanics model,” *Eng. Fract. Mech.*, vol. 75, no. 18, pp. 5057–5071, Dec. 2008.
[60] V. Lihavainen and G. Marquis, “ESTIMATION OF FATIGUE LIFE IMPROVEMENT FOR ULTRASONIC IMPACT TREATED WELDED JOINTS.”
[61] D. Radaj, F. Sonsino, and W. Fricke, *Fatigue assessment of welded joints by local approaches*. Cambridge: Woodhead Pub. and Maney Pub. on behalf of Institute of Materials, Minerals & Mining, 2006.
[62] Taylor and Wang, “The validation of some methods of notch fatigue analysis,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 23, no. 5, pp. 387–394, May 2000.
[63] P. Lazzarin, T. Lassen, and P. Livieri, “A notch stress intensity approach applied to fatigue life predictions of welded joints with different local toe geometry,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 26, no. 1, pp. 49–58, 2003.
[64] P. Lazzarin, R. Tovo, and G. Meneghetti, “Fatigue crack initiation and propagation phases near notches in metals with low notch sensitivity,” *Int. J. Fatigue*, vol. 19, no. 8–9, pp. 647–657, Sep. 1997.
[65] G. Qylafku, Z. Azari, N. Kadi, M. Gjonaj, and G. Pluvinage, “Application of a new model proposal for fatigue life prediction on notches and key-seats,” *Int. J. Fatigue*, vol. 21, no. 8, pp. 753–760, Sep. 1999.
[66] Y. Verreman and B. Nie, “Early Development of Fatigue Cracking at Manual Fillet Welds,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 19, no. 6, pp. 669–681, Jun. 1996.
[67] K. J. Miller and K. P. Zachariah, “Cumulative damage laws for fatigue crack initiation and stage I propagation,” *J. Strain Anal. Eng. Des.*, vol. 12, no. 4, pp. 262–270, Oct. 1977.