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A guideline for fatigue strength improvement of high strength steel welded structures using high frequency mechanical impact treatment

Gary B. Marquis[a,b,]*, Zuheir Barsoum[b]

[a]Aalto University, School of Engineering, Espoo, 00076, Finland
[b]KTH-Royal Institute of Technology, Division of Lightweight Structures, Stockholm, 100 44, Sweden

Abstract

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 paper presents a proposed fatigue design and assessment guideline for HFMI improved welded joints. Stress analysis methods based on nominal stress, structural hot spot stress and effective notch stress are discussed. The document especially considers the observed extra benefit that has been experimentally observed for HFMI treated high strength steels. The proposal is considered to apply to steel structures from plate thickness 5 to 50 mm and for yield strengths ranging from 235 MPa to 960 MPa. Several fatigue assessment examples are also provided. Lessons learned concerning appropriate HFMI procedures and quality assurance measures are presented. Due to differences in the HFMI tools and the wide variety of potential applications, certain details of a proper treatment procedures and quantitative quality control measures are presented generally. It is proposed that specific details should be documented in a HFMI Procedure Specification for each structure being treated. It is hoped that this guideline proposal will provide a stimulus to researchers working in the field.

Keywords: HFMI, fatigue design , guideline

1. Introduction

Since 2002, 46 IIW Commission XIII documents reporting on HFMI technology development or experimental studies involving HFMI have been published. Numerous other studies and research reports have also been presented internationally. In 2010 Commission XIII introduced the term high frequency mechanical impact (HFMI) as a generic term to describe several related technologies for improving the fatigue strength of welded structures by

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locally modifying the residual stress state using ultrasonic, pneumatic or other technology. HFMI makes use of cylindrical indenters which are accelerated against a component or structure with high frequency (>90 Hz). The impacted material is highly plastically deformed causing changes in the local weld toe geometry as well as modifying the residual stress state in the region of impact. 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. Devices are known by many 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) [1,2].

2. HFMI Design Guidelines

In 2007 the IIW Commission XIII on Fatigue of Welded Components and Structures approved a best practice guideline concerning post-weld treatment methods for steel and aluminium structures [3]. This guideline covers four commonly applied post weld treatment methods: burr-grinding, TIG re-melting (or TIG dressing), hammer peening and needle peening. Burr-grinding and TIG re-melting are generally classified as geometry improvement techniques for which the primary aim is to remove or reduce the size of the weld toe flaws and to reduce the local stress concentration due to the weld profile by achieving a smooth blend at the transition between the plate and the weld face. Hammer peening and needle peening are classified as residual stress modification techniques which eliminate the high tensile residual stress in the weld toe region and induce compressive residual stresses at the weld toe. These methods also result in a reduced stress concentration at the weld toe. The guideline also gives practical information on how to implement the four improvement technologies including good work practices, training, safety, and quality assurance.

In 2011, Commission XIII began work on developing a new design and quality assurance guideline for welds improved using HFMI. In comparison to hammer peening, HFMI is generally considered to be more user-friendly. Because of the higher operating frequency, the spacing between alternate impacts on the work piece is very small resulting in a finer surface finish.

For low strength steel welds (f_y < 355 MPa) improved by burr grinding, TIG re-melting, hammer peening or needle peening, the fatigue strength benefit for design in the existing guideline corresponds to an increase in allowable stress range by a factor of 1.3. This is equal to a factor of 2.2 increase in life (for S-N slope m = 3). However, the maximum class which can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two (2) fatigue class increase based on the IIW Fatigue Design Recommendations [4]. For welds in higher strength steel (f_y > 355 MPa) improved by hammer peening or needle peening, the fatigue strength benefit consists of an upgrade by a factor of 1.5 applied to the stress range. For ease of computation, this corresponds to a three (3) fatigue class increase. The slopes of the S-N curves, m = 3, are the same as is used for as-welded joints.

The selection of an S-N slope m = 3 in the IIW guideline [3] was partially due to the convenience of having S-N lines for improved welds which are parallel to the lines for joints in the as-welded condition. This results in a constant computed improvement in fatigue life for all ΔS or, conversely, a constant computed increase in allowable stress for any target fatigue life. Similar logic is also observed in other fatigue assessment guidance documents that included weld improvement techniques. A recent comprehensive review of published of experimental data on the fatigue strength of welded joints improved by HFMI peening methods has been completed [5]. The available test data was statistically analysed and it was found that an S-N slope of m = 5 is suitable to be used for both the available HFMI treated fatigue data and the existing data for hammer peened welds. Thus, all of fatigue design methods for HFMI improved welds are based on an assumed S-N slope of m = 5 and fatigue strength improvement factors are defined at $N = 2 \cdot 10^6$.

It is proposed that the benefit of HFMI treatment can be claimed only for details in design Class FAT 50 to FAT 90 in the IIW notation for S-N curves [4]. This limitation is due to the fact that the higher classes include non-welded details, details whose lives are not governed by weld toe failure or welds that have been already been improved, e.g., a butt weld ground flush with the plate surface. Weld details lower than FAT 50 have not been studied experimentally with respect to HFMI improvement. For these details there is also increased risk of root side fatigue which is not influenced by HFMI [1, 3]. For steels with specified yield strength lower than 355 MPa, the proposed fatigue strength benefit following HFMI treatment consists of an upgrade by a factor of four (4) fatigue classes. For specified yield strengths above 355 MPa, the number of fatigue classes increases by one for every 200 MPa increase in yield strength. For example, when a weld detail which, in the as-welded condition, would be classified as FAT 80 is treated by HFMI, the new FAT value is FAT 125 to FAT 180 depending on the steel grade. These are shown in Fig. 1. In Fig. 1 the number in parentheses indicates the as-welded fatigue strength, i.e., 125(80) indicates FAT 80 in the as-welded condition [4] and FAT 125 following proper HFMI treatment.

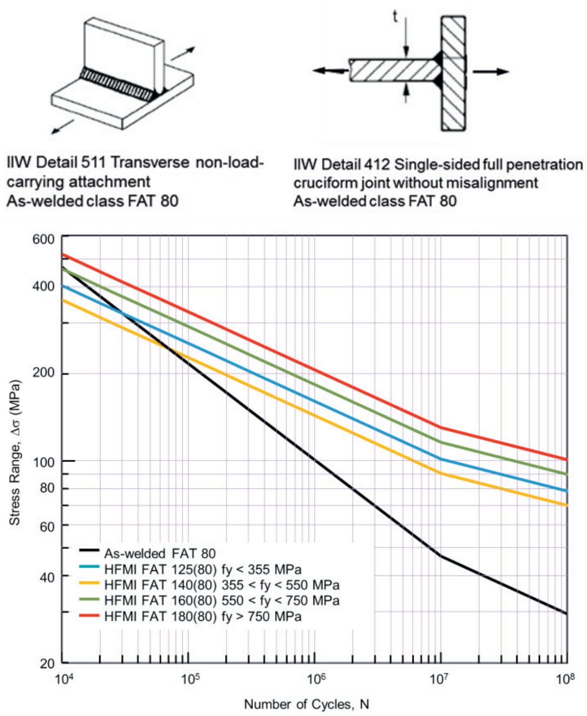


Fig. 1. Characteristic nominal S-N curves for HFMI improved and as-welded FAT 80 welded joints for various steel grades for $R \leq 0.15$.

In 2006 the IIW published fatigue design recommendations based on the use of the structural hot spot stress which includes details for determining the structural hot spot stress and proposals for design S-N curves expressed in terms of the hot-spot stress range [6]. The HFMI fatigue strength enhancement factors in this current document can also be applied to those curves.

For fatigue design based on the structural hot spot stress, stress analysis procedures as described by Niemi et al. are recommended [6]. As is the case with the nominal stress method, fatigue resistance curves for HFMI improved welds are based on an assumed hot spot S-N slope of $m = 5$. In the case of steel in the as-welded condition, two structural hot spot stress design curves are proposed. For load-carrying fillet welds a FAT 90 curve is recommended and for non-load carrying welds a FAT 100 curve is recommended.

Figure 2 shows characteristic structural hot spot stress S-N curves for non-load carrying HFMI improved welded joints for $R \leq 0.15$. For comparison S-N curves for as-welded [6] and hammer or needle peened welded joints [3] are also shown. For load-carrying welds, all the curves in Fig. 2 would be reduced by one fatigue class (about 12.5%) which is consistent with the existing IIW recommendations for fatigue design based on the use of the structural hot spot stress range [6].

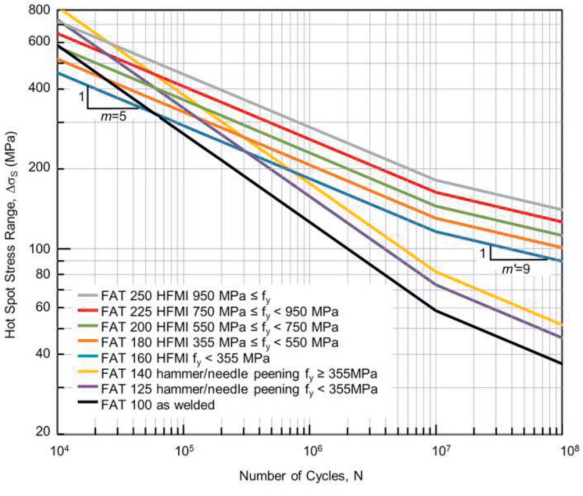


Fig. 2: Characteristic structural hot spot stress S-N curves for non-load carrying HFMI improved welded joints for R ≤ 0.15.

In 2008 the IIW approved a guideline encompassing fatigue design recommendations based on the effective notch stress approach to fatigue assessment [7]. This approach represents one method for explaining the experimental observation that, in fatigue, notches are less severe than what would be expected based on fatigue properties of a material and the elastic stress concentration at a notch. Stress averaging over a certain depth can be achieved by imposing a fictitious enlargement of the notch radius. During finite element assessment, the notch stress approach for fatigue assessment of welded joints considers the highest elastic stress at the weld toe or root. In order to avoid arbitrary or infinite stress results, a rounded shape with a reference radius instead of the actual sharp toe or root is assumed. The default reference radius is 1 mm.

With respect to the effective notch method and HFMI the actual notch radius at the weld toe can be from 1.5 mm to more than 7 mm. In theory, HFMI treated welds with larger radii should perform better in fatigue. However, there is a complex interaction between treatment parameters, toe radius, microstructure of the treated zone and residual stresses which is not fully understood. The extra benefit of modelling a weld toe notch with radius equal to the actual radius of the HFMI treated zone is therefore difficult to define. The current design proposal is to perform the stress analysis using an artificial notch radius of 1 mm using procedures as described by Fricke [7].

Characteristic effective notch stress S-N curves for HFMI improved welds are shown in Fig. 3 for various steel grades. For comparison the FAT 225 S-N curves for as-welded joints is also shown.

In the IIW recommendations for fatigue design of welded components in the as-welded state, the nominal normal stress range is required to remain below 1.5 * f_y while the nominal shear stress range must remain below 1.5 * f_y / √3 [4]. In the structural hot spot stress approach hot spot stress range is assumed to remain below 2 * f_y [6]. In practice this requirement is quite comparable to that for the nominal stress. For welded structures improved by needle peening or hammer peeing, the guideline states that the techniques are not suitable for R > 0.5 or when σ_{max} > 0.8 f_y [3]. These restrictions are intended to influence the fatigue design assessment of structures when the beneficial compressive residual stress state due to post weld improvement may not be stable. Weich et al. [8] have found that material strength has a strong influence on the stability of residual stresses for HFMI treated welds. These relationships demonstrate the critical importance of f_y in the design of welded components subjected to high mean stresses, low cycle fatigue loading or large stress cycles as part of a variable amplitude load history.

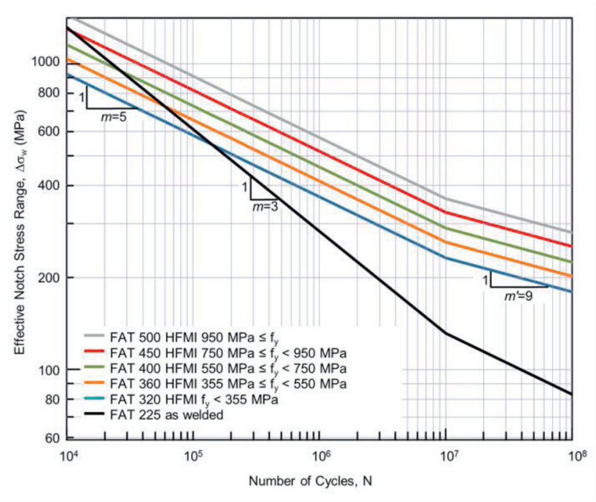


Fig. 3: Characteristic effective notch stress S-N curves for HFMI improved welded joints for R ≤ 0.15.

According to the IIW fatigue design guidelines [4], the fatigue assessment of welded joints is generally performed without consideration the mean stress on the joint. However, in special cases of joints with low or medium levels of residual stress, a fatigue enhancement factor can be used which increases the computed fatigue resistance curve used during assessment. For low residual stress situations the enhancement factor is given by Eq. (1)

$$f(R) = 1.2 - 0.4 \cdot R \text{ for } -1 \leq R \leq 0 \quad (1)$$

Since HFMI effectively introduces residual compressive stresses at the critical weld toe, treated welds can justifiably be considered to be low residual stress joints. Equation (1) results in a linearly increasing enhancement factor from to at f(R) = 1.16 at R=0.1 to f(R) = 1.6 at R=-1. Because all of the basic design information in this proposal has been derived from R=0.1 test results, it is reasonable to expect the fatigue strength of joints loaded at R=-1, for example, to be 38% greater than what is indicated in Figs. 1-3.

3. Quality Assurance Guidelines

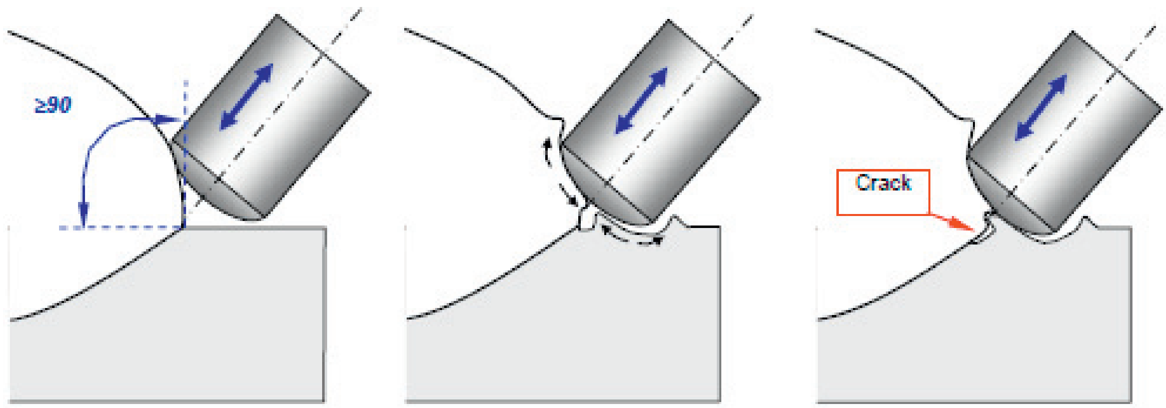
Improvement techniques described defined by the IIW are intended to be used both for increasing the fatigue strength of new structures and repair or upgrading of existing structures. The IIW has consistently emphasized that, especially with respect to new structures, weld improvement techniques should never be implemented to compensate for poor design or bad fabrication practices. Instead, improvement measures should be implemented as a means of providing additional strength after other measures have been taken. Because HFMI is normally specified as a fatigue strength improvement technology for new structures or during repair and retrofitting operations, it is always essential to consult fatigue experts to ensure that all critical regions in a structure identified and properly treated. Most fatigue loaded structures will normally have only a limited number of locations that are critical from a fatigue point of view. Proper identification of these regions is also important to avoid extra costs and treatment of regions which are not fatigue critical. Additionally, the possibility of a failure starting at some other location must always be considered. For instance, if the failure origin is merely shifted from the weld toe to the root there may be no significant improvement in fatigue life.

Proir to HFMI treatment the weld cap and adjacent parent material shall be fully de-slagged and wire brushed or ground to remove all traces of oxide, scale, spatter and other foreign material. HFMI treatment of a convex weld profile or of a weld with a large weld angle can cause the plastically deformed metal to fold over the original weld toe and leave a crack-like lap feature that resembles a cold lap [2]. The weld bead profile should meet the acceptance limits for weld profile quality level B in ISO 5817 [15]. This requirement does not imply that the weld must fulfil all quality level B criteria in ISO 5817. However, weld profile-related quality criteria in ISO 5817 need to be evaluated. These include Undercuts (imperfection 1.7), Excessive overfill (imperfection 1.19), Excessive concavity (imperfection 1.10) and Overlaps (imperfection 1.13). If the weld profile does not comply with these acceptance limits, light grinding before treatment may be desired. It should be noted, however, that HFMI treatment is most effective when the weld toe region itself is treated. Thus, grinding operations which make it difficult for the HFMI operator to distinguish the exact location of the weld toe should be avoided. Decisions on the need for weld grinding and the proper grinding procedure should be agreed on with an experienced HFMI operator.

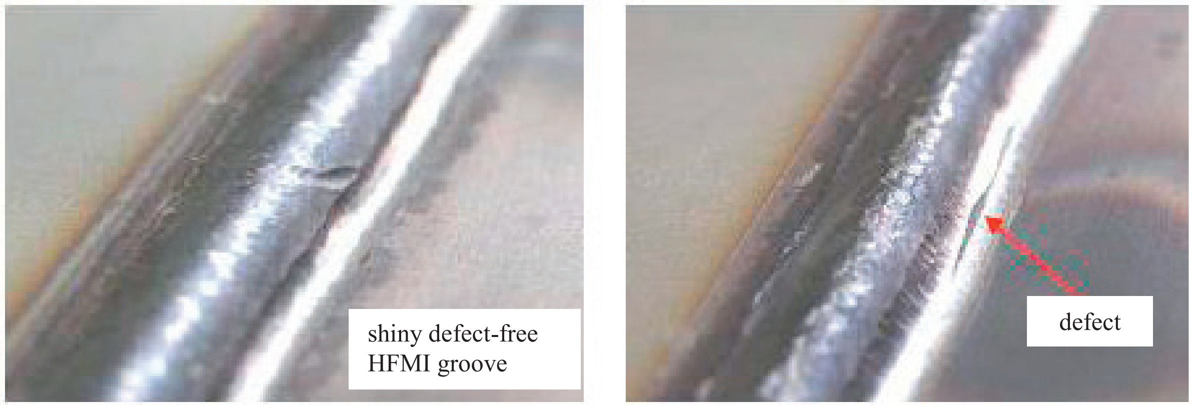
The need for proper weld profile before HFMI is illustrated in Fig. 4 a) which illustrates the formation of a crack-like defect due to improper contact between the indenter and weld toe. Surface inspection of such a defect reveals a dark crack-like line in the middle of the otherwise smooth and shiny HFMI groove as seen in Fig. 4 b). Figure 4 c) shows section micrographs of these defects. The resulting fatigue performance of a welded joint with such defects may actually be less than that of the original as-welded joint. The same type of flaw has been observed in welds with adequate profiles but with improper indenter se-lection or too severe treatment, i.e. too many passes over the same region. For specific applications it may be needed to consult with the HFMI tool manufacturer in order to select the proper treatment procedures and optimal indenter configuration to avoid crack-like defects.

The depth of the HFMI groove is an excellent indicator of the extent of HFMI treatment [29]. Depending on the yield strength of the steel and the size of the indenters, typically the optimum HFMI groove will be 0.2 - 0.6 mm in depth and the width will be 3 - 6 mm [10-12], see Fig. 5. However, it should be noted that no single groove dimension is optimal in all situations. A welded structure with relatively deep undercuts at the weld toe may require light grinding of the weld toe before HFMI and will have a deeper groove following HFMI. Also, HFMI grooves in high strength steel structures will typically be shallower and narrower than grooves in low strength steel. Groove depth can be checked relatively easily by using simple depth gauges such as is shown in Fig. 6. Callipers can be used to measure the width of the groove. The centre of the HFMI groove should correspond to the fusion line of the weld. The portion of the HFMI groove in the weld metal must be between 25% and 75% of the total HFMI groove width [11].

a)



b)



c)

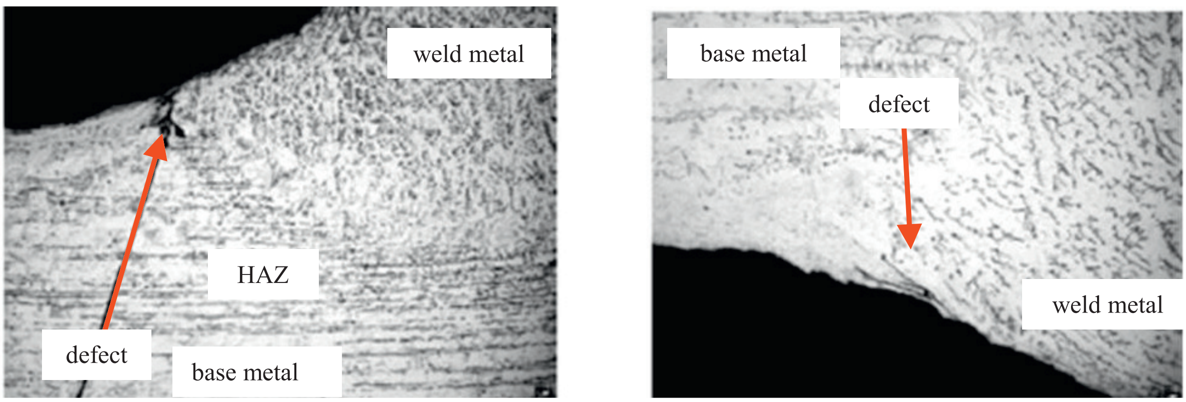


Fig. 4: a) Potential introduction of crack-like defect due to HFMI treatment of a weld with a steep angle or with too large of an indenter and b)

resulting groove for a properly treated (left) and improperly treated weld toe (right) and c) micrographs of the induced crack-like defects due to improper HFMI treatment [16].

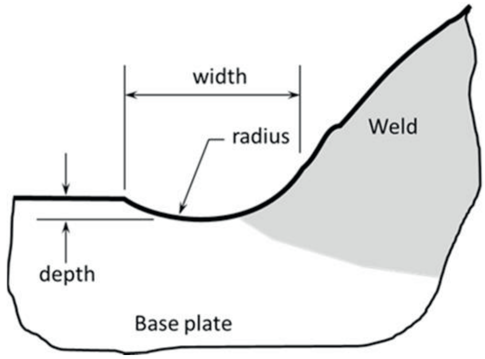


Fig. 5: The HFMI indentation depth following treatment should be 0.2-0.6 mm while the resulting width is typically 2-5 mm.

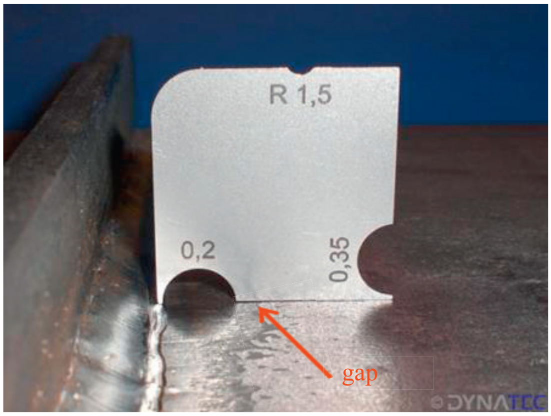


Fig. 6: Depth inspection using simple gauges [13]. The gap between the base plate and the gauge indicates that 0.2 mm has not been achieved.

A HFMI Procedure Specification (HFMI-PS) similar to a Welding Procedure Specification (WPS) should be prepared for the HFMI treatment. The HFMI-PS includes information concerning the component being treated; base and filler material; HFMI equipment type and power settings; number, size and shape of the indenters to be used; special inspection requirements including HFMI groove dimension, etc. Lopez Martinez and Haagensen have developed a HFMI-PS template which is prepared for each weld in a structure [14, 2].

4. International Collaboration

The development of a new IIW best practice guideline concerning HFMI-based fatigue strength improvement of welded components has involved many partners from at least 12 countries. Table 1 lists the countries which have been involved in various phases of development of the best practice guideline. Most of the 12 countries involved had several partner organisations contributing to the research. All contributions have been self-financed in that the IIW provides a strong network but does financially support research goals. Such strong multinational cooperation which involves the joint efforts and commitment of industry, research institutes and universities can only be accomplished in organisations like the IIW. This simple example illustrates the mission of the IIW in action *"To act as the world-wide network for knowledge exchange of joining technologies to improve the global quality of life"*.

Table 1: Scope of countries involved in various phases of the development of a best practice guideline concerning HFMI

International Cooperation	Austria	Canada	China	Finland	France	Germany	Norway	Russia	Sweden	UK	Ukraine	USA
Technology Development		x	x		x	x		x			x	x
Initial test data	x	x	x	x	x	x	x		x	x		x
Specialized data	x			x	x	x			x	x		
Data synthesis	x			x		x	x		x			
Quality assurance		x		x	x	x			x			x
Guidance on training				x		x						
Guideline preparation				x					x			

5. Discussion and Conclusion

A design proposal for HFMI treated welded joints in steel based on experimental evidence published within the IIW and presented in the open international literature has been briefly presented. Aspects of this guideline and the unique international nature of the IIW which has made it possible are described.

The design proposal in this paper is considered to apply to plate thickness 5 to 50 mm and for 235 MPa $\leq f_y \leq$ 960 MPa. Fatigue resistance curves for HFMI improved welds are based on an assumed S-N slope of m = 5 in the region $1{\cdot}10^4 \leq N < 1{\cdot}10^7$ cycles and, for variable amplitude loading, m' = 9 for $1{\cdot}10^7 \leq N$. As is the case with the nominal stress method, characteristic curves are defined at $N = 2{\cdot}10^6$. Stress assessment may be based on nominal stress, structural hot spot stress or effective notch stress using stress analysis procedures as defined by the IIW Commission XIII. The design proposal includes proposals for the 1) effect of material strength, 2) special requirements for low stress concentration weld details, 3) high R-ratio loading conditions and 4) variable amplitude loading. Several topics for future study with respect to HFMI are given.

A proposal for procedures and quality assurance for HFMI treated welded joints in steel based has also been presented. It was developed based on discussions, presentations and experimental evidence published within Commission XIII of the IIW. The proposal has been reviewed by several HFMI tool manufacturers and has been compared to other available technical documents. The proposal includes brief descriptions of HMFI equipment, operator training, weld preparation, safety aspects, treatment procedures, qualitative and quantitative quality control measures, procedure documentation and equipment. Certain details of the precise treatment procedures and quantitative quality control measures can vary greatly depending on the specific welded structure being treated. Aspects of this guideline and the unique international nature of the IIW which has made it possible are described.

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