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Fatigue strength of HFMI treated structures under high R-ratio and variable amplitude loading

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Abstract

High frequency mechanical impact (HFMI) is a post-weld treatment method for improving fatigue strength of welded joints. Much of the experimental research on fatigue performance of HFMI treated welded joints has concentrated on the beneficial compressive residual stresses created by the treatment and the fatigue strength of these joints under constant amplitude loading and relatively low mean stresses. Critical experimental data has been developed in a nearly completed European RFCS project. New mean stress and variable amplitude fatigue data are presented and evaluated with respect to a proposed International Institute of Welding (IIW) design guideline concerning HFMI treated welded joints.

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Keywords: High frequency mechanical impact (HFMI); Fatigue, Stress relaxation, Mean stress, Variable amplitude loading

1. Introduction

The fatigue strength of welded joints can be improved through a variety of post-weld treatment methods. One such method is high frequency mechanical impact (HFMI), which is a residual stress modification technique. In addition to the compressive residual stresses created at the weld toe, the treatment also improves weld toe geometry and creates a highly cold-worked surface at the treated area. Other benefits of HFMI include user-friendliness and a
uniform treatment region that can be produced with good repeatability. The method also results in greater treatment depths than conventional shot or hammer peening. For these reasons, the method is increasing in popularity. There are a number of commercial organisations who provide HFMI technology, each with their own technique name such as: ultrasonic impact treatment (UIT) [1], ultrasonic peening treatment (UPT) [2] and high frequency impact treatment (HiFIT) [3]. All the technologies have, however, the same working principle where small indenters are accelerated with high frequency into the material surface to create compressive residual stresses. The method was originally invented by Statnikov at Sevmash Shipping Enterprise in Russia and further developed at Northern Scientific and Technological Foundation in Russia and in Paton Welding Institute in Ukraine [4,5].

The beneficial compressive residual stresses created by the HFMI treatment are relatively well known due to the large number of studies concentrating on their effects and the resulting fatigue life. The stability of these stresses is however less clear, as much of the data is from constant amplitude loading (CAL) tests with relatively low mean stresses. Residual stress relaxation rate depends on the global and local welding geometry, type of loading, material condition, initial residual stress state and mean stress. High applied mean stresses, e.g. due to dead loads and individual large stress cycles in spectrum loading, can be especially harmful as they may result in applied maximum stresses close to the yield strength of the material. This in turn can lead to relaxation of the beneficial compressive stresses [6]. For example, for needle or hammer peening it is assumed that the treatment is not suitable if the stress ratio (minimum stress/maximum stress), \( R > 0.5 \), or the maximum stress \( \sigma_{\text{max}} > 0.8f_y \), where \( f_y \) is yield strength [7]. This is why high stress ratios of around \( R = 0.5 \) and variable amplitude loading (VAL) spectrums with large stress cycles have been of interest lately [8,9,10,11,12,13,14,15,16,17,18]. Recently, critical fatigue test data with high mean stresses has also been created in the joint European Research Fund for Coal and Steel (RFCS) project “Improving the fatigue life of high strength steel welded structures by post weld treatments and specific filler material”.

The International Institute of Welding (IIW) guidelines do not currently include HFMI treatment methods. However, an IIW proposal for fatigue design of HFMI treated welded joints is currently being developed [19]. The proposed guideline considers the different effects of loading, steel strength as well as thickness and size. A stepwise penalty for different stress ratios is suggested based on a continuous reduction factor proposed in [15] and the current IIW recommendation [7]. The yield strength dependence is according to [20]. In addition, the suggested S-N curve slope of \( m = 5 \) [21] instead of the current IIW recommendation of \( m = 3 \) [22] is used. In this study, available high stress ratio and VAL data will be evaluated with respect to the proposed design guideline concerning HFMI treated welded joints. The data is compared to the S-N curves that take into account the improvement due to the treatment and the steel strength, as well as the proposed reduction due to high mean stresses. Very high stress ratios of \( R > 0.52 \) are of special interest.

2. Methods

2.1. Available data

The considered joint types are longitudinal attachments, transverse non-load-carrying attachments and butt joints under axial loading (shown in Figure 1). In the case of transverse and longitudinal attachments only double-sided joints are taken into account due to possible secondary bending effects in one-sided joints. The data is taken from literature [8,9,10,11,12,13,14,15,16,17,18] and the European RFCS project “Improving the fatigue life of high strength steel welded structures by post weld treatments and specific filler material”. The data comprises mostly of constant amplitude loading test under stress ratio \( R = 0.5 \). Some tests have however been done with higher stress ratios up to \( R = 0.7 \). Only limited data is currently available for tests performed under variable amplitude loading.

Fig. 1. Investigated joint types a) butt joint, b) non-load carrying transverse attachment and c) longitudinal attachment according to [22].
2.2. Evaluation of data

The data is evaluated based on the proposed IIW guideline concerning HFMI treated welded joints [19]. Yildirim and Marquis [21] evaluated experimental data from 18 studies on HFMI treated welded joints and showed that the S-N data best-fit line typically has a slope larger than the currently assumed $m = 3$. This means that the obtained improvement is not constant, but depends on the number of cycles, and that the treatment might even result in reduction of fatigue strength in the low cycle fatigue region [21]. Here the evaluation of data follows the suggested nominal stress S-N curves where the slope of $m = 3$ is updated to $m = 5$ and the characteristic fatigue class (FAT) is determined as the applied characteristic stress range corresponding to $2 \times 10^6$ cycles. Knee point is determined at $1 \times 10^7$ cycles where the slope of $m = 5$ becomes $m'$. In the case of HFMI treated welded joints, a slope of $m' = 22$ is assumed for constant amplitude loading and $m' = 9$ for the more general case of variable amplitude loading [19]. These values follow the current IIW recommendations as data in this region is very limited. In addition, it is assumed that the treatment is beneficial for details with FAT classes between FAT 50 and 90. A survival probability of 95% and a confidence level of 75% were used in the analysis.

According to IIW recommendations [22] the fatigue classes apply for plate thicknesses between 5 and 50 mm. However, for plates thicker than 25 mm, a correction factor is required [22]. It has also been observed in various studies that steel strength affects the improvement in fatigue strength in HFMI treated welded joints. Here, fatigue strength dependent improvement suggested by Yildirim and Marquis is used [20]. This proposal is an updated version of the current guideline that covers only needle and hammer peened details. The minimum increase in fatigue strength is four FAT classes for yield strengths $235 < f_y \leq 355$ MPa i.e. steels with yield strength of 355 MPa will have a fatigue strength increase of four fatigue classes. After this, roughly one FAT class increase is gained for every 200 MPa increase in yield strength. This is shown in Figure 2. The proposal is based on the following relationship by Yildirim and Marquis [20], where $k_y$ is the strength magnification adjustment considering yield strength.

$$\Delta S_H = \Delta S_A (k_0)^{1/(1-k_y)}$$

$$k_y = \alpha (f_y - f_{y,0}) / f_{y,0}$$

(1)

$\Delta S_H$ is the nominal stress range following HFMI treatment, $\Delta S_A$ is nominal stress range in the as-welded specimen, $k_0$ is the strength magnification factor for HFMI treatment for steel with a yield strength $f_y = f_{y,0}$ and $\alpha$ is the strength correction coefficient for yield strength after HFMI treatment. Values $\alpha = 0.27$ and $f_{y,0} = 355$ MPa are used as suggested in [20]. Equation (1) is used in the subsequent analysis to account for the different yield strengths.

![Fig. 2. Proposed increase in number of FAT classes as a function of yield strength according to [20].](image-url)
High mean stresses decrease the fatigue endurance of welded details and several proposals for taking this effect into account have been made [7,15,19]. Some of them are continuous functions where an effective stress range is a function of the stress ratio and some, like the proposal according to Marquis et al. [19] shown in Table 1, are stepwise functions relating certain stress ratio intervals to a predetermined reduction in FAT classes. In the case of $0.52 < R$, due to lack of data and the severity of the loading, the degree of improvement still needs to be confirmed. The general limitation of $\sigma_{\text{max}} \leq 0.8f_y$ should also be considered in all cases [7]. In terms of maximum allowable stress range this is $\Delta \sigma_{\text{max}} \leq 0.8f_y(1-R)$. Also an upper limit of $\Delta \sigma \leq 0.9f_y$ was suggested in the proposed guideline for HFMI treated welded joints to take into account the possibly damaging effect of very large compressive cycles [19].

Table 1. Minimum reduction in the number of FAT classes in fatigue strength improvement for HFMI treated welded joints as presented based on R-ratio according to [19].

<table>
<thead>
<tr>
<th>$R$-ratio</th>
<th>Minimum FAT class reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R \leq 0.15$</td>
<td>No reduction due to stress ratio</td>
</tr>
<tr>
<td>$0.15 &lt; R \leq 0.28$</td>
<td>One FAT class reduction</td>
</tr>
<tr>
<td>$0.28 &lt; R \leq 0.4$</td>
<td>Two FAT class reduction</td>
</tr>
<tr>
<td>$0.4 &lt; R \leq 0.52$</td>
<td>Three FAT class reduction</td>
</tr>
<tr>
<td>$0.52 &lt; R$</td>
<td>No data available. The degree of improvement must be confirmed by testing.</td>
</tr>
</tbody>
</table>

For variable amplitude loading, no separate penalty is given. Equivalent stress range is used instead of nominal stress range and the penalty depends on the stress ratio used. This is considered to be the stress ratio of the largest i.e. the most critical stress cycle [19]. The equivalent stress is determined as

$$\Delta \sigma_{\text{eq}} = \left( \frac{1}{D} \cdot \frac{1}{\sum N_i + \sum N_j} \cdot \frac{1}{\sum \Delta \sigma_i N_i + \sum \Delta \sigma_j N_j} \right)^\frac{1}{m}$$

where $\Delta \sigma_i$ is the stress range associated with knee point in S-N curve, $\Delta \sigma_j$ and $N_i$ are for cycles with stresses higher than the knee point stress and $\Delta \sigma_j$ and $N_j$ are for cycles with stresses lower than the knee point stress. The damage sum is conservatively assumed to be 0.5 due to the detrimental effect of high peak stresses. Equation (2) correlates constant and variable amplitude data and makes it possible to use the nominal S-N curves described earlier, for plotting, variable amplitude data.

3. Results

Assumed FAT classes for as-welded joints are FAT 90 for butt joints, FAT 80 for non-load carrying transverse attachments and FAT 71 for longitudinal attachments. For a stress ratio of $R = 0.5$ and a yield strength of 355 MPa this means that the fatigue classes are FAT 100 for butt joints, FAT 90 for non-load carrying transverse attachments and FAT 80 for longitudinal attachments. This is due to an increase of four FAT classes for HFMI treatment and a decrease of three FAT classes for the high stress ratio of $R = 0.5$. The total increase in fatigue life is then one FAT class. All the data has been fitted with equation (1) to adjust for the differences in yield strength. Figures 3-5 show the currently available data as well as the as-welded and HFMI characteristic curves for the three different joints with a stress ratio of $R = 0.5$ and constant amplitude loading. Constant amplitude data with stress ratios of $0.15 < R \leq 0.4$ and $R > 0.52$ is shown in Figures 6-8. For the case $R > 0.52$, a reduction of four fatigue classes was used in the analysis based on the available data as the proposed HFMI design guideline does not give a FAT class reduction for these stress ratios. The VAL data with stress ratios of $R = -1$ and 0.1 is then plotted in Figure 9. For VAL data, the HFMI characteristic curve corresponds to the CAL HFMI curve with stress ratios $R \leq 0.15$. Equivalent stresses as given by authors are used. Runouts are indicated with arrows in all the figures.
In general, only toe failures were included in the evaluation. The data from Maddox et al. [11] was however an exception. Here all the specimens failed from the root. This is also the only case where the plate thickness exceeded 25 mm. However, there was no need for thickness correction as the ratio \( L/t \) between characteristic length \( L \) and plate thickness \( t \) was larger than two. In Mori et al., both fillet and gusset welds were used. Only gusset weld data points were included in this study as these fractured from the weld toe whereas the fillet welded specimens fractured from the root.

Some of the studies also investigated the HFMI treatment of existing structures and the effect of large static cycles e.g. due to mounting of the component [10, 11, 13, 15, 16]. Therefore the evaluation includes data on pre-
fatigued specimens, specimens where the HFMI treatment was done under stress, e.g. maximum applied stress during constant amplitude cycling, and tests with quasi-static loading before the actual cycling.

Slopes for individual data sets and different joint types were evaluated following ASTM standard practise [23]. For longitudinal attachment data with CAL, the slope was estimated to be \( m = 4.4 \). For VAL, the slope was clearly larger with an estimated value of \( m = 9.3 \). The slopes for transverse attachment and butt joint data were estimated to be \( m = 6.8 \) and \( m = 9.6 \), respectively. The slopes for individual data sets varied between \( m = 3 \) and \( m = 13.2 \). However, it should be noted that for many data sets, the number of data points was very small and therefore the results may not be representative in all cases.

Fig. 5. High \( R \) ratio data on HFMI treated butt joints under CAL and a stress ratio of \( R = 0.5 \).

Fig. 6. High \( R \)-ratio data on HFMI treated longitudinal non-load carrying attachments under CAL and stress ratios of \( R > 0.52 \).
Fig. 7. High $R$ ratio data on HFMI treated longitudinal non-load carrying attachments under CAL and stress ratios of $0.15 < R \leq 0.4$.

Fig. 8. High $R$-ratio data on HFMI treated a) transverse non-load carrying attachments under CAL and a stress ratio of $R = 0.25$ and b) butt joints under CAL and a stress ratio of $R = 0.7$.

In the case of longitudinal attachments tested with constant amplitude loading, the stress ranges were always below the allowable maximum stress range $\Delta \sigma_{\max} \leq 0.8f_y(1-R)$. Figure 10 shows the comparison of data points with applied stresses above and below this limit stress range for transverse attachments and butt joints under constant amplitude loading and $R = 0.5$. Similar results were obtained also for other stress ratios. In the case of transverse attachments there were only six data points with applied stresses larger than $\Delta \sigma_{\max}$. With VAL longitudinal attachments the maximum stress range was considered to correspond to the largest individual cycle in the spectrum. Figure 11 shows the comparison of VAL data with respect to $\Delta \sigma_{\max}$. 
Fig. 9. VAL data on HFMI treated longitudinal non load carrying attachments with stress ratios of $R = 0.1$ and $R = -1$.

4. Discussion

The comparison of CAL and VAL data with the proposed HFMI design guidelines [19] in Figures 3-9 show that all the data points fall above the suggested HFMI curves for high stress ratios and variable amplitude loading. In some cases, the curves are even conservative with respect to the data. When the data was analysed with adapting the characteristic curves depending on the yield strength, rather than using yield strength correction, some data points were left below the characteristic curves but the results were very similar in both cases. For the case $R > 0.52$, a reduction of four fatigue classes was used in the analysis based on the available data. More data with these stress ranges is required to confirm an applicable penalty for these stress ratios. No negative effect on fatigue strength due to different testing conditions was observed in the current analysis.

Fig. 10. Comparison of data points with applied stress ranges above and below the allowed maximum stress range for (a) butt joints and (b) transverse attachments under CAL and a stress ratio of $R = 0.5$. 
For longitudinal attachments it should be noted that a single FAT class of 71 was assumed even though the actual joint classes varied between 63 and 80. The data points with actual FAT class of 80, which might give conservative results, were compared to the actual higher fatigue class. In all cases, the data points stayed above the characteristic curve. As stated earlier, in the study of Maddox et al. [11], all specimens failed from the root. This indicates that the fatigue strength of the HFMI treated weld toes in this study is probably better than what the current results show. In general, the assumed slope of \( m = 5 \) fitted the data. As there were only two data points beyond the knee point of \( N = 1 \times 10^7 \) cycles, the suitability of the assumed slopes \( m' = 22 \) for constant amplitude loading and \( m' = 9 \) for variable amplitude loading remains unclear.

There are many data points where the \( \nu_{\text{max}} \) limit is exceeded. This is the case especially with high stress ratios and steels of low yield strength. However, the data seems to fit the proposed characteristic curves well even in these cases. For transverse attachments and butt joints, the data points with maximum applied stress exceeding the limit tended to be below the data points with less severe applied stresses. However, in all cases even these data points fell above the characteristic curve. For variable amplitude loading, the largest stress cycle with respect to the limit was considered. Here no negative influence of these individual cycles is seen on the fatigue performance. It should be noted however, that the data with maximum applied stress below the limit is mostly with a stress ratio of 0.1 whereas the data with maximum applied stress above the limit is all with a stress ratio of \( R = -1 \). As a result, little or no decrease in fatigue strength is expected based on the current data. One probable reason for this is the behaviour of the induced compressive residual stresses. For CAL and VAL tests in various investigations, residual stresses induced due to HFMI treatment have often been observed to be relatively stable for a number of cycles until failure i.e. no significant relaxation even up to 100,000 cycles. This is especially the case for steels of grade S690QL. However, for lower grade steels, e.g. S355J2, slight relaxation in the HFMI induced residual stress has been observed [17,18,24].

5. Conclusions

Currently available high stress ratio and variable amplitude loading data on HFMI treated longitudinal attachments, non-load carrying transverse attachments and butt joints was evaluated with respect to proposed IIW guidelines for HFMI treated steel [19]. The additional benefit of HFMI treatment for high strength steels was taken into account using a previously developed relationship as given in the proposed guideline. In general, the current data fitted well with the proposed characteristic curves. In some cases, the curves could even be considered conservative with respect to the current data. More data is however needed, especially of stress ratios other than \( R = 0.5 \) and variable amplitude loading. For \( R > 0.52 \), a reduction of four fatigue classes was used in the analysis based on the current data. The estimated slopes for the different joint types varied between \( m = 4.4 \) and \( m = 9.6 \) confirming...
the assumption of using $m = 5$ rather than $m = 3$. Cases where the applied stresses exceeded the maximum limit of $\sigma_{\text{max}} \leq 0.8f_y$ were considered separately. For data points with maximum applied stresses larger than $\sigma_{\text{max}}$, the fatigue strength tended to be somewhat lower than for data with $\sigma_{\text{max}} \leq 0.8f_y$, as expected. However, the data fitted the proposed characteristic curves well even in these cases. This might be due to limited residual stress relaxation, especially in higher strength steels [17, 18, 24].

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