Review of Weld Quality Classification Standard and Post Weld Fatigue Life Improvement Methods for Welded Joints.

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Abstract. In typical fabricated structures, there are hundreds of joints, which acts as a potential location for fatigue cracking. Ageing and life extension (ALE) of such structures could be developed further by creating an optimal measure between the required quality level and fatigue performance defined in quality inspection code of welded joints. The quality system for welds is described in ISO 5817 standard, where acceptance criteria have been specified for different types of weld geometry imperfections. Challenge of establishing link between the fatigue performance and defined weld quality classes is not consistent in these inspection codes i.e. link between the design of weld having required fatigue strength and described fabrication quality as per acceptance criteria is missing. Furthermore, weld quality optimal assessment during the lifecycle of welded joints can sustainably improve their fatigue life by the adoption of good design practices. Fatigue loading is identified as one of the most important factors for degradation of complex welded structures, which are highly influenced by local and geometric features modifications at weld toe locations. In recent years, the International Institute of Welding (IIW) Commission XIII has recommended guidelines related to fatigue design & assessment of welded structures under which various fatigue life improvement techniques have become available lately. The focus of this manuscript is on recommendations specified by IIW on post weld fatigue life improvement of steel structures by High-frequency Mechanical Impact (HFMI) methods, a residual stress improvement technique. Residual stress improvement techniques contribute to fatigue strength increase by reducing harmful tensile residual stresses and by inducing beneficial compressive residual stresses at weld toe regions. These recommendations include major fatigue assessment based on nominal stress, structural stress, and effective notch stress methods. Major influencing factors namely thickness and size effects, influence of steel strength, loading effects, stress ratio are reviewed in detail for fatigue design class improvement of HFMI treated welds.

Keywords: HFMI, IIW, Residual stress, ISO 5817

1 Introduction

Welded structures are mostly vulnerable to adverse geometric and metallurgical effects induced by welding[1]. The geometries of most welded joints introduces sudden changes of sections leading to local stress concentrations during loading and offering sites for crack initiation[2]. Structural welded components exhibit poor fatigue properties in comparison to samples without any discontinuities due to the fact that majority of their resulting fatigue life are spent on propagating the crack[3]. Whereas fatigue crack initiation period can occupy majority of lives in unwelded components [3]. Increased service life of welded structures can be ensured by following a good design practice, use of high quality fabrication and post weld improvement techniques[4]. Operational parameters like appropriate welding process, weld penetration parameters, weld geometry, low stress concentration factors etc. [2] aligned with accepted weld quality inspection code, assists in improving fatigue strength of welded joints.

Weld class systems are part of standards like ISO 5817[5] & Volvo STD 181-0004, [6] defining quality system for welds. However, inconsistencies have been found between weld quality systems and corresponding fatigue performance [7]. This led international institute of welding (IIW) to establish recommendations on weld quality level and corresponding fatigue strength [7] which are based on different assessment methods [8-10] namely nominal stress, hot spot stress and notch stress methods. Nominal and structural hot spot stress method does not take the effect of geometric parameters of the weld toe into consideration, whereas effective notch stress method and fracture mechanics considers the effect of toe radius. Weld toe geometry primary controlling parameters for fatigue properties are transition angle of weld toe, radius of weld toe and wall thickness, which have been used to derive stress raising notch effect of the toe by various researchers.[11, 12]

In the last few decades there has been considerable work done in welded joints, post weld fatigue life improvement methods. These fatigue life improvement methods relies on principle of improving the stress fields around the weld toe [13]. These methods are mainly divided into two groups, namely modification of weld toe geometry and residual stress improvement methods around weld toe. In the first group, modification of weld toe geometry is done by grinding of weld toes or re-melting by TIG (tungsten inert gas) welding. Secondly, in residual stress improvement methods, shot/ hammer/or needle peening and high-frequency mechanical impact (HFMI) techniques are well known established techniques [14]. In 2007, IIW commission XIII based on fatigue life of welded components and structures recommended guidelines on various techniques on post weld, fatigue improvement in welded joints[4]. HFMI treatment methods are included under IIW recommendations, based on numerous research studies results conducted between 2002-2012 [4].

In this manuscript, various weld quality level standards correlation with fatigue strength of welded joints is presented as recommendations to design engineers for adopting these standards as tool to measure weld performance during design and fabrication process. Fatigue life improvement techniques recommended by IIW namely HFMI, a residual stress improvement technique is discussed in detail. These recommendations also include fatigue assessment based upon nominal, structural and effective notch stress methods. Major influencing factors like thickness, influence of steel yield strength, fluctuating load effects, stress ratio is reviewed in detail for fatigue design class improvement of HFMI treated welds.

2 Classification of weld quality level standards

ISO 5817:2014 standard [5] defines quality levels for various imperfections in welded joints of steel, nickel etc. and their alloys. In this standard, defined quality levels are classified as B, C, or D. Level B corresponds to best level and level D towards lowest weld quality level. These levels correspond to different quality levels with each weld discontinuity and imperfection having defined acceptance limits. ISO 5817:2014 defines 40 different types of weld discontinuities and some imperfections corresponding to different quality levels as illustrated in figure 1. ISO 5817 contains 23 outside imperfections, 13 inside imperfections, two weld geometry imperfections and two types of multiple imperfections[5]. A non-consistent relationship has been determined between the quality level and required fatigue life, implying that weld having best quality level should have a longer fatigue life in comparison to a low quality level weld [15].Whereas, Volvo Group STD 181-0004[16] has defined three different types of quality levels for fatigue. As-welded normal quality is classified as VD, high quality as VC and quality after post-weld treatment as VB. In Volvo Group STD 181-0004[16], a change in quality level, leads to 25 % increase in fatigue strength from previous class.

Welding introduces risk of fatigue failures by introduction of sharp notches and high stress raisers due to inhomogeneity created by welded geometries[3]. Improved weld quality is not achieved for welded component as fatigue strength remains same for welded steel as illustrated in figure 2.a [17]. Weld defects, imperfections, irregularities are common in welded joints and various weld quality standards [5, 6] are available to determine acceptance criteria for them. Fatigue life is determined by weld defects size as shown in figure 2.b and supported by Kitagawa diagram [17]. However, a weak correlation has been observed between weld quality levels and fatigue properties in ISO 5817 a weld quality assurance standard [5, 7, 16-18]. In ISO 5817, little influence on fatigue strength have been found for some weld imperfections as per their defined acceptance criteria. Whereas, imperfections that influence fatigue strength results in non-uniform changes in fatigue strength of their respective acceptance criteria between weld quality classes [7].

Current version of ISO 5817:2014, Annex C bridges the gap between required weld quality level and corresponding fatigue strength. As per IIW fatigue design recommendations [7, 9] notation, FAT 63 and FAT 90 class, has been related as imperfections limits for quality levels in Annex C of ISO 5817. Hobbacher and Kassner [19] had established this link between ISO 5817 and welds having consistent fatigue strength [7] in IIW recommendations [9]. IIW guidelines on weld quality in relationship to fatigue strength[7] presents a practical basis for ISO 5817, aligning quality levels consistent with fatigue strength. Such alignment can specify weld quality levels for required fatigue strength and vice versa [7].

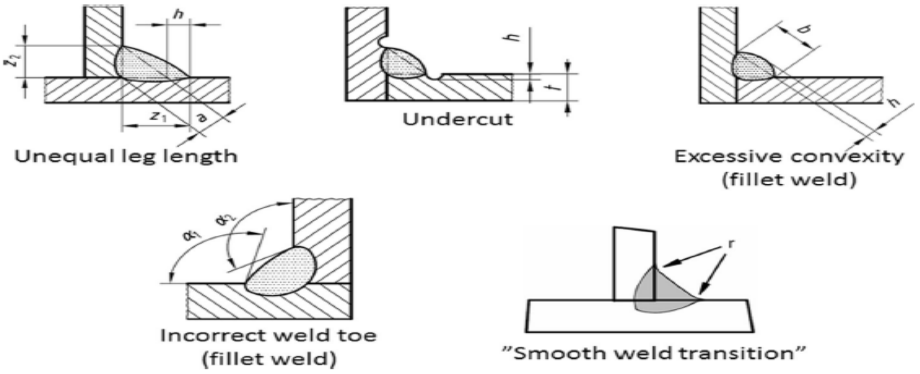

Fig. 1. Weld discontinuities mentioned in ISO 5817 [5]

Weld quality standards like ISO 5817 are so widely used for determining weld defects acceptance criteria that they are often interpreted as measure for structural performance, which is not their prime function. Design engineers often misinterpret these weld quality standards as a reference to determine high quality level welded joints. However design engineers should adopt methods like good design practices, high quality fabrications and various weld improvement techniques in their design that contributes to higher fatigue strength[2].

Adoption of best design practice can be achieved by minimization of fatigue loads e.g. by avoiding resonance and vibrations locations, using connections with low stress concentration factors and placing welds in area of low weld concentrations.[2] Conversely, high quality fabrication methods and using weld improvement techniques etc. results in increased fabrication cost. Hence, an effort should be made to increase fatigue strength in design, fabrication and inspection stage in line with IIW recommendations for fatigue improvement techniques [4, 7, 9, 20].

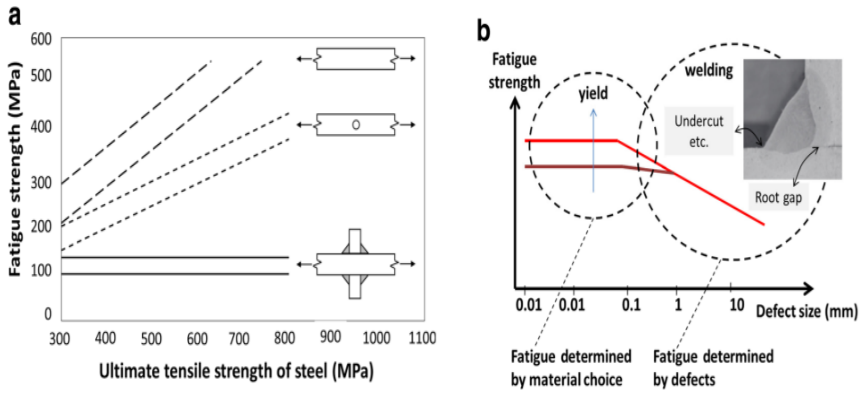

Fig. 2. a) Fatigue strength vs tensile strength for, notched, unnotched and welded components. **b)** Kitagawa diagram, fatigue strength versus defect size, with indicated weld positions[17]

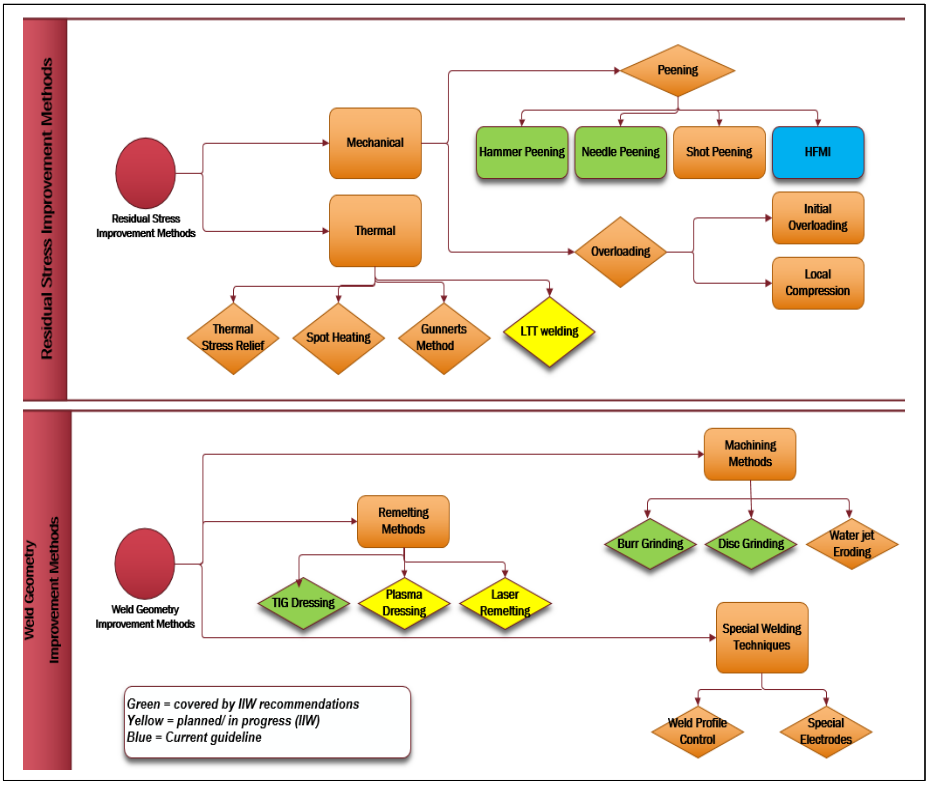

Fig. 3. Overview of Fatigue Improvement Techniques adapted from [21]

3 Fatigue improvement methods

The IIW commission has recommended techniques and procedures for improvement of welded steel structures fatigue strength [4]. As demonstrated in figure 3. an overview of various fatigue improvement techniques is presented [20]. These techniques are divided into, two broad categories. First category relies on the principle of reducing local stress concentration factor at weld toes, which improves the fatigue strength and ensures an uninterrupted transition between the profile of weld toe and base material. The second category ensures induction of beneficial compressive residual stresses and reduction of harmful tensile residual stresses in the weld toe region, eventually contributing to fatigue strength improvement [1, 5-7]. Fatigue improvement techniques may be applied during design, fabrication or post fabrication. These recommendations of IIW [4] on fatigue improvement of welded components and structures verifies all methods, e.g. component testing, nominal stress, structural hot spot stress in 2006 [8], notch stress method in 2008 [10] as well as fracture mechanics assessment procedures [3, 9, 10].

These guidelines cover four commonly applied post weld treatment methods. Reduction of stress concentration points by material removal mechanically are the basic principle on which, the first method (burr grinding or weld toe grinding) depends. It can be achieved by rise of the weld toe radius and fall of weld flank angle [22]. This method also helps in removal of any underlying defect close to weld toe. The second method (TIG re-melting) results in two main advantages, firstly reduction of stress concentration points around weld toe and secondly by improving hardness around weld toe zone region. Re-melting around weld toe results in effortless transition between the weld toe radius and the base material [23].

The first two techniques defined under the IIW recommendations namely burr grinding and TIG dressing benefits are claimed in FAT 90 class leading maximum improvement up to FAT 125 class as per IIW notation of SN curves. This corresponds to an increase in allowable stress range by a factor of 1.3 and 2.2 on life (for SN slope m=3) [24]. For simplification purpose, an improvement of two (2)-fatigue class based on the IIW fatigue design notations [4].

For steels having yield > 355 MPa, improvement of welds by hammer or needle peening gives a upgrade by a factor of 1.5 in fatigue strength benefit, applied to the stress range as per IIW guideline [4]. In simplified terms, an increase of three (3) fatigue class[4]. Needle and hammer peening are grouped under the family of high frequency mechanical impact (HFMI) family. Reduction of stress concentration increase in hardness and introduction of beneficial compressive stresses at weld toes are major advantages of these methods. The affected region around weld toe becomes plastically deformed, which leads to large changes in the microstructure and corresponding local geometry. Simultaneously as mentioned before, residual stress state changes around welded toe region, leading to introduction of beneficial compressive residual stresses[25] [23]

Welding with special electrodes called low transformation temperature (LTT) electrodes, have emerged as other recent approach to improve welds fatigue strength. This technique has advantage of being more cost effective in contrast to HFMI techniques as it does not require any additional treatment after welding [26-29]. Special welding methods like friction stir welding, welded joints have shown excellent fatigue properties compared to conventional welds which shows fatigue strength comparable to base material [2]. In structural welding code of the American welding society (AWS), overall shape of weld can be controlled by achieving a concave profile on weld toe having a low stress concentration.[30].

4 Fatigue improvement by High Frequency Mechanical Impact methods –HFMI

The innovation and the pioneer work of locally modifying the residual stress state using ultrasonic technology goes to the researchers based in the former Soviet Union [31, 32]. Since 2010, IIW Commission XIII uses the term HFMI as a universally accepted term to generalize several related techniques. Following are the names of different techniques having almost the same principle for which separate recommendations was published by the commission. Ultrasonic impact treatment, ultrasonic peening, ultrasonic peening treatment, high-frequency impact treatment , pneumatic impact treatment and ultrasonic needle peening [24, 33, 34] are generalized terms for these technologies [20]. These guideline are applicable to steel structures of plate thickness ranging from five to fifty mm (5-50 mm) and yield strength stretching from 235-960 MPa [20].

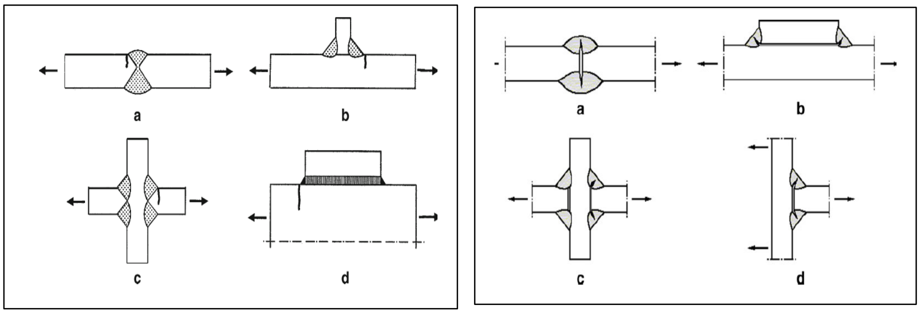

Fig. 4 a & b. Weld joint configurations not suitable for post weld improvement [25]

HFMI treatment is the more advanced term accepted for hammer or needle peening. Its principle relies on high frequency impacts of needles on areas around weld toes resulting in smooth indentations due to smaller spacing of needles. At the same time HFMI tools are found to be more comfortable and less noisy for the operator [35]. IIW guidelines clearly specifies that HFMI improved welds are recommended to improve the fatigue live of the welds, where probability of occurrence of failures are more from locations close to weld toe. Hence, occurrence of a failure originating from locations other than weld toe example weld root etc. must be taken into account before HFMI application, as illustrated in figure 4 a & b respectively [25]. As per IIW notation, fatigue strength (FAT value) at no of cycles to failure = $2x10^6$ has been characterized as index point for defining improvement in fatigue for HFMI improved welds having a slope of 5 on SN curve.[9]

4.1 Fatigue improvement for HFMI improved welds based on nominal stress

It has been validated and recommend by IIW guidelines [4], that fatigue lives of welds can be best observed in SN curve having slope greater than m=3 . Recent studies have established SN curve having slope m= 5, shows a best fit with available fatigue data for HFMI treated welds [36]. HFMI treated welds benefit can be claimed between FAT classes 50 & 90, as defined in IIW notation of SN curves in their recommendations. If failure dominates from root other than weld toe, than these recommendation tends to fail [20]. HFMI benefit of four-fatigue class can be claimed in IIW notation of SN curves for steel having yield strength ≤355 MPa. [20]

As illustrated in figure 5 in black line, welded joint (without any post weld improvement) having yield less than 355 MPa are classified as FAT class 90 with a slope of 3, as per IIW recommendations on fatigue strength of welded joints. After HFMI treatment FAT class of 140 with a slope of five, is shown as red line in figure 5. This red line intersects with black line of as weld condition at about N=72,000 cycles. This illustrates that welded structures with yield≤355 MPa, fatigue strength improvement benefit cannot be claimed, if the fatigue life is less than N=72,000 cycles. Similar cycle limit for steels having yield greater than 355 MPa is specified in the recommendations [22]

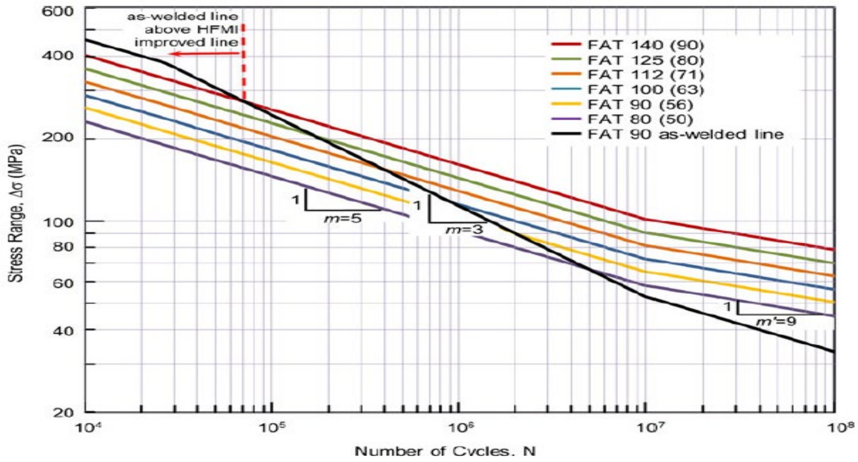

Fig. 5. Nominal stress SN curve for HFMI treated welds adapted from [9]

In nominal stress approach actual weld geometry is not considered hence its application of the assessment is in principle clear [22]. Due to high cost involved in conducting experiments in nominal stress approach and replication of its results to similar weld configurations may lead to overly conservative analysis. IIW recommendations for post-weld treatment methods [4] partitions a single division between steels having yield strength less or greater than 355 MPa. After a round robin exercise in 2003 supported with numerous studies and research results, IIW commission XIII a concluded relationship between yield and fatigue strength.[36]

4.2 Influence of steel strength stress on HFMI treated welds

Steels having different yield strengths showed a different trend in FAT class improvement when treated with HFMI. [4, 20, 36]. Yildrim and Marquis [36] had proposed a distinction between yield strength range and corresponding improvement in fatigue class after assessment of published data. Steels having thickness ranging from 5-30mm and yield strength ranging between 260 to 969 MPa were grouped under a yield strength correction method under IIW recommendations for HFMI treated welds[20]. It is recommended that there is an increase of one fatigue class for every 200 MPa increase in static yield strength as per IIW recommendations [20] as illustrated in figure 6.

For steels having yield strength greater than 950 MPa, the maximum increase in fatigue strength is up to 8 fatigue class [37]. As defined earlier all fatigue classes are defined at cycle to failure at N = 2 x10^6 cycles with slope of five in SN curve, for HFMI-treated welds as per IIW notation scheme. However, IIW recommends an increase of two-fatigue class for all improvement methods irrespective of its type as it classifies yield strength criteria into high and low strength steels only. Whereas in TIG dressing technique an increase of three fatigue class has been found for longitudinal stiffeners as an example and four for HFMI treatment welds [25]. Most importantly, it should not be missed that assumed SN slope for as welded joints is 3, m = 4 for TIG-dressed welds and m = 5 for HFMI-treated welds [14].

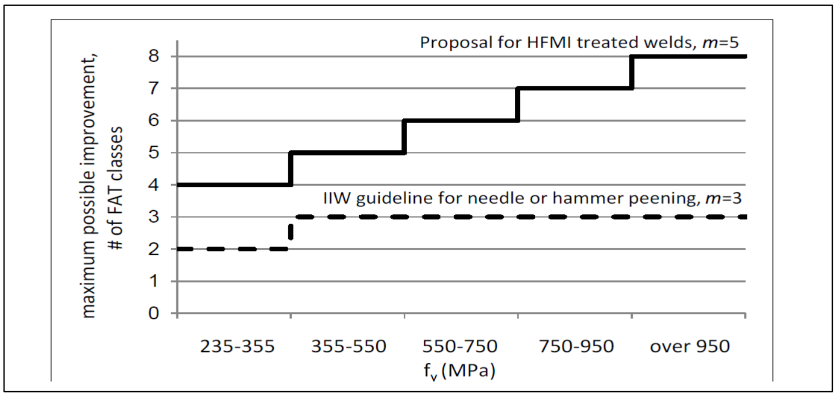

Fig. 6. Maximum improvement in fatigue class vs yield strength adapted from [21]

4.3 Thickness and size effects on HFMI treated welds

As thickness of welded components are increased, its fatigue strength is reduced with increasing plate thickness of the load-carrying plate. Geometric features like weld fillet size, attachment plate size, main plate width etc. are known to make major influence in term defined as size effect [35]. Due to large stress concentrations created at weld toe critical locations, weld toe is largely affected by plate thickness and size of weld. Nominal stress and hot spot stress method uses the criteria of thickness reduction factor for thickness exceeding 25mm [25]. Existing thickness reduction factor in IIW guideline[4] are based on Hobbacher [9], which is again referred for HFMI recommendations due to lack in extensive experimental data. Current guideline for HFMI improved welds, a thickness exponent of 0.2 is used as per IIW recommendations [20].

4.4 Loading effects on HFMI treated welds

HFMI treated welds improvement is greatly benefited to induction of beneficial compressive residual stresses at weld toe regions. Areas where applied stress equals or nears yield value, amount of fatigue improvement decreases in regions of high mean stresses and R-ratios. Welded components operating at $R > 0.5$ (applied stress ratios) and applied stresses above 80% of yield value, are not suitable for improvement by HFMI technique [36]. IIW recommendations is valid for $R \leq 0.15$ as fatigue strength improvement benefit of hammer, penning is largely influenced by applied stress ratio[4]. Without testing, fatigue improvement cannot be claimed for R ratio greater than 0.5[20]. For high stress ratios situations, IIW guidelines gives special limitation and FAT classes improvement for welded joints improved by needle or hammer peening [4]. Reduction in FAT classes are imposed as an penalty for high stress ratios for HFMI treated welds as illustrated in Table.1, referred form IIW guidelines[25].

Table 1. Penalty of FAT classes having high stress ratio for HFMI-treated welded joints[25]

Stress Ratio	Minimum FAT class reduction
$R \leq 0.15$	No reduction due to stress ratio
$0.15 < R \leq 0.28$	One FAT class reduction
$0.28 < R \leq 0.4$	Two FAT classes reduction
$0.4 < R \leq 0.52$	Three FAT classes reduction
$0.52 < R$	No data available

Variable amplitude loading can drastically change the residual stress state around the weld toe in HFMI treated welds[20]. In practical situations variable loading are more prevalent, hence failure mode changes in HFMI treated welds in contrast to constant amplitude loading recommendations available from lab experiments [38]. IIW guidelines [20] follows the maximum amplitude stress ratio limitation criteria as illustrated in figure 7, for situations involving variable amplitude loading in HFMI treated welds. [25]. It should be noted that HFMI benefit cannot be claimed without fatigue testing, if the stress ratio exceeds the limit value for a given yield strength. [20]

Available recommendations are based on constant amplitude loading results and limited data is available for variable amplitude testing which needs further studies for more accepted use of these recommendations in practical world. Accurate prediction of residual stresses in complex welded structures and its relaxation and redistribution during loading is a major challenge in defining improvement in FAT classes for post weld treatment methods of fatigue improvement.

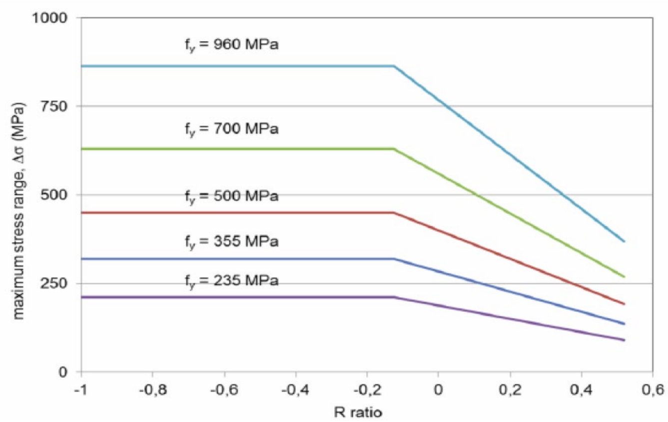

Fig. 7 Penalty of maximum constant amplitude stress range for HFMI treated welds [25]

4.5 HFMI treatment through local approaches

Effective notch stress method (ENS) and structural hot spot stress method (SHSS) are local approaches defined by IIW commission XIII of fatigue of welded components [9]. In SHSS, characteristic SN curves defined in the recommendations [8] were applied by Yildrim [39] on HFMI treated welds. Two types of fatigue class improvement class have been suggested for load and non-load carrying joints for HFMI treated welds. In SHSS approach, weld geometry is not considered in detail hence uncertainty in extrapolation often leads towards conservative results. Whereas in ENS method[10], only one type of SN curve have been proposed by Yildrim [39]. In case of HFMI treated welds, correct understanding of toe radius, microstructure of treated zone and residual stress needs to be understood for use ENS approach with actual radius of HFMI treated welds. Local approaches proposed in the guideline shave been found to be conservative and consistent with all type of weld geometries and existing fatigue data points [39].

4.6 HFMI treatment of Ultra-high strength steels

As mentioned in section 4.2, yield strength plays an important role in deciding improvement in fatigue strength or FAT class improvement as per IIW guidelines on HFMI treated welds. For steel having strength ranging between 960-1400 MPa, Berg and Stranghöner [40], investigated steel shaving strength greater than 1000 MPa. Their findings concluded an increase in fatigue strength of 15% for steels having yield between 1100-1300MPa and 10% for steels having yield between 960-1100MPa. Further studies and inclusion under IIW guidelines are needed to correlate HFMI improvement in ultra-high strength steels as various studies claims different degree of improvement.

5 Conclusion

Weld discontinuities are classified into a grouping scheme in ISO 5817 standard. This standard helps in measuring weld performance in terms of its quality. ISO 5817 is found to be inconsistent in terms of corresponding fatigue performance, as welds termed, as high quality in standard, should correspond to high fatigue strength joints. This led IIW fatigue design recommendations to include Annex C in ISO 5817, where consistency in quality levels in terms of fatigue properties of welded joints have been improved.

Under fatigue improvement methods, HFMI is the universal term under which various ultrasonic techniques have been grouped. Fatigue data analysis of HFMI treated welds are found to fit well with existing fatigue weld joints recommendations having a slope of five in comparison to classic characteristic SN curve slope of three as per IIW notation scheme. Stepwise grouping of material yield strength and corresponding improvement in fatigue class are included in IIW recommendations whereas penalty in fatigue class improvement due to varying loading does have a skeptical acceptance. Due to lack of experimental data for different weld geometries and varying load conditions, improvement in fatigue classes as per IIW recommendations should be validated beforehand application guidance.

Weld toe modification has been found one of the most critical weld geometry features, which has novice notion of acceptance by a smooth transition. In areas of low cycle fatigue, weld profile changes can be more effective way in contrast to areas of high fatigue loading, where residual stress modification can be more effective. As per IIW guidelines on post weld fatigue improvement, HFMI improved welds are found to be more effective when there are more chances of occurrence of failure from weld toe in contrast to weld root region. However, failures at weld toe have been found to move to other locations such as inter-bead toes and the weld root as per the loading condition. Hence, role of the weld root is more important in relation to weld improvement. Hence, designer engineers should establish appropriate weld quality levels on the drawings for fatigue improvement, considering interactions of weld imperfections and fatigue properties during design of cyclic loaded welded components.

During design stage, a designer should strike a balance between fatigue improvement methods and should design welds for purpose. Design engineers should consider possible methods for post-weld treatment like placing welds in areas of low stress concentration areas, reducing stress concentrations, improvement of weld with use of LTT electrodes and fatigue crack arrest (FCA) steels. For fatigue-loaded structures, quality guidelines should be more detailed in contrast to static loading, where role of local weld geometry profile and features can be overlooked.

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