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OVERVIEW OF FATIGUE DATA FOR HIGH FREQUENCY TREATED WELDED JOINTS

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This paper provides an overview of published experimental data on the fatigue strength of welded joints improved by high frequency treatment methods. In total, 387 data points from four specimen types are available. Most tests were performed using constant amplitude R=0.1 axial tension fatigue, but some data for other R-ratios, variable amplitude testing and bending fatigue are also reported. An S-N slope of m=5 gives a very good description of both individual data sets and of the composite data. Design curve recommendations for the four joint types and for the structural stress-based design curve are given. High frequency treated specimens generally follow the same trend as experimental data for hammer peened specimens, but the degree of improvement is better. Data for large structures, at stress ratios other than R=0.1 and for variable amplitude loading are still needed in order to update the IIW guideline for post-weld improvement. There is a general trend for increasing fatigue strength improvement as a function of steel yield strength but this influence needs further study in order to develop guidelines. Quality assurance measures for high frequency treatment methods must also be defined.

Keywords: Fatigue, ultrasonic peening, ultrasonic impact treatment, pneumatic impact treatment, high frequency impact treatment, weld toe improvement, fatigue strength improvement, high strength steel

Overview of fatigue data for high frequency treated welded joints

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Keywords: Fatigue, ultrasonic peening, ultrasonic impact treatment, pneumatic impact treatment, high frequency impact treatment, weld toe improvement, fatigue strength improvement, high strength steel

Nomenclature

A	Statistical intercept
B	Statistical slope
$\hat{A}$	Estimate of the intercept
$\hat{B}$	Estimate of the slope
C_i	Fatigue capacity of specimen i
$C_{50\%}$	Computed mean fatigue capacity of test series
$C_{97.7\%}$	Characteristic fatigue capacity of the test series
f_y	Yield strength
f_u	Ultimate tensile strength
FAT	Characteristic fatigue class in MPa at $2x10^6$ cycles to failure
$FAT_{97.7\%}$	Characteristic fatigue class in MPa based on 97.7% survival probability at $2x10^6$ cycles to failure at 75% level of confidence
k	Number of test specimens in a data set
K_{hs}	Structural hot-spot stress coefficient
m	Slope of the S-N curve
N_f	Cycles to failure
N_i	The number of cycles to failure of specimen i
P_f	Probability of failure

S_i	Stress range of specimen i
S_{nA5}	Nominal stress amplitude at 5% failure probabilities
S_{nA95}	Nominal stress amplitude at 95% failure probabilities
T_σ	Scatter range in stress
t_p	Student distribution
X_i	$\log N_i$
Y_i	$\log S_i$
$\overline{X}$	Average of $\log N_i$
$\overline{Y}$	Average of $\log S_i$
σ	Standard deviation
$\widehat{\sigma_N}$	Estimate of the normal distribution variance

1 Introduction

In 2007 the International Institute of Welding (IIW) Commission XIII on Fatigue of Welded Components and Structures approved the best practice guideline concerning post-weld treatment methods for steel and aluminium structures [1]. 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 order to improve the reproducibility of the four methods, and to produce guidance for the degree of improvement that could be expected when using the methods in design, an inter-laboratory round-robin test programme was undertaken by IIW. Results of this round-robin programme were reported by Haagensen [2]. In this report, Haagensen reported S-N slopes ranging from $m = 5.3$ to $m = 12.2$ for the six laboratories who performed fatigue tests on hammer peened specimens [2]. The slope for all data collectively was $m = 4.5$, but the scatter was larger than that normally observed for inter-laboratory comparison studies of specimens in the as-welded condition. In spite of this, $m = 3$ was selected as the S-N curve slope in the post-weld treatment guideline.

The IIW guideline for post-weld improvement applies to plate thickness 6 to 50 mm for steel and 4 to 20 mm for aluminium. The improvement methods are only relevant to fatigue failures initiating from the weld toe. Thus, in some situations the analyst may also need to consider alternate failure modes. For welds improved by burr grinding or TIG re-melting or for hammer peening or needle peening of low strength steel ($f_y < 355$ MPa), the fatigue strength benefit corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life (for $m = 3$). 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 [3].

For aluminium and high strength steel ($f_y > 355$ MPa) welds 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, with a change in slope $m = 3$ to $m = 5$ at $N = 1x10^7$ cycles. 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 1.5. For ease of computation, this corresponds to a three (3) fatigue class increase.

For example, when a weld detail which, in the as-welded condition, would be classified as FAT 63 is hammer peened, the new FAT value is FAT 90. The highest detail class for which an improvement can be claimed is FAT 90, and the highest S-N curve that can be claimed following improvement is FAT 125. The slopes of the S-N curves follow the IIW Fatigue Design Recommendations [3].

An important practical limitation on the use of improvement techniques that rely on the presence of compressive residual stresses is that the fatigue lives are strongly dependent on the applied mean stress of the subsequent fatigue loading. In particular, the beneficial effect decreases as the maximum applied stress approaches tensile yield. Thus, in general, the techniques are not suitable for structures operating at applied stress ratios R > 0.5 or maximum applied stresses above around 80% yield. The guideline gives special limitations for high stress ratio situations. Even occasional application of high stresses in tension or compression, can also be detrimental in terms of relaxing the compressive residual stress but systematic guidelines are not yet available. Special limitations also exist for improved large-scale structures. It is recommended that for steel structures with plate thickness greater than 20 mm the benefit for hammer peening is assumed to be the same as for burr grinding and TIG dressing. Burr grinding and TIG re-melting can be applied only to conditions where the nominal stress range is less than twice the material yield strength, $\Delta\sigma < 2f_y$.

As previously mentioned, the existing IIW guideline allows the same degree of fatigue improvement for all steels with f_y > 355 MPa. Numerous researchers have observed that the degree of improvement increases with material strength, see, e.g., Maddox [4] and Bignonnet [5]. There has been a desire to develop an IIW guideline covering high strength steel (HSS) and in 2003 a new round robin exercise was initiated within IIW Commission XIII. Simultaneously with the increased interest in HSS, there has been an interest in new weld improvement techniques like low transformation temperature filler material [6] [7] and high frequency peening treatments.

The technology for high frequency ultrasonic impact treatment was developed at the Northern Scientific and Technological Foundation in Severodvinsk, Russia in association with Paton Welding Institute in Kiev, Ukraine [8]. The past decade has seen steady increase in the number of high frequency peening equipment manufacturers and service providers. Numerous technologies are employed, e.g., ultrasonic piezoelectric elements, ultrasonic magnetostrictive elements or compressed air. In all cases, however, the working principal is identical: cylindrical indenters are accelerated against a work piece with high frequency. The impacted material is plastically deformed causing both a change in the local geometry and residual stress state in the region of impact. In comparison to hammer peening, the operation is more user-friendly and the spacing between alternate impacts on the work piece is very small resulting in a finer surface finish. The indenters are high strength steel 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 the names: ultrasonic impact treatment (UIT) [9], ultrasonic peening (UP) [10], ultrasonic peening treatment (UPT) [11] [12], high frequency impact treatment (HiFiT) [13], pneumatic impact treatment (PIT) [14] and ultrasonic needle peening (UNP) [15] [16].

The choice of m = 3 for the S-N curve slope in the post-weld improvement guideline results in conservative design curves in the high cycle fatigue regime but less conservative or even non-conservative results for lower cycles to failure, i.e., $N = 1x10^4$. Individual experimental studies for high frequency peening treatments also typically observe that the slope of the best-fit line through the S-N data is typically greater than the m = 3.0 using in the IIW guideline. The goal of the current study has been to collect and assess the available fatigue test data for a variety of high frequency peening treatments. Special attention is given to the S-N slope because the assumed S-N slope has a major impact on the measured degree of fatigue strength improvement and will eventually influence the improvement factors proposed for HSS. Virtually all the testing has been done using constant amplitude testing at R = 0.1, but some constant amplitude tests and other R ratios and variable amplitude tests are available and have been reported. From a mechanical point-of-view, the high frequency peening techniques are considered to most closely resemble hammer peening. For this reason a comparison is made between fatigue data following high frequency peening and hammer peening.

2 Methods

2.1 Published Data

The authors were able to locate 15 publications containing fatigue data for welded steel joints improved by one of the high frequency peening methods mentioned in the introduction. Some of these studies contained multiple materials, improvement techniques of specimen types. Thus, a total of 35 data sets for four specimen types have been reviewed. Data sets contained between 5 and 21 test results. Many of the references considered in this study provide fatigue data only as points on a graph. When numerical values were not provided, they were extracted from the S-N plots using open source software. This was not considered to introduce significant errors in the results or conclusion.

The specimen types were longitudinal attachments, T-joints, cruciform joints, and butt joints. The T-joints were loaded in bending while the others axially loaded. Virtually all tests were constant amplitude R = 0.1, but some tests at alternate R ratios (-1 ≤ R ≤ 0.5) or with variable amplitude loading were also reported. Relatively few of the studies reported the fatigue failure locations so all failed test results are taken into account for analyses. Run-outs were excluded. The yield stress of steel grades varies from 235 to 1100 MPa, and specimen thickness varies from 5 to 30 mm. Data is summarized in Tables 1-4.

Table 1. Extracted experimental fatigue data for high frequency peened longitudinal welds (constant amplitude axial loading).

Ref.	Steel Type	f_y [MPa]	f_u [MPa]	R-ratio	Method	Plate Thickness [mm]	Best-fit m	k	% imp. at m=5 to IIW*	% imp. at m=free to IIW*
[17]	Domex 700	700[1]	750[3]	0.1	UP+UIT	8	5.5	16	69	74
[18]	S690QL	786[2]	870[2]	0.1	UIT	16	4.5	16	81	78
[18]	S690QL	786[2]	870[2]	0.1	HiFIT	16	4	15	72	65
[19]	16Mn	390[1]	590[1]	0.1	UP/UPT	8	14	6	89	106
[20]	Domex 350	398[2]	503[2]	0.1	UP/UPT	12	5.3	5	93	98
[20]	Weldox 700	780[2]	850[2]	0.1	UP/UPT	12	3.9	7	79	69
[20]	Weldox 900	900[2]	1010[2]	0.1	TIG+UP	12	4.48	10	118	110
[21]	SS800	700[2]	830[2]	0.1	UP/UPT	8	9.4	8	154	173
[21]	16Mn	390[2]	591[2]	0.1	UP/UPT	8	15.8	6	92	111
[21]	Q235B	267[2]	435.5[2]	0.1	UP/UPT	8	11.7	7	101	99
[22]	S355	355[1]	600[1]	0.1	UIT	8	3.71	10	170	153
[23]	S355J2	390[1]	545[1]	0.5	UIT	30	2.97	7	~0	10
[24]	S960	969[2]	1104[2]	-1	UIT	6	4.81	11	308	307
[24]	Domex 700	700[1]	750[3]	-1	UIT	8	4.24	5	169	163

Table 1-4 shows the specimen type, thickness, high frequency improvement method, and R ratio for each data set. The number of test specimens, k, and best-fit S-N slope based on linear regression is also reported. The FAT class of each specimen type is taken from the IIW Recommendation [3] and the stress range corresponding to 50% survival probability for as-welded specimens at N = $2x10^6$ are evaluated as described in the BS 5400 [25]. These are presented in Table 5. Some of material properties in Tables 1-4, such as yield strength, f_Y, and ultimate tensile strength, f_U, are fully defined in the references. In such cases values are taken from published datasheets [26] [27] and the superscript [3] is used in Tables 1-4. The last two columns in Tables 1-4 show the calculated fatigue strength improvement with respect to the 50% failure probability stress range for the fatigue strength improvement (%) is computed assuming both a fixed S-N slope m=5 and based on the best-fit regression line for the respective data set.

Table 2. Extracted experimental fatigue data for high frequency peened T-joint welds (constant amplitude bending loading).

Ref.	Steel Type	f_y [MPa]	f_u [MPa]	R-ratio	Method	Plate Thickness [mm]	Best-fit m	k	% imp. at m=5 to IIW*	% imp. at m=free to IIW*
[28]	S420	420^1	490^3	0.1	UIT	20	11.7	8	166	198
[29]	S700	700^3	750^3	0.1	UIT	6	6.9	10	194	256
[30]	S700	700^1	800^1	0.1	UIT	6	4	21	258	238
[31]	S420	420^1	490^3	0.1	UIT	20	7.5	7	161	181

Table 3. Extracted experimental fatigue data for high frequency peened cruciform welds (constant amplitude axial loading).

Ref.	Steel Type	f_y [MPa]	f_u [MPa]	R-ratio	Method	Plate Thickness [mm]	Best-fit m	k	% imp. at m=5 to IIW*	% imp. at m=free to IIW*
[32]	S355J2	398.3^2	537.2^2	0.1	UIT	12	6.6	7	106	141
[32]	S355J2	398.3^2	537.2^2	0.1	UIT	12	11.1	4	47	205
[32]	S460ML	503.5^2	553.4^2	0.1	UIT	12	5.27	5	105	113
[32]	S460ML	503.5^2	553.4^2	0.1	UIT	12	6.09	5	128	153
[32]	S690QL	812.8^2	870.8^2	0.5	UIT	12	7.22	6	33	70
[33]	S260	260^1	465^1	0.0	UIT	20	9.55	9	61	72
[34]	S355J2	477^2	556^2	0.1	PIT	12	11.6	8	132	170
[34]	S690QL	781^2	827^2	0.1	PIT	12	6.5	7	164	177

Table 4. Extracted experimental fatigue data for high frequency peened butt joint welds (constant amplitude axial loading).

Ref.	Steel Type	f_y [MPa]	f_u [MPa]	R-ratio	Method	Plate Thicknes s [mm]	Best-fit m	k	% imp. at m=5 to IIW*	% imp. at m=free to IIW*
[18]	S355J2	422[2]	524[2]	0.1	UIT	16	7	14	76	79
[18]	S355J2	422[2]	524[2]	0.1	HiFIT	16	4.2	18	75	68
[18]	S690QL	786[2]	870[2]	0.1	UIT	16	4.5	18	122	120
[18]	S690QL	786[2]	870[2]	0.1	HiFIT	16	3.36	12	120	99
[18]	S355J2	422[2]	524[2]	0.5	UIT	16	8.9	15	31	35
[18]	S355J2	422[2]	524[2]	0.5	HiFIT	16	9	11	15	27
[18]	S690QL	786[2]	870[2]	0.5	UIT	16	5	10	48	49
[18]	S690QL	786[2]	870[2]	0.5	HiFIT	16	5	12	44	44
[35]	E690	763[2]	836[2]	0.1	UP	9.5	3.74	8	89	79

[1] Nominal value

[2] Measured value

[3] Not reported at the reference, but estimated using datasheets [26] [27].

Table 5. FAT values for different types of test specimens

Specimen Type	FAT [MPa] values according to IIW [3]	Calculated ΔS [MPa] for 50% survival probability at $N_f = 2x10^6$	Assumed 2σ in Log(N)
Longitudinal attachment	71	102	0.594
T-joint	80	118	0.561
Cruciform joint	80	118	0.561
Butt joint	90	125	0.617

2.2 Statistical Methods

Fatigue test data includes k data points representing logS_i and logN_i, where S_i is the stress range, and N_i is the endurance in cycles. Special attention should be given when representing logS_i on the vertical axis and logN_i on the horizontal axis in an S-N plot. The statistically appropriate approach in linear regression analysis is to assume that the independent variable is plotted on the horizontal axis and the dependent variable on the vertical axis, i.e., for historic reasons fatigue data is plotted contrary to current scientific practice.

Statistical methods are used in this section to assess the best-fit S-N slopes, the confidence interval of the S-N slope and the observed degree of improvement in fatigue strength at N = 2x10^6 for a specified S-N slope.

As is normally assumed, the S-N relationship is represented by a linear model $\log N_i = A + B \log S_i$ and fitted to each set of results in Tables 1-4 by regression analysis. Confidence intervals associated with a defined confidence level for both A (intercept) and B (slope) were evaluated based on the Student distribution, t_p, as described at ASTM standard practice [36]. Values of t_p were taken directly probability tables. A cumulative probability of 97.7% is chosen in this exercise. Parameter A is given by Eq. (1);

$$\hat{A} \pm t_p \widehat{\sigma_N} \left[\frac{1}{k} + \frac{\overline{X}^2}{\sum_{i=1}^{k} (X_i - \overline{X})^2} \right]^{1/2} \quad (1)$$

and for B is given by Eq. (2);

$$\hat{B} \pm t_p \widehat{\sigma_N} \left[\sum_{i=1}^{k} \left(X_i - \overline{X} \right)^2 \right]^{-1/2} \quad (2)$$

where the symbol "caret" ($\widehat{\ }$) denotes estimate, the symbol "over bar" ($\overline{\ }$) denotes average and k is the number of specimens. The expression for estimating the variance of the normal distribution ($\widehat{\sigma_N}$) for log N can be calculated by the Eq. (3).

$$\widehat{\sigma_N}^2 = \frac{\sum_{i=1}^{k} \left(Y_i - \hat{Y}_i \right)^2}{k-2} \quad (3)$$

With respect to the observed degree of improvement in fatigue strength at $N = 2 \times 10^6$ for a specified S-N slope, fatigue data is evaluated according to following Equations from 4 to 8.

$$\Delta S_i^{\ m} . N_i = C_i = FAT^m \cdot 2 \times 10^6 \quad (4)$$

$$\log C_{50\%} = \frac{\sum \log C_i}{k} \quad (5)$$

$$\sigma = \sqrt{\frac{\sum (\log C_i - \log C_{50\%})^2}{k-1}} \quad (6)$$

$$\log C_{97.7\%} = \log C_{50\%} - 2 \cdot \sigma \quad (7)$$

$$FAT_{97.7\%} = \sqrt[m]{\frac{C_{97.7\%}}{2 \times 10^6}} \quad (8)$$

The scatter ranges, T_σ, are also indicated at Figures 9 to 13. In the Equation 9, the nominal stress amplitudes S_{nA5} and S_{nA95} refer to failure probabilities $P_f = 5\%$ and $P_f = 95\%$, respectively.

$$T_\sigma = \frac{S_{nA5}}{S_{nA95}} \quad (9)$$

3 Results

3.1 Assessment of S-N Curve Slopes

Test results from Tables 1-4 are statistically evaluated according to the methods in the previous section. Figures 1 to 4 present the results for each data set for the four most commonly used specimen types, longitudinal attachment, T-joint, cruciform, and butt joint specimens, respectively. Most tests were constant amplitude R = 0.1, but some tests at alternate R ratios (-1 or 0.5) are also included. In each figure, the confidence interval of the S-N slope for each study is indicated by a scatter band. The best estimate of the S-N slope is indicated by a point near the centre of the scatter band. The horizontal axes in these figures represent the number of test specimens, k, in a data set.

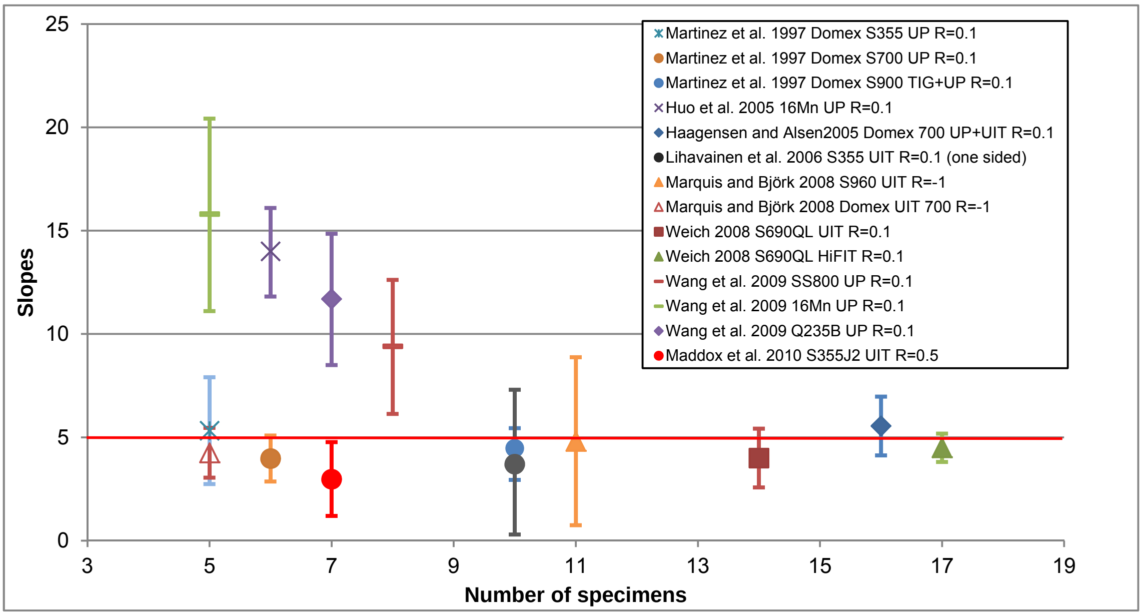

Figure 1. Estimates of slopes for longitudinal attachments.

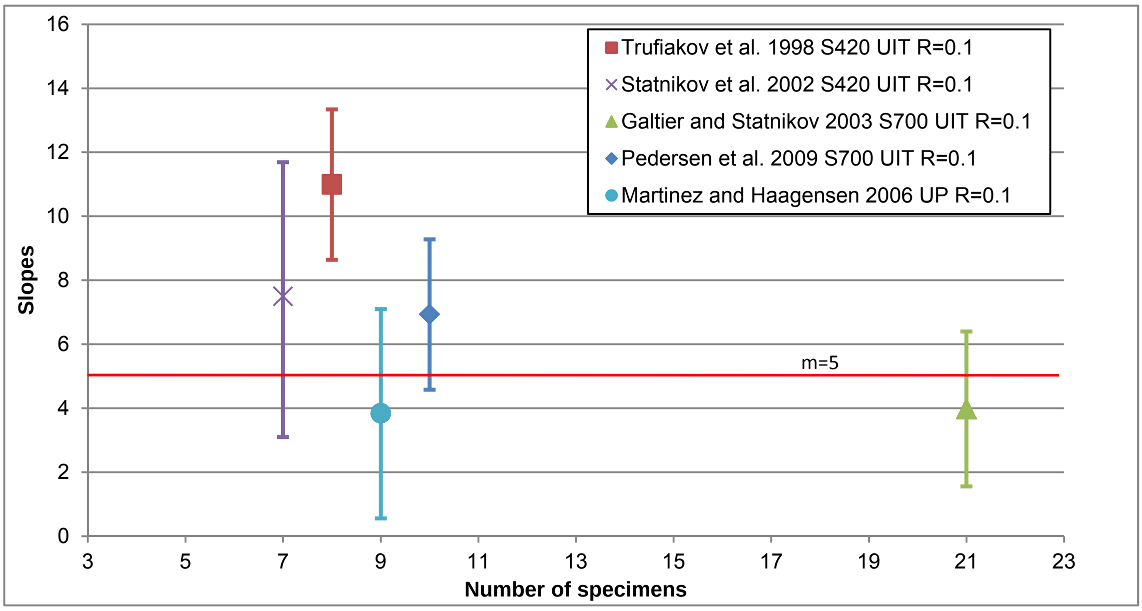

Figure 2. Estimates of slopes for T-joints.

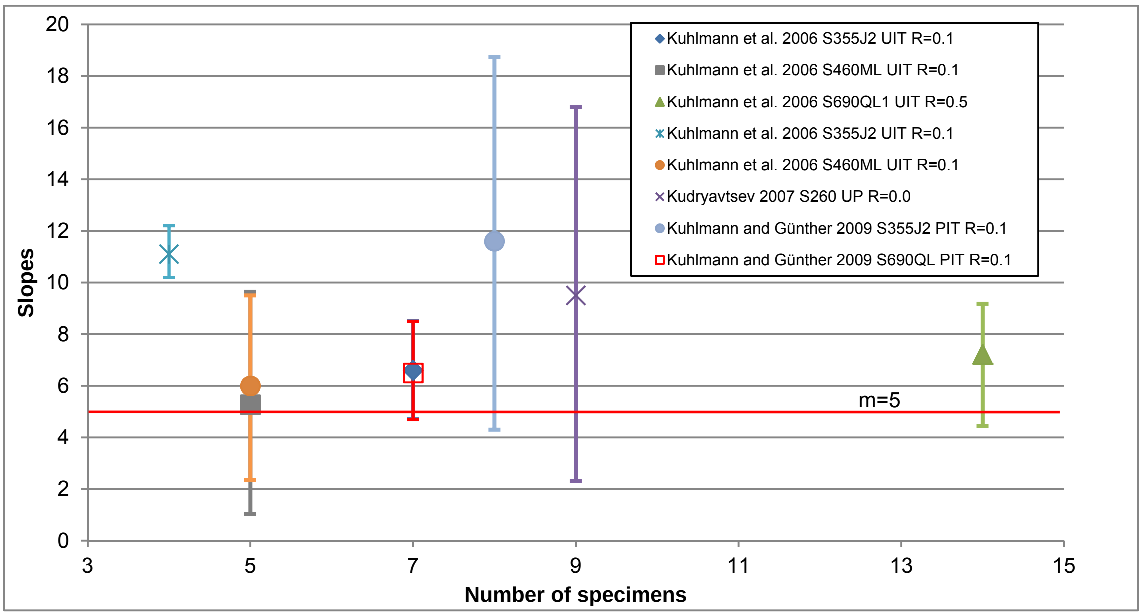

Figure 3. Estimates of slopes for cruciform joints.

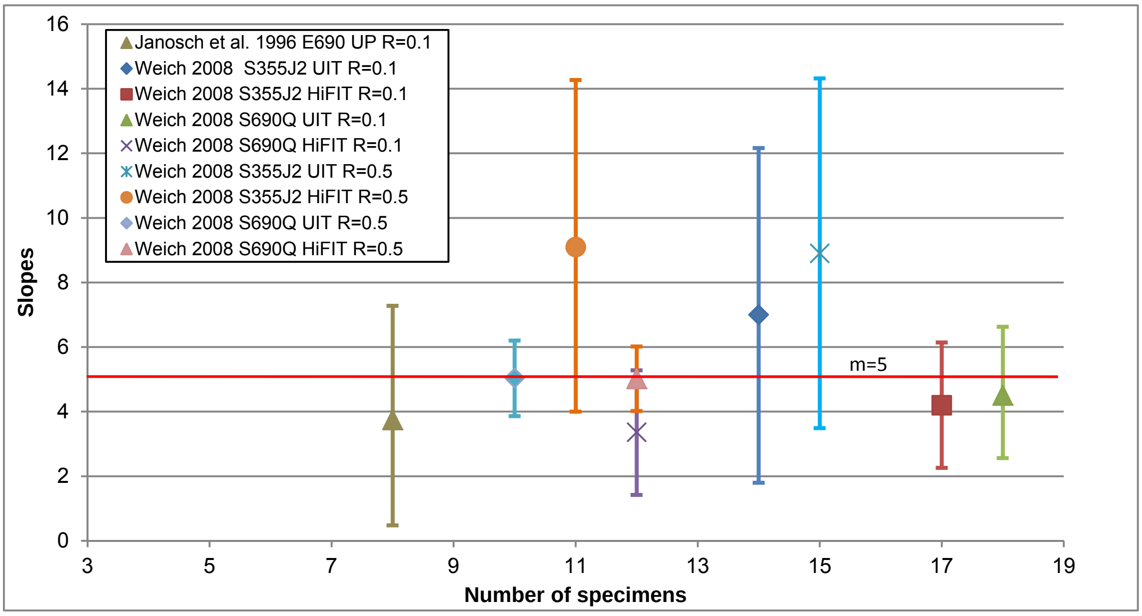

Figure 4. Estimates of slopes for butt joints.

3.2 Available Experimental Data

As can be seen from Figs. 1-4, the S-N slope m=5 passes through or is below the scatter band for virtually all data sets for all four specimen types. Figures 5-8 present all data for a particular specimen type on a single plot. In each case an S-N slope m=5 is assumed and the regression lines representing the 50% and 97.7% survival probability lines are shown. In these plots only the fatigue data obtained using constant amplitude R = 0.1 testing is considered. No adjustment has been made for the steel grade or plate thickness. It has been assumed that failure has occurred at the weld toe even though this is not fully clear in all studies. Fatigue strength values for 50% survival probability for each specimen type in the as-welded condition are taken from Table 5. Fatigue strength improvements at N = 2×10^6 are calculated and indicated in the plots.

Figure 9 shows available fatigue results for longitudinal non-load carrying attachments for R = 0.5 and R = -1 constant amplitude testing and variable amplitude loading. The figure also shows the regression lines from Fig. 5, i.e., the 50% and 97.7% survival probability lines for longitudinal attachments based on constant amplitude R = 0.1 and assuming m = 5.

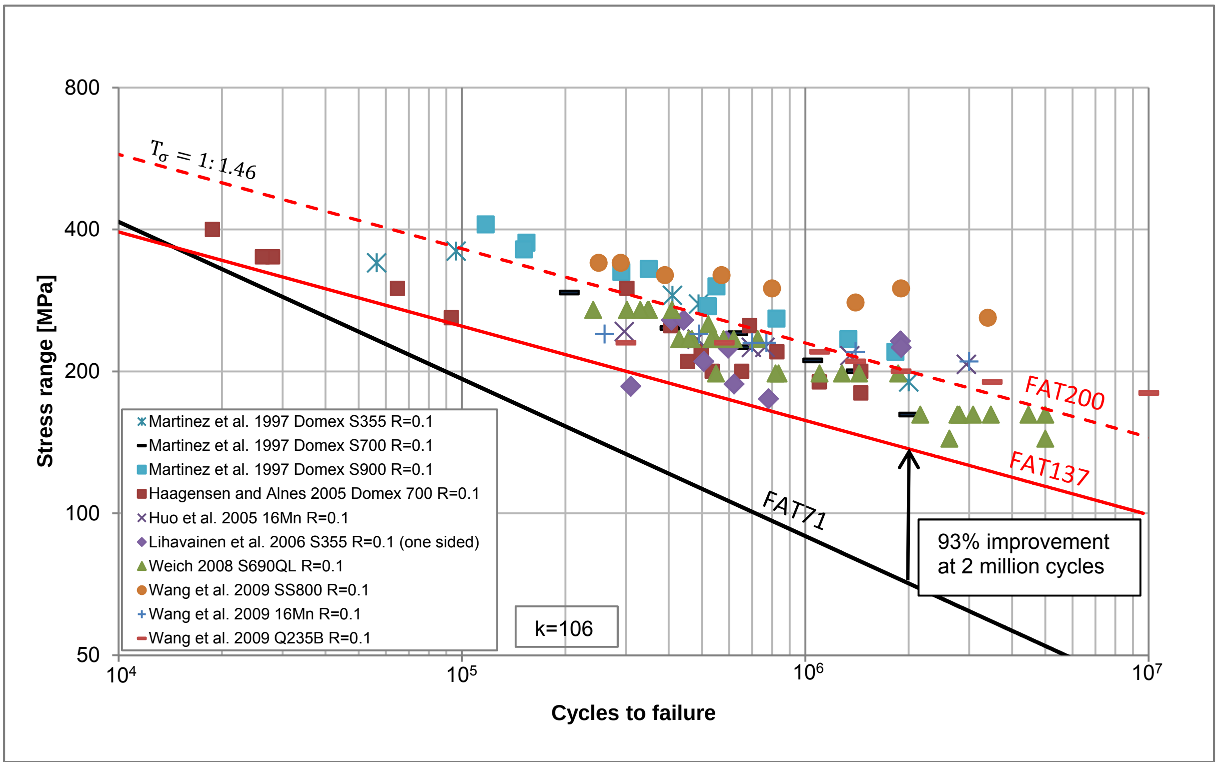

Figure 5. Extracted high frequency peened fatigue data from references in Table 1 for non-load carrying longitudinal attachments at R=0.1.

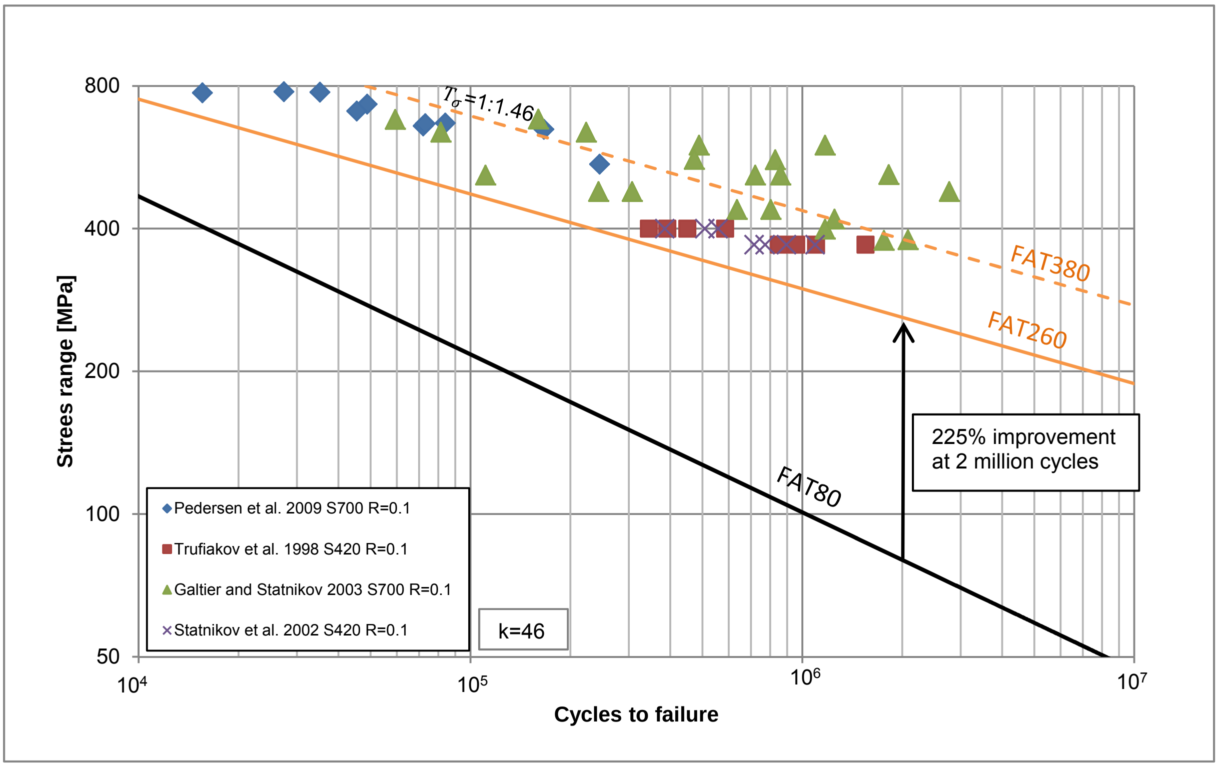

Figure 6. Extracted high frequency peened fatigue data from references in Table 2 for T-joints in bending at R=0.1.

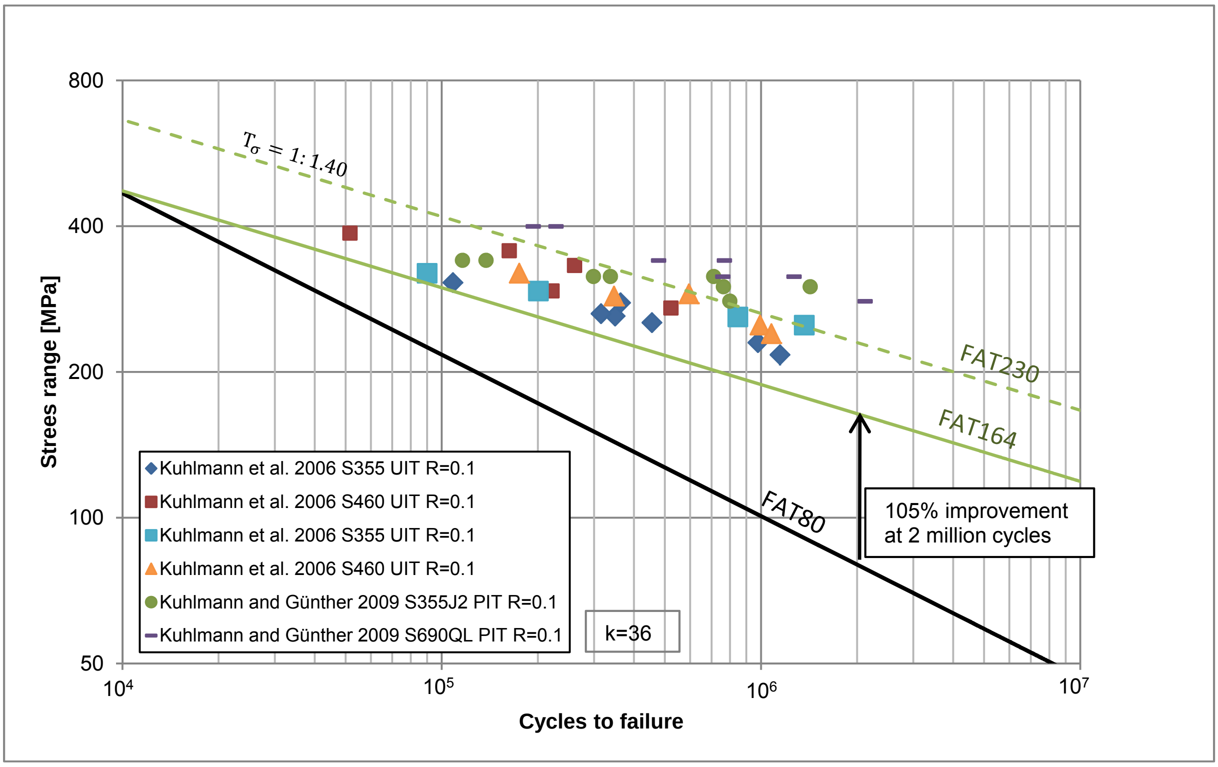

Figure 7. Extracted high frequency peened fatigue data from references in Table 3 for cruciform joints at R=0.1.

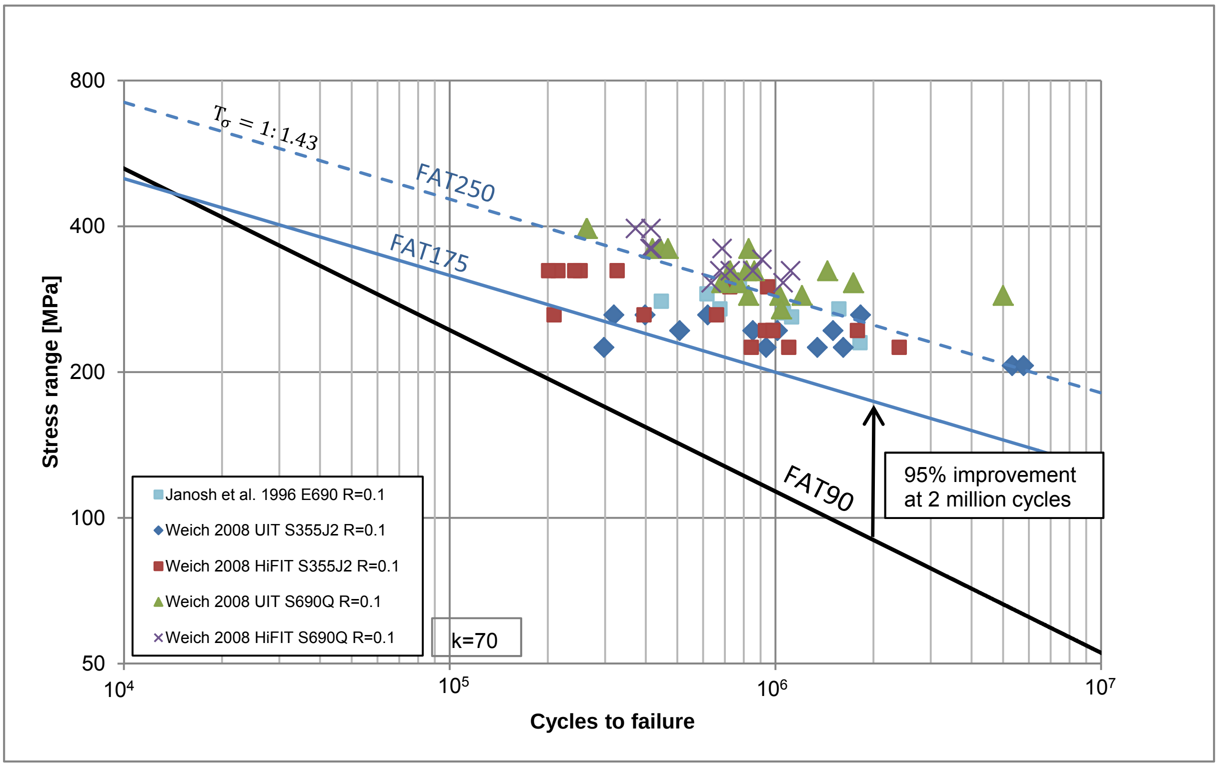

Figure 8. Extracted high frequency peened fatigue data from references in Table 4 for butt joints at R=0.1.

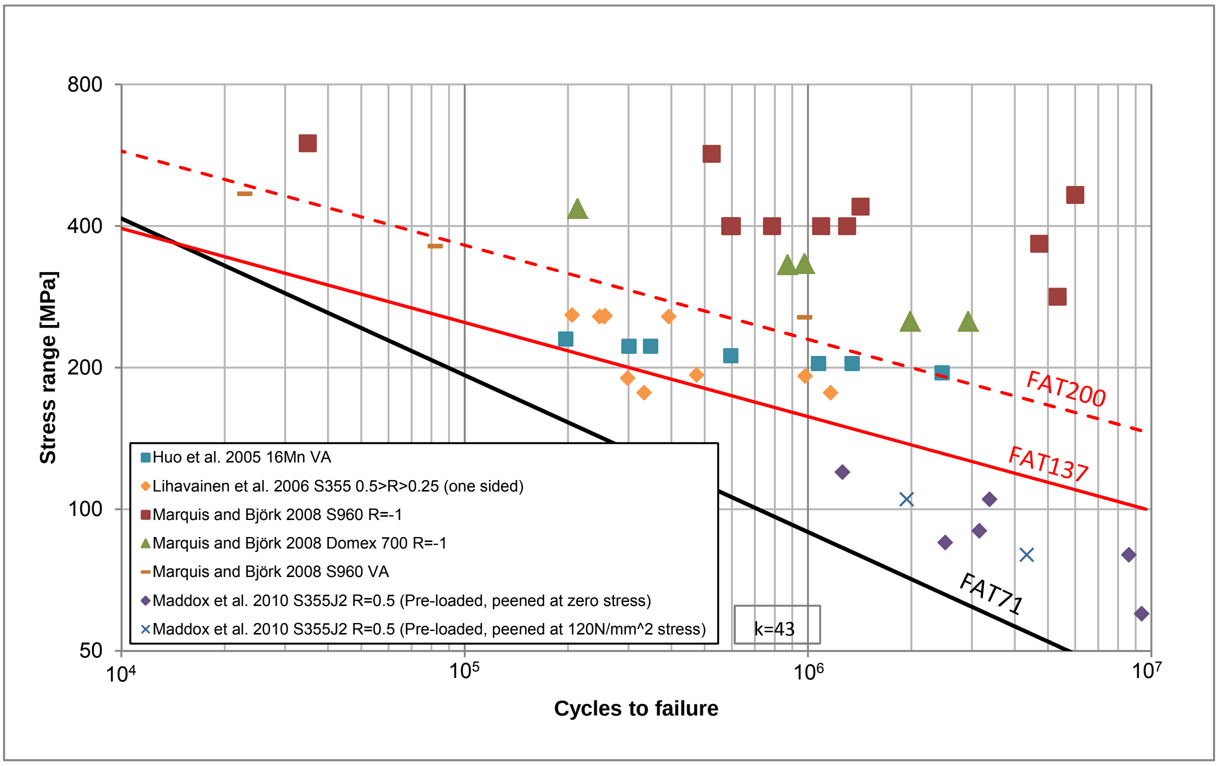

Figure 9. Extracted high frequency peened fatigue data from references in Table 1 for non-load carrying longitudinal attachments at constant amplitude R=-1 and R=0.5. Variable amplitude loading from [19] and [24]. Regression lines FAT 200 and FAT 137 are from Figure 5**.**

4 Discussion

4.1 S-N Curve Slopes and Effect of Loading

Figures 1-4 show that the horizontal line corresponding to an S-N slope m=5 passes through, or is slightly below, the scatter band computed using Eq. (2) for virtually all data sets. This observation is consistent for all four specimen types. For some data sets the best-fit slope (based on $\widehat{B}$) is clearly greater than m=5. In some cases this may be due to a too narrow variation in the stress ranges used during testing. For example, in the extreme situation that all tests are performed using the same stress range, a slope $m = \infty$ would necessarily be computed. The suitability of the slope m = 5 is further confirmed from Figs. 5-8 which present all constant amplitude R=0.1 data for a particular specimen type on a single plot. Scatter ranges, T_σ, are also shown for reach graph

In Figs. 5-8 only fatigue test results obtained using constant amplitude R = 0.1 testing are presented and used to compute the 50% and 97.7% survival probability regression lines. Figure 9 shows available fatigue results for longitudinal non-load carrying fillet weld attachments for R = 0.5 and R = -1 constant amplitude testing and variable amplitude loading. For reference, the 50% and 97.7% survival probability regression lines from Fig. 5 are also shown in this figure. Most of the data points in the Fig. 9 are above the 97.7% survival probability regression line (FAT 137). However, data points from Maddox et al. [23] fall below the line. One reason may be that a high stress ratio, R=0.5, was used during testing. Additionally, some specimens in this study were pre-loaded before peening while others were peened under tensile load. All other specimens presented in this overview were (apparently) high frequency treated without any loading.

For the longitudinal non-load carrying fillet weld attachments used, the as-welded specimens have high tensile welding residual stresses. This means that the fatigue life is dependent only on stress range with no influence of mean stress. Following high frequency treatment, the tensile residual stresses are removed and mean stress starts to have significant influence. The variable amplitude load spectrum used by Marquis and Björk [24] had R=-1 for each cycle. The same is study also reports R=-1 constant amplitude fatigue data. The variable amplitude data falls approximately along the P_f = 50% line while constant amplitude results are significantly above this line. This is probably the result that only a fraction of the compressive portion of the fatigue cycle is damaging. Additionally, Marquis [37] has observed significantly different failure modes for these tests. Treated specimens tested using R=-1 variable amplitude loading consistently failed in the weld toe region while specimens tested at R=-1 constant amplitude loading failed at a variety of other locations. Data for variable loading and for $R \neq 0.1$ is limited and more studies are needed before design guidelines can be extracted.

4.2 Comparison with Hammer Peening

In technical literature high frequency peening methods are frequently qualitatively compared to hammer peening, e.g. see [23]. Figures 10-12 show a quantitative comparison of high frequency peening and hammer peening for longitudinal non-load carrying attachments (Fig. 10) [38] [39], for T-joints (Fig. 11) [2] [40] and for cruciform joints (Fig. 12) [41] [42]. In each of these figures the regression lines from high frequency treated welds in Figs. 5, 6 or 7 are presented, i.e., the 50% and 97.7% survival probability lines for the similar weld specimen type based on constant amplitude R = 0.1 and assuming m=5.

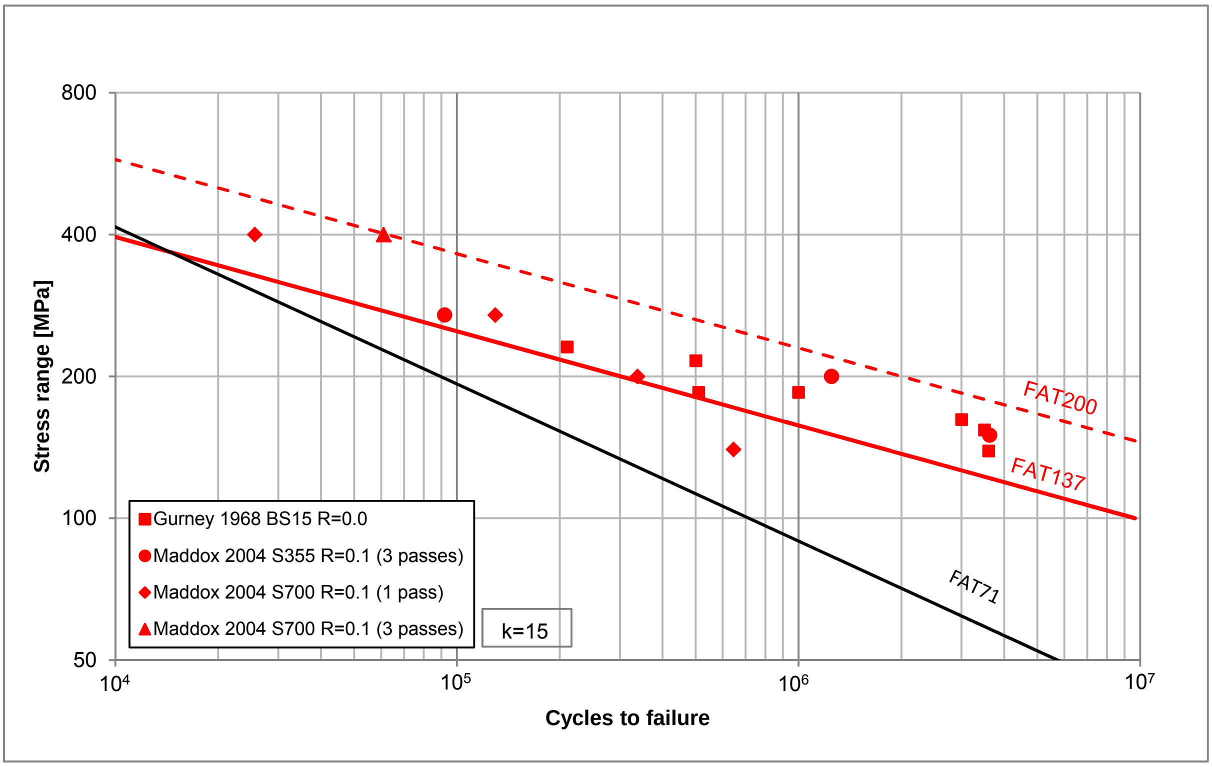

Figure 10. Some of hammer peened data for non-load carrying longitudinal attachments [38] [39] in comparison with FAT 137 calculated in this study for high frequency peening. Regression lines FAT 200 and FAT 137 are from Figure 5.

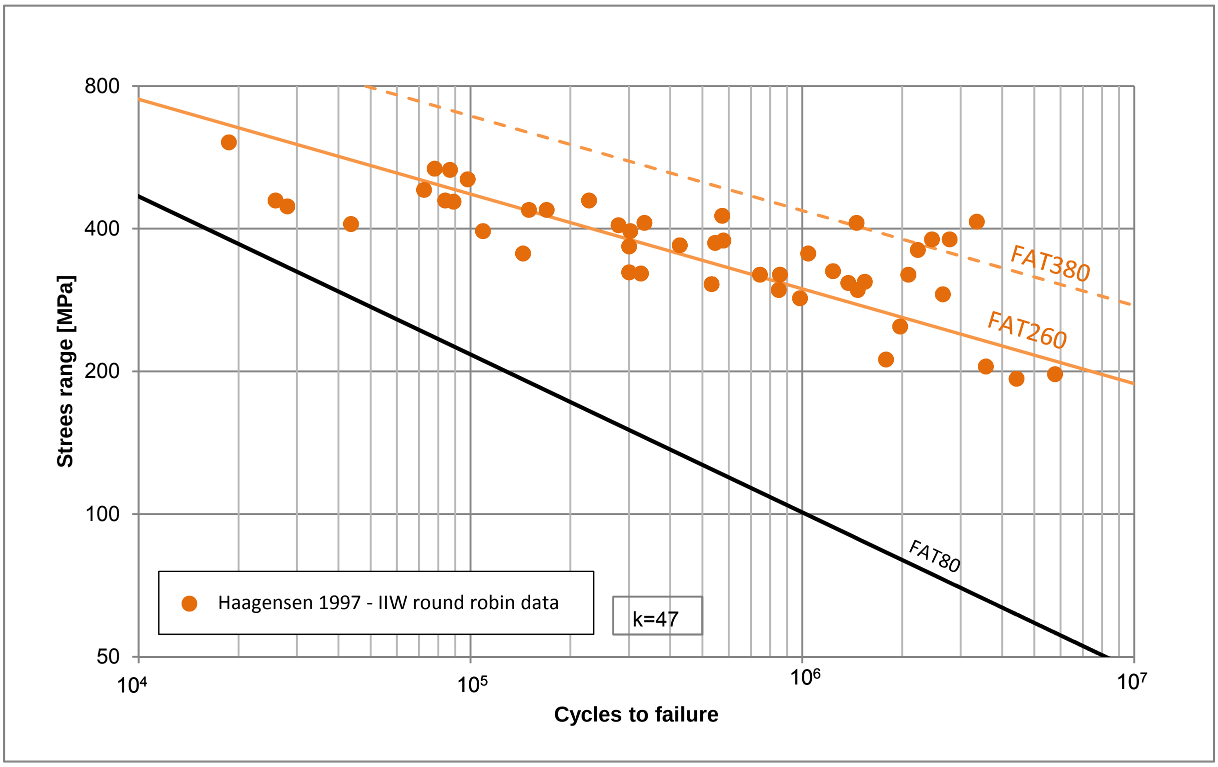

Figure 11. Some of hammer peened data for T-joints [2] [40] in comparison to FAT 260 calculated in this study for high frequency peened specimens. Regression lines FAT 380 and FAT 260 are from Figure 6 (bending loading).

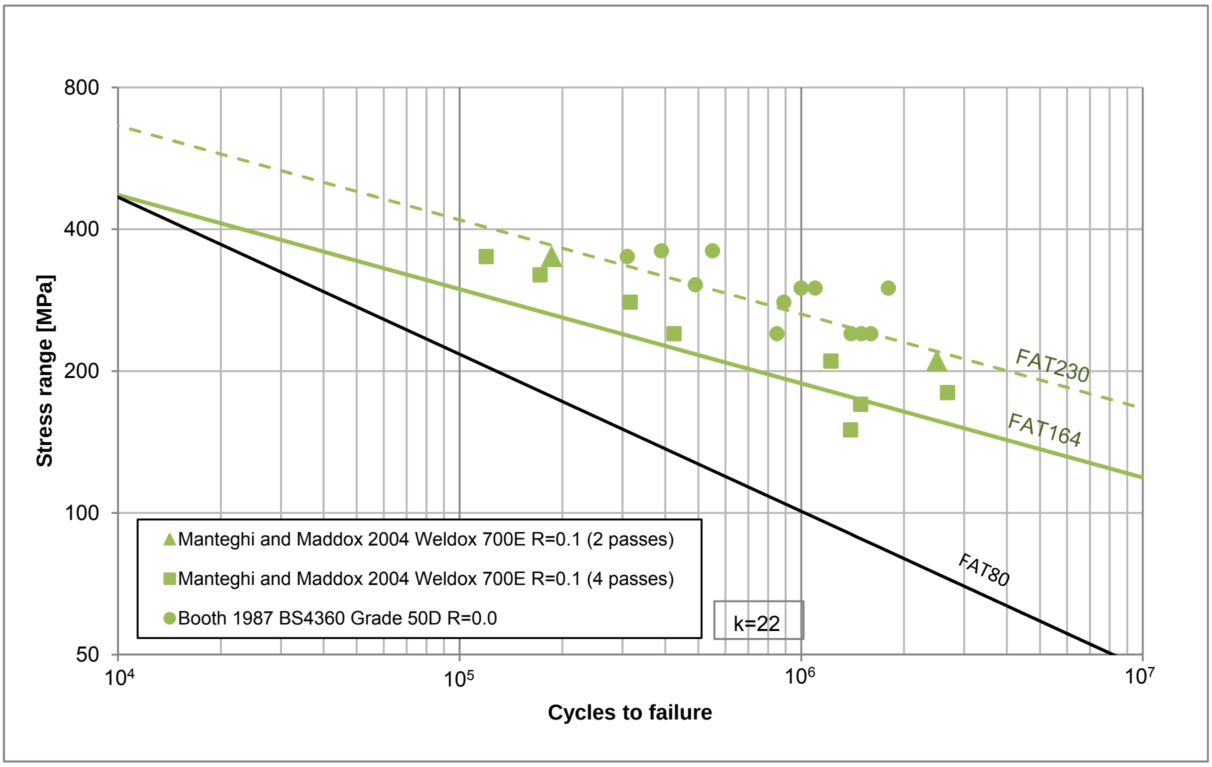

Figure 12. Some of hammer peened data for cruciform joints [41] [42] in comparison with FAT 164 calculated in this study. Regression lines FAT 230 and FAT 164 are from Figure 7.

It can be seen from Figs 10-12 that the S-N slope m=5 also tends to follow the trend of the hammer peened data. In each of these figures the dashed line represents the P_f = 50% line for the high frequency treated specimens while the solid line represents P_f = 2.3%. It can be observed that for all three specimen types, the hammer peened data tends to be lower than the high frequency peened data. For longitudinal non-load carrying welds (Fig. 10), only one data point involving one-pass hammer peening fell below the P_f = 2.3% line but all other data points fell between P_f = 2.3% and P_f = 50%. For cruciform joints (Fig. 12) only two data point involving one-pass hammer peening fell below the P_f = 5% line but many of the points from an early study by Booth [42] were above the P_f = 50% line. For the T-joints tested in bending (Fig. 11) data is approximately evenly distributed around the P_f = 2.3% for high frequency treated welds.

4.3 Structural Stress for High Frequency Improved Welds

The IIW best practice guideline concerning post-weld treatment methods for steel and aluminium structures contains a section on recommendations related to the structural hot spot stress [1]. For non-load carrying fillet welds such as the longitudinal attachments, T-joints and cruciform joints reported here, the appropriate hot spot structural stress design curve is FAT 125 for mild steel (f_y < 355 MPa) and FAT 140 for higher strength steel (f_y > 355 MPa). For load-carrying butt welds the appropriate hot spot structural stress design curve is FAT 112 for mild steel (f_y < 355 MPa) and FAT 125 for higher strength steel (fy > 355 MPa). Structural hot spot stress concentration factors, K_{hs}, were computed according to IIW [3] for a typical joint of each type. The nominal stress range for a specimen was multiplied by the suitable K_{hs} value for that specimen type: K_{hs} = 1.4 for longitudinal attachments, K_{hs} = 1.2 for cruciform joints and K_{hs} = 1.0 for butt joints. Results are compiled in Fig. 13. The computed FAT curves for P_f = 50% and P_f = 2.3% are FAT 267 and FAT 189, respectively. These are rounded down to FAT 250 and FAT 180 in order to be consistent with the IIW system. These are shown in Fig. 13.

Figure 13 also shows the P_f = 2.3% FAT lines from Figs. 5, 7 and 8 which have then been multiplied by the suitable K_{hs} value for that specimen type. The resulting lines are FAT 191 for longitudinal attachments and FAT 201 for cruciform joints. These are in good agreement with a proposed hot spot structural stress design curve of FAT 180 (m=5) for non-load carrying high frequency treated welds. For load-carrying welds the proposed design curve is FAT 160 (m=5). Thus far data has not been separated based on f_y so this proposal may be slightly lowered for mild steel and increased for higher strength steel.

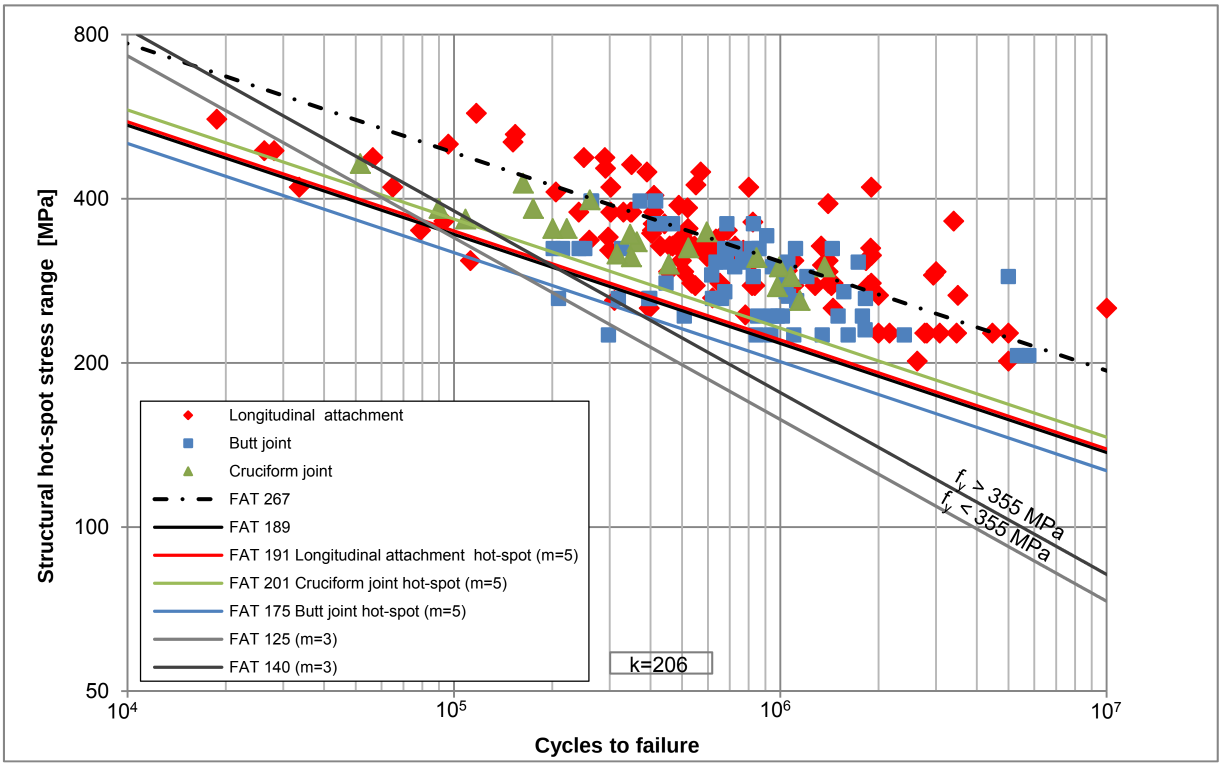

Figure 13. Structural hot-spot stresses for axial loaded specimens in comparison with FAT values calculated in this study. The two line with m=3 are the current design lines for non-load carrying welds, FAT 125 for and FAT 140.

4.4 Degree of Improvement

The existing IIW guideline [1] allows up to 25% increased design stress for mild steel (f_y < 355 MPa) and up to 40% increased design stress for steel f_y > 355 MPa. Numerous researchers have observed that the degree of improvement increases with material strength even beyond this range, see, e.g., Maddox [4] and Bignonnet [5]. The constant amplitude fatigue test data at R=0.1 with m=5 for longitudinal attachments and cruciform welds as a function of f_y is shown in Fig.14. The data generally shows an increasing trend with material strength but the large amount of variation indicates that more attention to the topic is needed. Figure 14 also shows the existing IIW rules with respect to steel strength. An additional line representing an 8% increase in fatigue strength with yield strength above 355 MPa is also shown. This line is conservative with respect to the available data and represents a 40% increase in allowable design stress for f_y = 355 MPa and 91% increase in design stress for f_y = 1000 MPa.

The degree of improvement for the four weld types and the recommended FAT values for the high frequency treatment methods are summarized in Table 3. Based on experiments the T-joints had significantly greater fatigue strength than did the cruciform welds. However, experiments for T-joints were performed using bending loading while the recommended FAT values assume axial loading as for cruciform joints. Thus the recommended FAT class is the same for both joint types. The recommendations for T-joints, cruciform welds and butt welds are higher than the IIW

Recommendation for plate edges [3]. To attain such high values in practice, extra attention would need to be placed of the quality of the plate surface and edge condition both during fabrication and service.

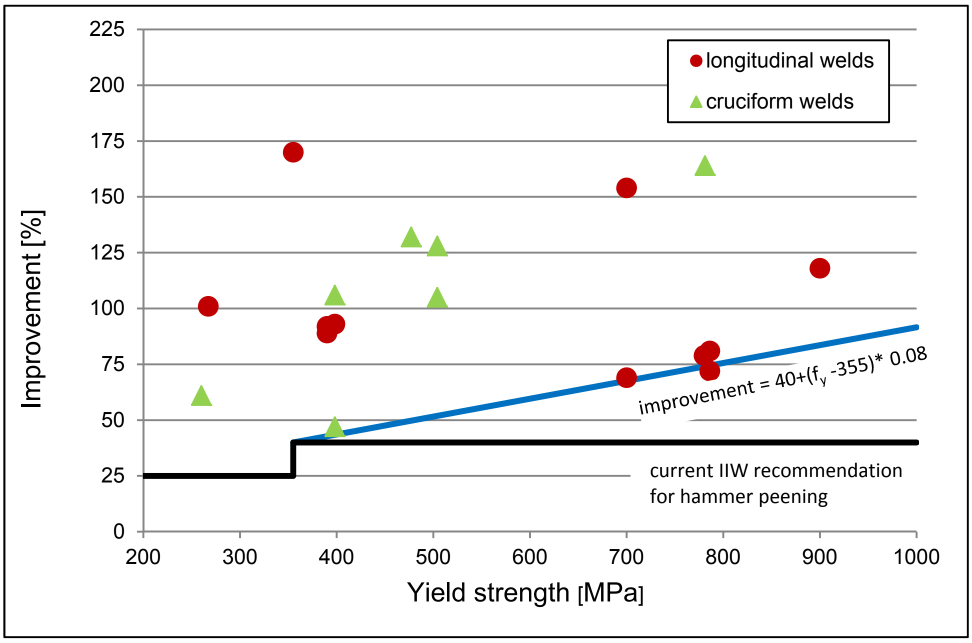

Figure 14. Fatigue strength improvement at N = $2x10^6$ for high frequency treated longitudinal welded attachments and cruciform joints as a function of f_y. Values are from Tables 1 and 3. Existing IIW rules with respect to steel strength for hammer peened specimens and an additional line representing an 8% increase in fatigue strength with yield strength above 355 MPa are also shown.

The IIW best practice guideline contains a correction values for hammer peened welds based on stress ratio [1]. The correction factors have been discretized as an integral number of stress class increases for a joint, i.e. from zero to up to three fatigue classes. The original function from which these were derived was proposed by Weich [18], see Eq. (10). This relationship is expected to also be valid for high frequency treated specimens, but some provision for R < 0 may also be considered.

$$\begin{aligned} k_R &= 1.075 - 0.75 * R \qquad & 0.1 \leq R \leq 0.5 \\ k_R &= 1.0 \qquad & R < 0.1 \end{aligned} \tag{10}$$

In this study the high frequency improvement methods have been reported using the names: ultrasonic impact treatment, ultrasonic peening, ultrasonic peening treatment, high frequency impact treatment, pneumatic impact treatment and ultrasonic needle peening. No distinction has been made between these various technologies. All technologies have the common features in that hardened steel indenters are excited against the weld toe using some power source and the impact frequency is significantly greater than what is found in conventional hammer peening devices.

Table 3. Summary of FAT values [MPa] for different joint types

Stress analysis method	Nominal stress				Hot spot stress	
Joint type	Longitudinal attachment	T-Joint[1]	Cruciform joint	Butt weld	Non-load carrying	Load carrying
FAT value (P_f=2.3%) for as-welded details according to IIW (m=3) [3]	71	80	80	90	100	90
FAT value (P_f=2.3%) for high frequency improved welds found in this study (m = 5)	137	260	164	175	191-201	175
Fatigue strength increase at N=2x10^6 [%]	93	225	105	95	90-100	95
Recommended FAT value (P_f=2.3%) for high frequency improved welds (m = 5)	125	160	160	160	180	160

[1]for T-joints the experimental data was performed using bending loading but the recommended FAT values assume axial loading as for cruciform joints

5 Conclusions

This paper provides an overview of published experimental data on the fatigue strength of welded joints improved by high frequency treatment methods. Various high frequency peening methods are reported, but no attempt has been made to separate the methods or provide any ranking. In total, 294 data points from four specimen types are available. Most tests were performed using constant amplitude R=0.1 axial tension fatigue, but some data for other R-ratios, variable amplitude testing and bending fatigue are also reported. Material yield strength varied from 235 MPa over 900 MPa. The extracted fatigue test data was statistically analysed in order to estimate the best slope for the S-N line and to investigate the degree of improvement for each specimen type. The following conclusions can be drawn:

- An S-N slope of m=5 fits both the available high frequency treated fatigue data and the existing data for hammer peened welds. Thus, all of the following conclusions are based on an assumed S-N slope of m=5 and fatigue strength improvements are defined at N=2x10^6.
- Welded specimens treated by high frequency methods tend to have slightly greater fatigue strength than do specimens treated with traditional hammer peening. Hammer peened data tends fall below the P_f = 50% line for all specimen types.
- A fatigue strength improvement of [40 + (f_y - 355) * 0.08]% was conservative with respect to the available data for fillet weld specimens tested at R=0.1. This results in a 40% increase in allowable design stress for f_y = 355 MPa and 91% increase in design stress for f_y = 1000 MPa.
- During the statistical analysis data was not separated based on material strength so the proposed following recommendations are preliminary and may require further revision based of yield strength.
  - For longitudinal attachments the respective nominal stress design fatigue classes was 125 MPa.
  - For T-joints, cruciform joints and butt joints the respective nominal stress design fatigue class was 160 MPa.
  - For non-load carrying joints, the respective hot spot stress design fatigue classes was 180 MPa.
  - For load-carrying joints, the respective hot spot stress design fatigue classes was 180 MPa.

- R ratio rules for hammer peening seem suitable also for high frequency treated specimens but the available data is limited.
- In the future, data obtained for stress ratios other than R=0.1 and for variable amplitude testing are needed. Also, more basic studies on residual stress stability during loading for treated welds should be encouraged. Attention must also be given to defining quality assurance procedures for high frequency treated welds.

Acknowledgements

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