A review of fatigue test data on weld toe grinding and weld profiling

Authors: Moritz Braun, Xiru Wang

Institute for Ship Structural Design and Analysis, Hamburg University of Technology (TUHH), Hamburg, Germany

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Abstract:

The aim of this paper is to investigate the effects of weld toe grinding and weld profiling on the fatigue strength of welded joints and the main influencing factors. Thus, experimental test results of welds improved by different grinding techniques are reviewed. In total, 445 small- and full-scale fatigue test results of various weld types and steel grades with yield strengths up to 1100 MPa are analysed. The obtained improvements of two FAT classes correspond well with current guidelines; however, a new *S–N* curve slope of $m = 4$ is recommended—in line with proposals for other weld geometry improvement techniques.

Keywords: post-weld treatment; fatigue strength improvement; weld toe grinding; high-strength steel; burr grinding

1 Introduction

Welding is a widely used method to join steel plates. Due to the solidification of weld material, sharp notches at weld toes are created that decrease the fatigue strength compared to the parent material. The main reason is that local stress concentration and tensile residual stress occur at weld toes, which are the main driving factors for fatigue cracks. Thus, attempts to improve the fatigue strength of welded joints are either based on weld geometry improvement or on altering of the residual stress state at the weld toes [1], see Fig. 1 for an overview of available of post-weld improvement techniques.

Weld geometry techniques reduce the stress concentrations by smoothing the weld toe transition and removing possible welding defects, while residual stress methods alter tensile welding residual stresses or introduce compressive stresses. In recent years, methods that alter residual stress states at weld toes have been addressed in many research projects and in the industry [2-4]; however, weld geometry improvement techniques are still widely applied and within the focus of R&D activities as well [5-9].

Recently, a statistical assessments of high frequency impact treatment (HFMI) and tungsten inert gas (TIG) dressing were performed by Yıldırım and Marquis [10], and Yıldırım [9] in order to improve the fatigue assessment of post-weld treated welded joints. Although grinding is one of the oldest and most applied post-weld improvement techniques in many industries, no such assessment exists for weld toe ground and weld profiled joints. Thus, the aim of this paper is to investigate the effect of both techniques on the fatigue strength and the main influencing factors (weld details, steel strength, stress ratio etc.) in more detail. For this purpose, we collected 445 fatigue test results from different 33 publications—including butt-welded joints, longitudinal welds, doubling plates, load-carrying transverse, non-load carrying transverse welded steel joints, as well as I-section with cope holes, and longitudinal gusset plates. Moreover, fatigue test data of weld toe ground specimens with various yield strength and stress ratio are analyzed and evaluated. This study focuses exclusively on steel welded joints, since data on ground aluminum joints is limited; however, since Ye and Moan [11] obtained a fatigue strength improvement for aluminum joints similar to existing recommendations for steel, a transferability of the outcome of this study is probable.

At first, a general description of weld geometry improvement techniques and in particular weld toe grinding is given in Section 2. Section 3 serves to explain the assessment procedure for the obtained data on fatigue strength improvement by means of weld toe grinding and weld profiling. Subsequently, the results are presented and discussed in Section 4 and 5, respectively, and compared with current design guidelines in Section 6.

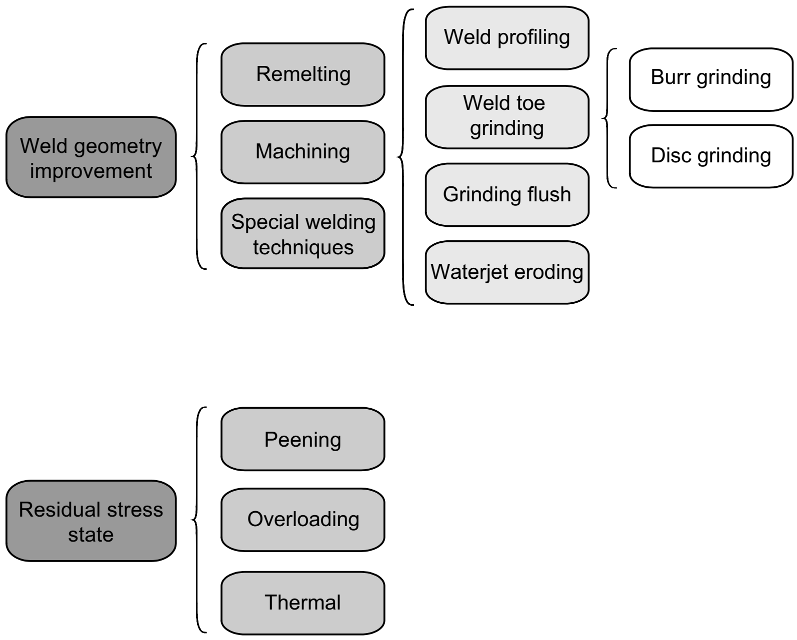


Fig. 1. Overview of post-weld improvement techniques based on Marquis and Barsoum [3]

2 State-of-the-art

2.1 Weld geometry improvement techniques and influencing factors

Among all post-weld improvement techniques, grinding is a widely applied technique to alter local stress concentrations at weld toes and to remove possible welding defects in order to increase the fatigue strength of welded joints; however, it is also frequently applied as a repair method after crack detection. Most of the existing literature focuses on weld toe grinding by means of burr grinding; however, studies from Clegg et al. [12], Mecséri and Kövesdi [13], Booth [14], and Knight [15] have shown the benefits of disc grinding and weld profiling as an alternative to burr grinding. The difference between weld toe grinding and weld profiling is that for the latter, the full weld is ground (not only the weld toe). Apart from that, the equipment and procedure is basically the same, see Fig. 2.

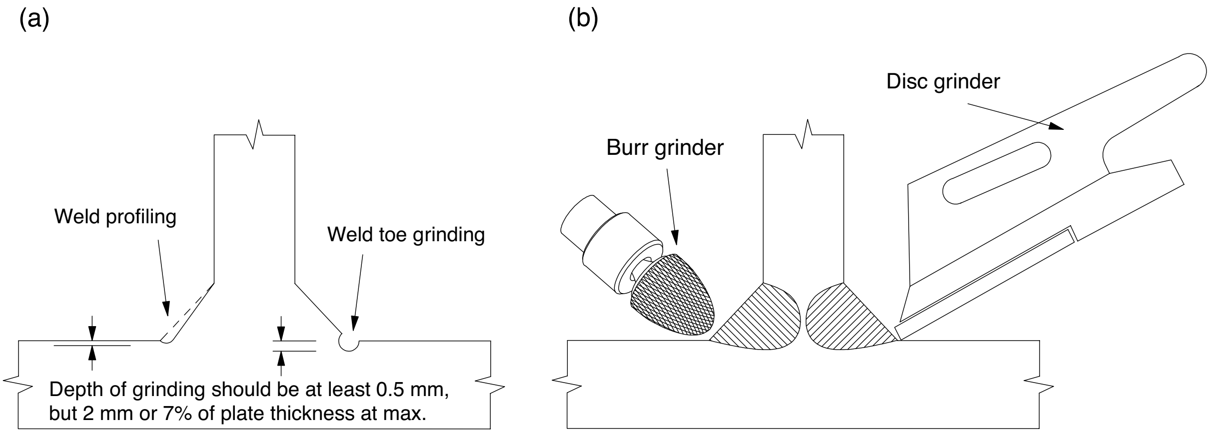


Fig. 2. Basic principle of weld toe grinding and weld profiling, including grinding depth recommendations by Haagensen and Maddox [1] (a) and equipment typically applied for grinding (b)

There are many parameters that may influence the effectiveness of grinding and that should be considered within the assessment of post-weld improved welded joints, see Kirkhope et al. [16, 17] for an extensive summary. Unsurprisingly, the radius after grinding has a major influence on the fatigue strength improvement, see Uchida et al. [18]. Furthermore, the plate thickness is expected to affects the fatigue strength improvement after grinding, see Mecséri and Kövesdi [13] and Hanzawa et al. [19]. In both studies, a higher fatigue strength after grinding was measured for the thicker steel plates; however, the number of performed tests is too small to draw conclusions from these comparisons.

Grinding is often applied for maritime structures. Thus, Booth [14], Matsumoto [20], and Baptista et al. [21] studied the effectiveness of burr grinding on the fatigue strength under the influence of corrosive media. Finally, Knight [15] and Braun et al. [22] performed tests with different steel types to explore the influence of parent material strength on the effectiveness of weld toe grinding and weld profiling. Similar to other post-weld treatment methods, a positive effect of parent material strength on fatigue strength was observed.

2.2 Equipment for weld toe grinding and weld profiling

The aim of grinding welds is to remove crack-like defects at the weld toe, from where fatigue cracks originate, and to increase the weld toe radii by smoothening the transition between the base plate and the weld face, which reduces the stress concentration at the weld toe and thereby improves fatigue strength, see Fig. 3.

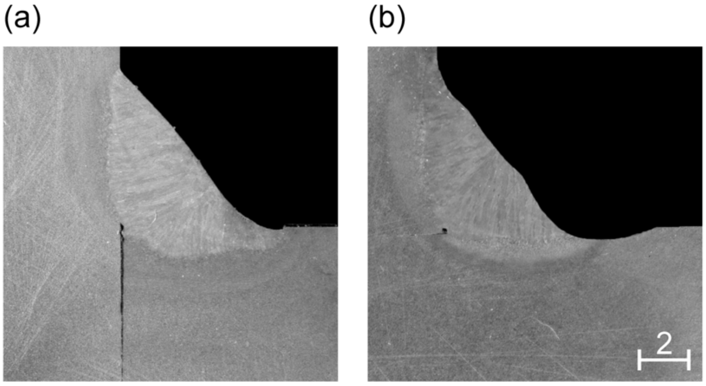


Fig. 3. Micrographs of welded joint in as-welded (a) and burr ground (b) state (as-welded micrograph taken from Braun et al. [23]); scale in millimeters

For burr grinding, it is possible to use high speed pneumatic, hydraulic, or electric grinders with hemispherical tool bits, often made of tungsten carbide. Moreover, the size of the tool should scale with the plate thickness t, and the resulting diameter should be no less than $0.25t$ [1]. Alternatively, bonded or coated abrasives may be used for disc grinding and CNC tools for weld profiling.

2.3 Effect of weld toe grinding and weld profiling on fatigue strength of joints

First of all, it is worth mentioning that the quality of grinding depends on the skills of the operator. Thus, design codes and the International Institute of Welding (IIW) recommendations [1, 24] account for poor workmanship and possibly low fatigue strength improvement after grinding. Consequently, the improvement of weld toe grinding and weld profiling is limited to fatigue design classes with a reference fatigue strength (FAT class) of FAT 90 or lower in accordance with the IIW recommendations [1]. Higher classes include already improved details and un-welded structural details. Thus, fatigue strength is not exclusively defined by weld toe failure. It is worth mentioning that improvement is limited to cases were fatigue cracking is expected to originate from weld toes. In some cases, grinding may lead to cracks initiating at weld roots. Thus, a separate assessment is required for welds with incomplete penetration [1].

An increase factor of 1.3 on stress range (corresponding to 2.2 on life, based on a *S–N* curve slope $m = 3$) is granted tor weld details, with FAT 90 or lower classes. The highest class that can be reached is the closest class below the FAT value obtained by multiplying the as-welded FAT value by 1.3, which roughly corresponds to an increase of two FAT classes. For steel welds, the highest class that can be claimed for ground welds is FAT 112, which corresponds to an increase of two FAT class relative to the highest detail class FAT 90. Towards the low cycle region, all *S–N* curves are limited by the design *S–N* curve for the parent material FAT 160 with a slope of $m = 5$ for steel. [1]

Interestingly, in DNVGL-RP-005 [25] and BS 7806 [26] an improvement in fatigue strength by grinding is granted by changing the $S-N$ curve slope to $m = 3.5$, but otherwise the same improvement factor (1.3) is used. This results in a smaller change in fatigue strength towards the low cycle fatigue regime but a larger increase for $N > 2 \times 10^6$.

3 Background on statistical assessment of fatigue data on ground welds and comparison with the as-welded state

Statistical methods are widely used to evaluate the experimental test data in order to characterize fatigue strength and to predict the performance of engineering structures. For different applications—such as bridges, offshore structures, and ships—the most efficient and reliable post-weld improvement method should be selected considering feasibility and fabrication costs. Post-weld improvement methods are often chosen based on comparisons of *S–N* curves derived from tests with small-scale fatigue test specimens; however, in order to ensure generality of conclusions, large data sets are required. In order to avoid biased conclusions based on small data sets, statistical analysis of test data collected from various literature sources is a well-accepted approach to improve design recommendations, see [9, 10].

3.1 Data obtained from literature study

In this study, fatigue test results obtained from 33 studies concerning fatigue strength improvement by weld toe grinding and weld profiling are analyzed. The fatigue data sets include the treatment by means of disc and burr grinding as well as weld profiling. In total, 445 fatigue test results from 69 data sets were evaluated. Except for a few studies using transverse load-carrying welds, the majority of fatigue test data was obtained under axial loading. Moreover, most tests were performed under constant amplitude loading—except for Tai and Miki [27], who transformed the variable amplitude loading test results into equivalent constant amplitude stress ranges. The yield strength of the parent material ranges from 235 to 1100 MPa, and thickness varies between 5 to 40 mm. In a study by Kliman et al. [28], butt joints between circular solid section (steel rods) with diameter of 16mm were used. In some studies, grinding leads to fracture originating from the weld roots after grinding; however, only specimens with fracture originating from ground weld toes are taken into account in the statistical assessment of this study.

3.2 Statistical assessment of obtained fatigue test results

The statistical assessment follows the recommended IIW practice [24, 29]. This procedure is found to be more reliable than other assessment procedures [30], especially for tests with small sample size and data sets without varying load level or small variance of stress ranges during the tests. After excluding run-outs, the two parameters of the *S–N* curve—slope m and intercept $log\ C$—as well as a 95% prediction bound (resulting in a survival probability of P_s = 97.5%) can be calculated by the following procedure. Here, the notation of the IIW recommendations is applied to calculate *S–N* curves in the form:

$$\log N = \log C - m \log \Delta\sigma \quad (1)$$

For as-welded steel joints, a fixed slope exponent $m = 3$ is recommended if the number of sample size is small (i.e. number of specimens $n < 10$), or if the data are not sufficiently spread to determine m exactly [24]. In this study, a slope $m = 3$ will be used for as-welded data, and a best-fit slope m will be calculated from the data of ground specimens in order to analyze the most suitable slope m to be recommended for welded joints improved by grinding. Since the IIW recommendations are based on the assumption of a fixed slope exponent $m = 3$, the best fit slope and standard deviation of the slope are calculated according to recommendations by the German Welding

Association for the assessment of fatigue test data [31]. From linear regression of the logarithm of the fatigue life $Y = \log N$ and the applied stress range $X = \log \Delta\sigma$, the slope exponent m is obtained by:

$$m = \frac{\sum XY - \frac{\sum X \cdot \sum Y}{n}}{\sum X^2 - \frac{(\sum X)^2}{n}} \quad (2)$$

Test results for a number of cycles to failure larger than the knee point typically assumed for small-scale specimens ($N_f = 2 \times 10^6$) are not included in the calculation due to the lack of data to sufficiently determine the actual knee point of each data set. A maximum likelihood approach might be applied for a statistical assessment of the knee point; however, this requires a small standard deviation of test results and data that spans a large range of cycles to failure, see Baumgartner et al. [32] for an extensive discussion. All of the data sets assessed in this study were too small to fulfil these two requirements. Thus, the typically assumed knee point for small-scale specimens was applied in this study.

Based on the estimate of the slope m, the intercept corresponding to stress range of $\Delta\sigma = 1$ MPa, $x_i = \log C_i$ can be estimated with:

$$x_i = \log Y - m \log X \quad (3)$$

The mean value of $\log C = x_m$ is then obtained from:

$$\log C = x_m = \sum \frac{x_i}{n} \quad (4)$$

and the standard deviation of the intercept $stdv(\log C)$ of $\log C$ with:

$$stdv(\log C) = \frac{\sqrt{\sum (x_m - x_i)^2}}{\mathrm{n} - 1} \quad (5)$$

Finally, the standard deviation of the slope exponent $stdv(m)$ is obtained with:

$$stdv(m) = \frac{stdv(\log C)}{\sqrt{\sum X^2 - \frac{(\sum X)^2}{n}}} \quad (6)$$

For design purposes, the characteristic value x_k (corresponding to 97.5% survival probability) is determined from Eq. (7):

$$x_k = x_m - k \cdot stdv(\log C) \quad (7)$$

where parameter k is obtained by using Eq. (8):

$$k = 1.645 \left(1 + \frac{1}{\sqrt{n}}\right) \quad (8)$$

Thus, the 95% confidence bands for the mean *S–N* curve can be computed by inserting Eq. (7) in Eq. (1):

$$\log N = (x_m \pm k \cdot stdv(\log C)) - m \cdot \log \Delta\sigma \quad (9)$$

For further details, see Hobbacher and Lefebrve et al. [24, 29]. Using the aforementioned assessment procedure, test results of data obtained from Huther et al. [33] are presented in Fig. 4 to illustrate the chosen assessment procedure.

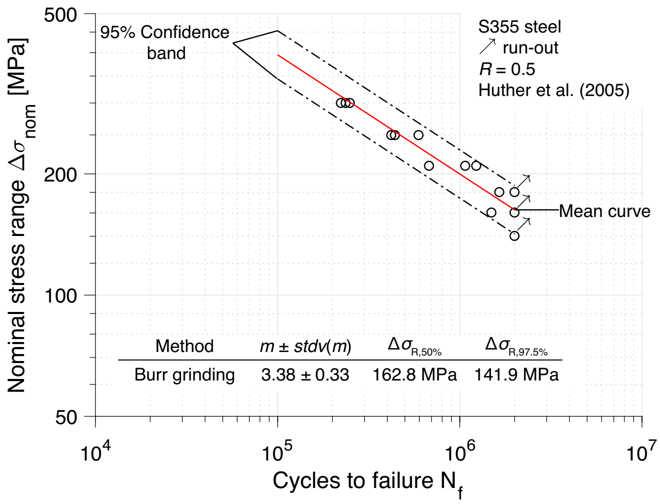


Fig. 4. Fatigue data of Huther et al. [33]-5 assessed by the IIW statistical assessment practice but applying a free slope exponent *m*

3.3 Mean fatigue strength of as-welded joints

Instead of using Eq. (1), fatigue strength of as-welded joints is often simply stated by the reference fatigue strength (FAT class) corresponding to stress range by 97.5% survival probability at $N_f = 2 \times 10^6$ cycles of failure $\Delta\sigma_{97.5\%}$; however, in order to calculate the mean increase in fatigue strength after grinding the stress ranges for 50% survival probability at $N_f = 2 \times 10^6$ cycles of failure $\Delta\sigma_{50\%}$ are used in this study. This is due to the higher reliability of correctly estimating the mean fatigue strength of small data sets.

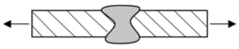
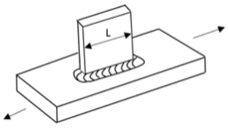
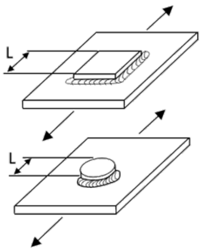
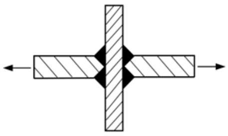
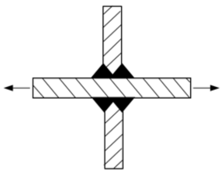
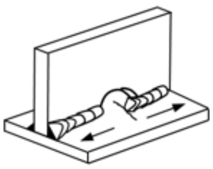
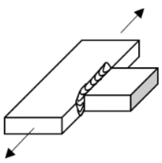
According to Fricke [34], $\Delta\sigma_{50\%}$ for as-welded specimens can be calculated assuming a standard deviation $stdv(\log C) = 0.0687$, which corresponds to a standard deviation of $stdv(C) = 0.206$ for a slope $m = 3$. Thus, the mean fatigue strength is calculated from

$$\Delta\sigma_{50\%} = \Delta\sigma_{97.5\%} \times 1.366 \tag{10}$$

Table 1 gives an overview of the mean and FAT classes according to the IIW recommendations [24] prior and after grinding for all specimen geometries considered in this study.

Table 1. Weld details with FAT classes for as-welded steel joints, corresponding mean fatigue strength, and FAT classes after grinding according to the IIW [24]

Type of welds	Description	FAT class for as-welded	Assumed mean fatigue strength (survival probability	FAT class after grinding

		recommended by the IIW [24]	of 50%) based on Eq. (10)	according to the IIW [24]
	Transverse butt welds	90	123	112
	Longitudinal fillet welded gusset of length			
	L < 150 mm	71	97	90
	L < 300 mm	63	86	80
	Doubling plates 50 mm < L ≤ 150 mm	71	97	90
	Transverse load-carrying welds	71	97	90
	Transverse non-load-carrying welds	80	110	100
	Longitudinal butt weld, fillet weld or intermittent weld (I-section) with cope holes	50	68	63
	Longitudinal gusset plates with L < 150 mm	50	68	63

4 Effect of weld toe grinding and weld profiling on fatigue strength of joints

4.1 Calculation of S-N curve slope exponent

Recent studies have found a change of slope exponent after applying different post-weld improvement techniques to welded joints (see [9, 10]). Thus, in a first assessment step, the best-fit slope and standard deviation of each data set obtained from literature are calculated based on the aforementioned procedure.

The results for butt joints, longitudinal attachments, doubling plates, transverse load-carrying welds, and transverse non-load-carrying welds are shown in Fig. 5 for different numbers of test specimens n. The slopes for I-section with cope hole and longitudinal gusset plate test specimens cannot be calculated due to a lack of fatigue data and tests performed for the same stress range. For comparison, Fig. 5 represents the *S–N* slope $m = 3$ (currently recommended for welded joints treated by burr grinding and similar processes) and the median value of all slopes with horizonal lines.

A possible explanation for the large range of obtained values of best-fit-slopes could be a small variation in applied stress range in the fatigue tests and the generally small number of less than 10 test specimens in most studies. Due to the aforementioned reasons, it was not possible to determine a best-fit slope for some of the data sets. In order to assess whether the number of specimens per study had an influence on the obtained slope exponent, Pearson correlation coefficients r and probability value p are computed. The probability value p is a measure for the statistical significance of the obtained correlation coefficient. Applying a typical significance threshold of 5%, a p-value below 0.05 means that the obtained result is statistically significant and the null hypothesis (there is no correlation or relationship) has to be rejected. It is important to note that the sample sizes of this study—as for most fatigue studies—are rather small. Thus, these two values should be treated with caution. In order to avoid a biased decision on which sample size is sufficient to calculate r and p, they have been computed for each comparison in Fig. 5.

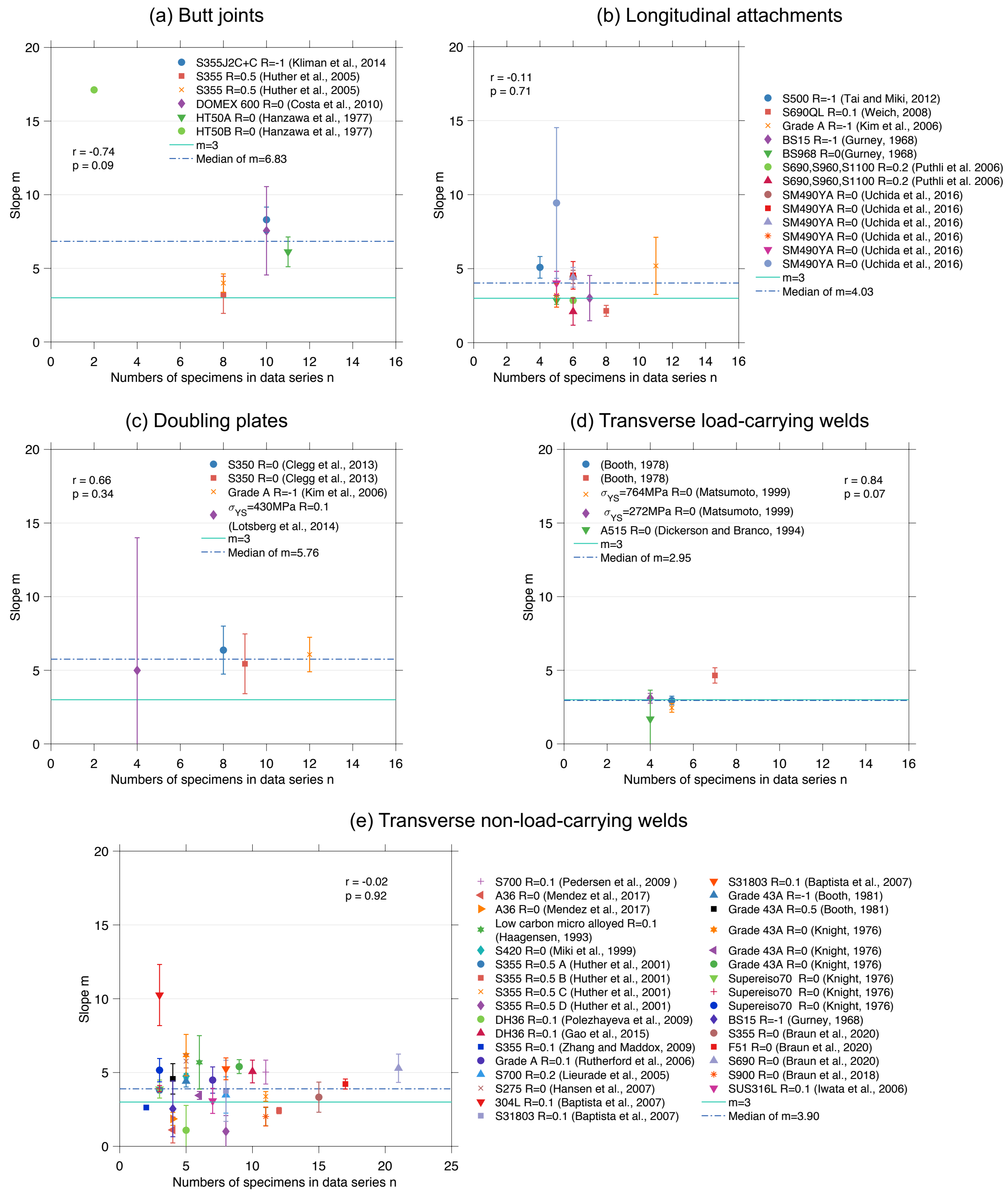


Fig. 5. Calculation of median slope exponent *m* for ground welded joints based on number of specimens and weld detail

As expected, the standard deviation of the slope exponent $stdv(\log C)$ generally decreases with increasing specimen number; however, there is no evidence of a correlation between specimen number per study and the slope exponent. Furthermore, as depicted in Fig. 5, $m = 3$ is below the best-fit slope of the majority of data sets and the median slope for most joint types—with the only exception of transverse load-carrying joints.

An unweighted median slope of $m = 4.13$ is calculated based on the best-fit slopes of all data sets (not separated according to weld detail). The benefit of the median over the mean is that it is less sensitive to being skewed by extreme results (outliers), e.g. very large or small calculated slopes due to small sample sizes. Thus, no weighting according to sample size is required. The so-obtained median slope agrees well with the expectation of shallower *S*–*N* curve slopes for mild notches as compared to sharp notches at weld toes. Moreover, results of studies on fatigue assessment of ground fillet welded joints by Ahola et al. [5] and weld geometry improvement by means of TIG-dressing by Yıldırım [9] found similar slopes. Moreover, the obtained slope is higher than the recommendation by DNVGL-RP-005 [25] and BS 7806 [26] of $m = 3.5$, but below slope exponents obtained for residual stress state altering techniques [3].

4.2 Influencing factors on slope exponent for ground welded joints

Based on the large amount of available fatigue data for transverse non-load-carrying welds, Fig. 6 shows the results for *S*–*N* slope estimates grouped by parent material yield strength. No correlation between median slope m and yield strength is observed within the three assessed yield strength ranges (if data for S900 from Braun et al. [35] is considered an outlier due to the apparently underestimated slope exponent m of this data set); however, a slight increase of the median slope is obtained if the three median slopes are compared. Clearly, more tests are needed to analyze the effect of yield strength on the slope of *S*–*N* curves.

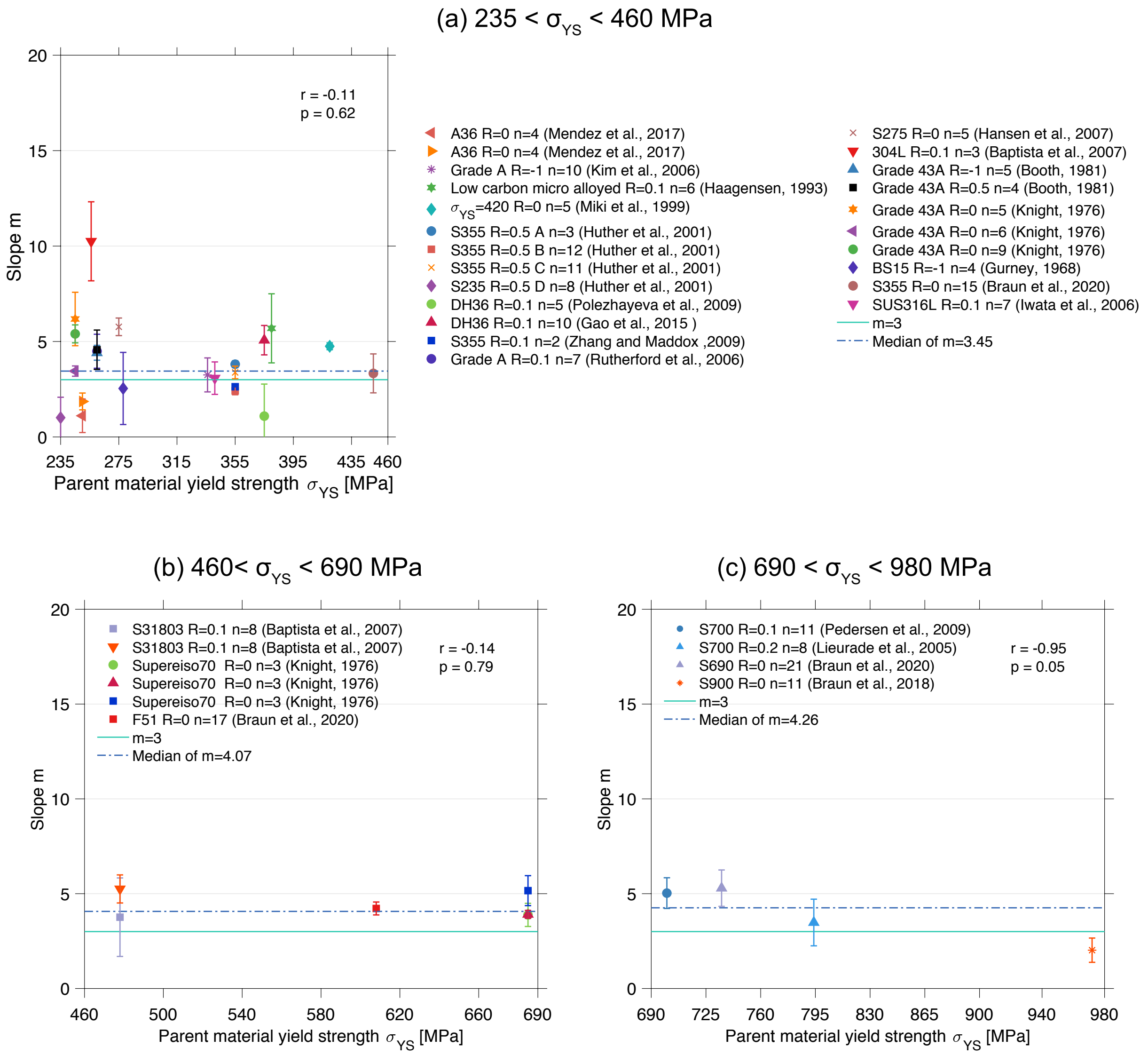


Fig. 6. Calculation of median slope exponent m for transverse non-load-carrying welds improved by weld toe grinding and weld profiling based on parent material yield strength σ_{YS}

It is often assumed that small-scale test specimens behave differently than full-scale structures or, in general, larger test specimens. Thus, the effect of plate thickness t on the slope exponent was analyzed next. As can be seen from Fig. 7, no correlation between plate thickness and slope was obtained for the transverse non-load-carrying welded joints.

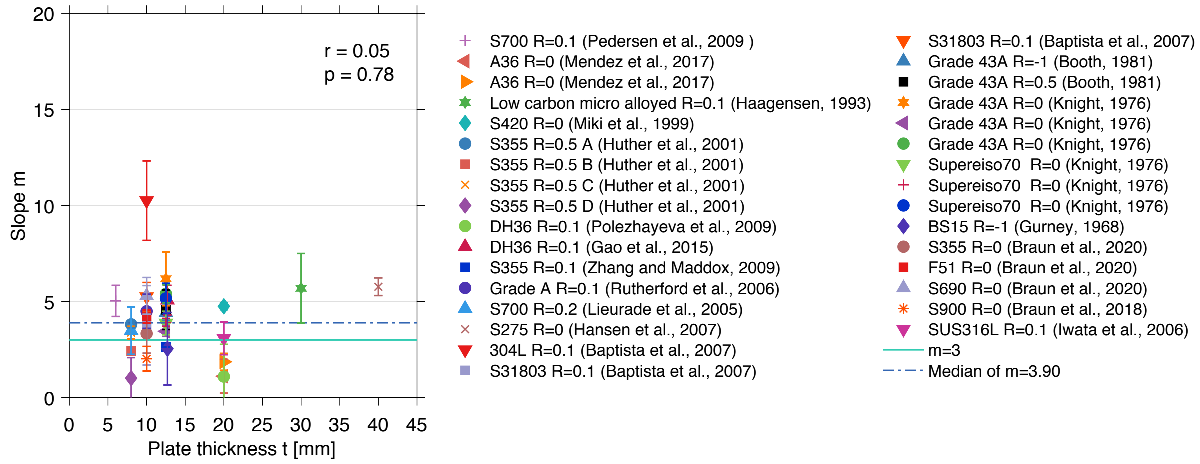


Fig. 7. Assessment of specimen thickness effect on slope exponent *m* of transverse non-load-carrying welded joints improved by weld toe grinding and weld profiling

Finally, the effect of the grinding techniques is assessed by comparing the distributions of slope exponents obtained for each method. Compared to the number of studies on burr grinding, there is not much data on disc grinding and weld profiling. The results are therefore presented as boxplots, showing the median values and scatter of slope exponents in Fig. 8. Interestingly, the highest median slope exponent ($\tilde{m}$) is obtained for the test series treated by disc grinding, and the lowest for the joints treated by weld profiling. Comparing the surface roughness for these methods, the opposite results would have been predicted; however, the number of test series and the scatter of the estimated slope exponents is too large to draw reliable conclusions from this comparison. Again, more tests are required to analyze the effect of grinding methods on the slope exponent.

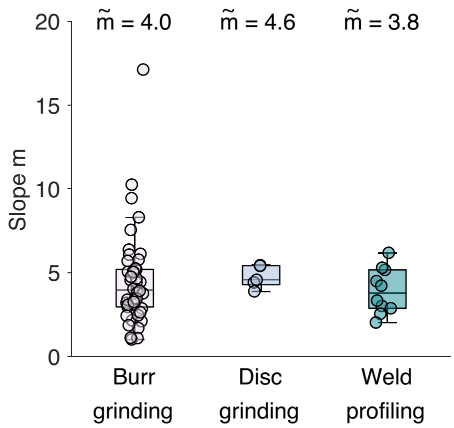


Fig. 8. Comparison of grinding method effect on obtained slope exponent *m*. The median values are above the boxplots ($\tilde{m}$), which were created with a default setting, i.e. the maximum whiskers length equals 1.5 times interquartile range.

In order to allow for an easy comparison between different weld geometry improvement methods and the as-welded state, all subsequent comparisons of fatigue strength improvement are given for a fixed slope exponent of $m = 4$ (rounded median slope) and $m = 3$, apart from the assessment results obtained for a free slope exponent.

5 Comparison of endurable stresses between as-welded and ground specimens

The results for all analyzed welding details improved by grinding are summarized in Tables 3 to 9. Results are given for the three mentioned slope exponents m_1 (index 1 indicating $N < 10^7$). As stated before, it was not possible to obtain results for a free slope exponent for all data sets. These data sets are commented in the tables. Moreover, in some studies, the yield stress of the specimens was not reported. Thus, the values corresponding to the minimum value according to the steel type are used to specify the yield stress. If the steel type was not stated in the studies, fields are marked with '-' in Tables 3 to 9.

For most data sets, the mean fatigue strength $\Delta\sigma_{50\%}$ after grinding assessed by a best-fit slope results in a positive fatigue strength improvement compared with mean fatigue strength for as-welded joints; however, in some cases the assessment yields a decrease in fatigue strength. The assessment with a fixed slope $m_1 = 4$ leads to a higher fatigue strength increase compared to fixed slope $m_1 = 3$ as one would expect.

5.1 Applied grinding technique and relevant process variations

In the Tables 3 to 9, the specimens from references Clegg et al. [12]-1, Mecséri and Kövesdi [13], Booth [14], and Knight ([15]-3, [15]-4) were either fully or partially improved by disc grinding, and specimens of data sets from Braun et al. [22, 35], Gurney [36], Rutherford [37], and Knight ([15]-1, [15]-6) were treated by weld profiling. If more than one series of tests was extracted from a reference, the number behind the reference refers to the test series number. Similar to the previous assessment, the effect of the grinding technique on fatigue strength improvement was assessed based on distribution and median values of improvement ($\tilde{y}$). From Fig. 9, it is possible to conclude that weld profiling leads to higher fatigue strength improvement on welded specimens than burr and disc grinding for both fixed slope exponents. This result agrees with expectations based on surface quality and studies where different grinding techniques were compared, see [12, 15].

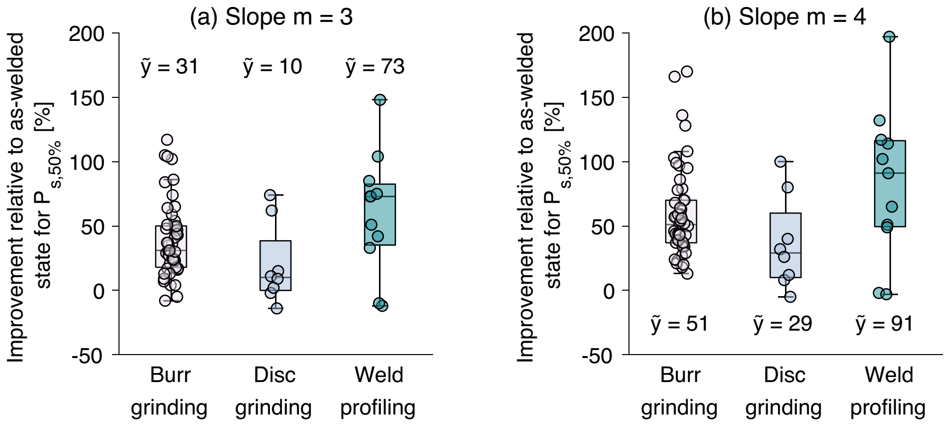


Fig. 9. Effect of grinding technique on fatigue strength improvement for $N_f = 2 \times 10^6$ cycles, P_s = 50%, and assumed slope of $m = 3$ (a) and $m = 4$ (b), with median improvements ($\tilde{y}$)

It is well known that not only the chosen post-weld treatment method affects the fatigue strength improvement, but also the procedure itself. Thus, Uchida et al. [18] investigated the effect of grinding radius (3 and 5 mm) and depth (0.1, 0.5, and 1.5 mm) on fatigue strength. No correlation between grinding depth and improvement was obtained, which is probably due to the small number of tests (five or six per series); however, an increase of groove radius led to higher fatigue strength at $N_f = 2 \times 10^6$, see [18].

Grinding is frequently applied in the maritime industry. Thus, a number of studies ([38]-2, [20], [21]-2 and [21]-3) performed fatigue testing in corrosive media. In all studies, a reduction of 20–30% was obtained under free corrosion compared to testing in air. Booth [14] investigated the effect of stress ratios *R* in order to assess the mean stress effect on fatigue strength after grinding. As expected, a higher fatigue strength was found for fully reverse loading compared to a high stress ratio of *R* = 0.5.

5.2 Parent material strength and specimen size

The influence of parent material strength on the effectiveness of weld toe grinding was investigated by Knight [15]. While the reported improvement for mild steel is only about 17% compared to the as-welded state, a significant improvement of about 100% is obtained for a high strength steel with a yield strength of 685 MPa. In recent tests with non-load-carrying transverse welds of four steel strengths improved by weld profiling and polishing, a strong positive correlation between fatigue strength improvement and yield strength was observed [22]; however, due to higher surface roughness, this effect might be less pronounced for burr and disc grinding.

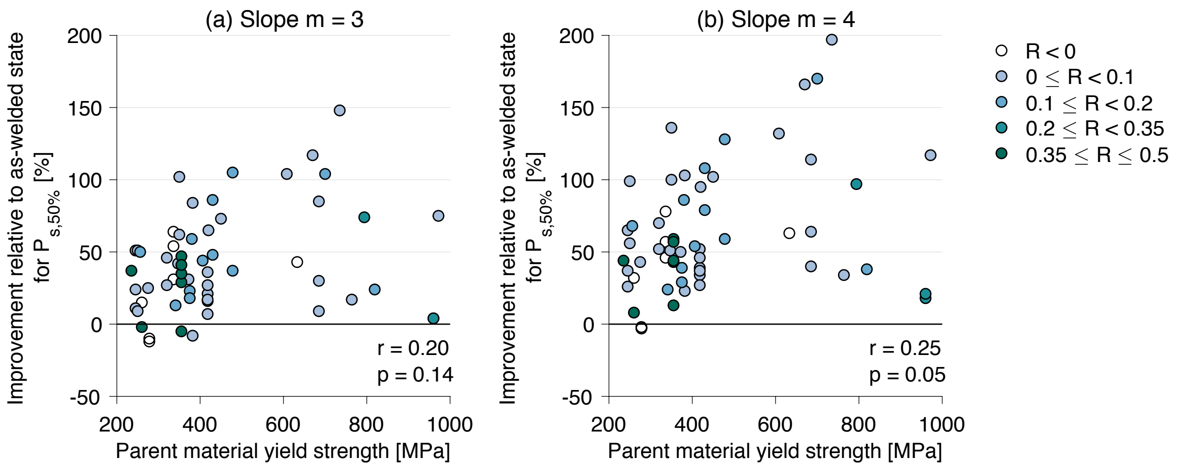


Fig. 10. Effect of parent material yield strength on fatigue strength improvement for $N_f = 2 \times 10^6$ cycles, P_s = 50%, and assumed slope of $m = 3$ (a) and $m = 4$ (b)

While there is no clear indication for a change of the *S–N* curve slope with increasing parent material yield strength, a moderate correlation between fatigue improvement relative to the as-welded state is obtained, see Fig. 10. The data is grouped by stress-ratio *R* to further allow an assessment of the mean stress effect on possible fatigue strength improvement. Since grinding leads to compressive residual stresses in the surface layer [5, 39], an effect of applied stress ratio is expected. Fig. 11 presents the improvements relative to the applied stress ratio *R* for both slope exponents. Excluding the data for $R = -1$, a moderate negative correlation that is statistically significant ($r = -0.26, p = 0.04$) is found for $m = 4$; however, no correlation is obtained if the entire data is assessed. If residual stresses are introduced by grinding, they are likely released by testing at either $R = -1$ or $R = 0.5$, as is often the case for stress state altering techniques. A systematic investigation into residual stress states after grinding would help to analyze this effect.

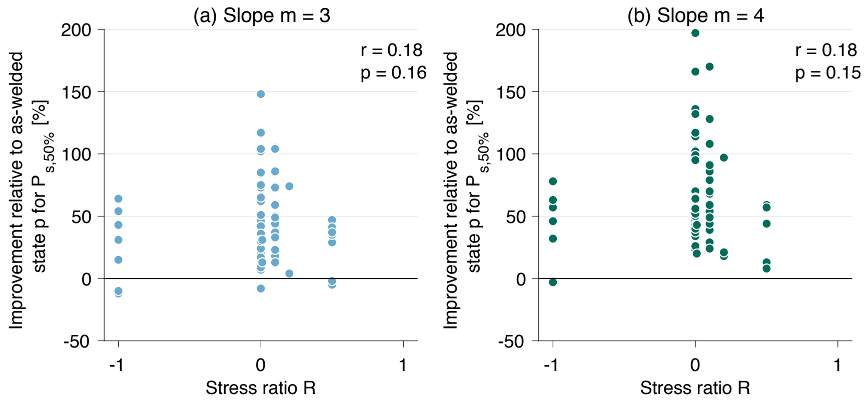


Fig. 11. Effect of stress ratio R on fatigue strength improvement for $N_f = 2 \times 10^6$ cycles, $P_s = 50\%$, and assumed slope of $m = 3$ (a) and $m = 4$ (b)

The majority of specimens in the analyzed studies are small welded components, whereas large doubling plates were tested by Clegg et al. [12] and Lotsberg et al. [40], and I-sections with cope holes by Choi et al. [41]. Interestingly, a rather high improvement relative to the IIW design curves is observed in these tests; however, Fig. 12 shows no correlation between plate thickness t and fatigue strength. In order to ensure a small level of additional conservatism, the results of specimens (four test series) with thickness $t > 25$ mm were not corrected for thickness effects; however, including a thickness correction would not affect the correlation significantly. Thus, the results by Mecséri and Kövesdi [13] and Hanzawa et al. [19] could not be confirmed in this study. It can be concluded that fatigue strength improvement by means of grinding is independent of the specimen thickness. Still, it is advisable to set a minimum plate thickness, as grinding thin plates ($t < 10$ mm) considerably increases the nominal stress level—due to the high effect of the notch depth to thickness ratio. This is particularly important if a minimum grinding depth of 0.5 mm is required to remove possible welding defects at the weld toes.

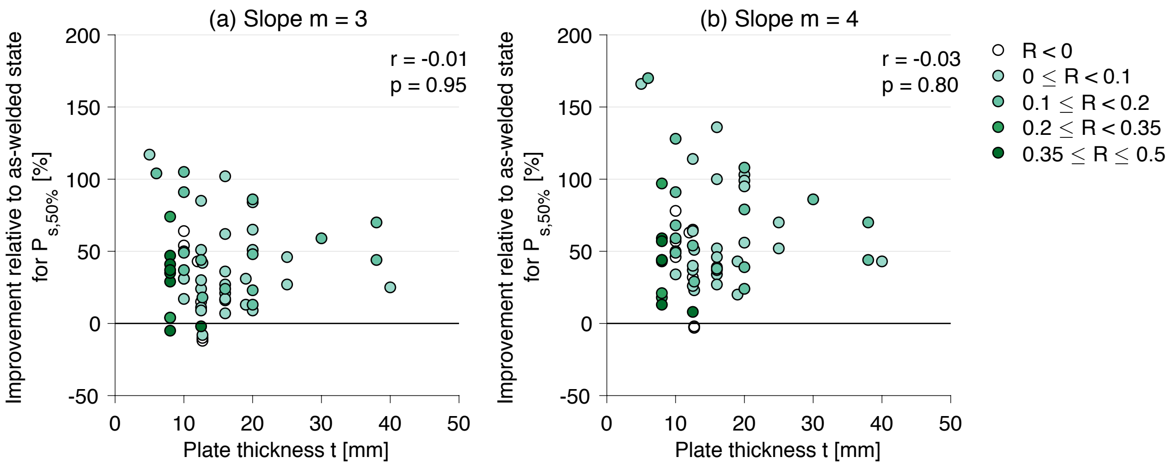


Fig. 12. Effect of plate thickness t on fatigue strength improvement for $N_f = 2 \times 10^6$ cycles, $P_s = 50\%$, and assumed slope of $m = 3$ (a) and $m = 4$ (b)

5.3 Test series without fatigue strength improvement

It is apparent that the improvements (given in %) of some of the data sets are negative, i.e. grinding has no positive effect compared to either the IIW recommendations or the as-welded specimens. The reason for this is either a very high initial weld quality of weld details with already low stress concentrations, such as in Huther et al. [33], or the introduction of a notch stress raising groove by grinding or significant reduction in cross-sectional area and, thus, a local increase in nominal stress, see Kliman et al. [28] and Méndez et al. [42]. A large proportion of the tests by Kliman et al. [28] were performed in the low-cycle fatigue regime and for stress ranges close to the yield strength of the parent material. Below 10^5 cycles, the fatigue strength after grinding is lower than in as-welded state, which indicates that the grinding might have caused a decrease in fatigue strength due to the reduction in cross-sectional area. The data was thus excluded from further assessment. As previously mentioned, grinding should be avoided for applications where a significant reduction in cross-sectional area might reduce the fatigue strength.

6 Comparison with current design guidelines

6.1 Assessment of fatigue strength improvement based on slope exponent m = 4

All extracted fatigue test results after grinding are presented in Fig. 13, including obtained *S–N* curves for a slope $m_1 = 4$ for 50% (dashed line) and 97.5% (solid line) survival probability and design curves for the as-welded state from the IIW recommendations [24] with $m_1 = 3$ and 97.5% survival probability (dash-dot line). In the *S–N* curve assessment, only test results for $N_f < 2 \times 10^6$ were included; however, the *S–N* curves are extended with a decrease in stress range of about 10% per decade, which corresponds to a slope of $m_2 = 22$, for $N_f > 10^7$ [24]. For the comparison with current guidelines, the increase of stress range at $N_f = 2 \times 10^6$ cycles is calculated between $\Delta\sigma_{97.5\%}$ and the corresponding FAT classes of the as-welded state.

First of all, a trend towards higher fatigue strength improvement relative to the as-welded state at lower stress ranges is observed for most analyzed weld details, which supports the assessment based on slope $m_1 = 4$ for weld details improved by grinding. Due to the chosen slope of $m_1 = 4$, the *S–N* curves for the as-welded state and after grinding are intersecting between 10^4 and 10^5 for some weld details similar to the rules for HFMI-treated welded joints [3]. In general, a tendency to higher fatigue strength increases is observed for larger numbers of cycles to failure. The applied slope of $m_1 = 4$ seems therefore reasonable.

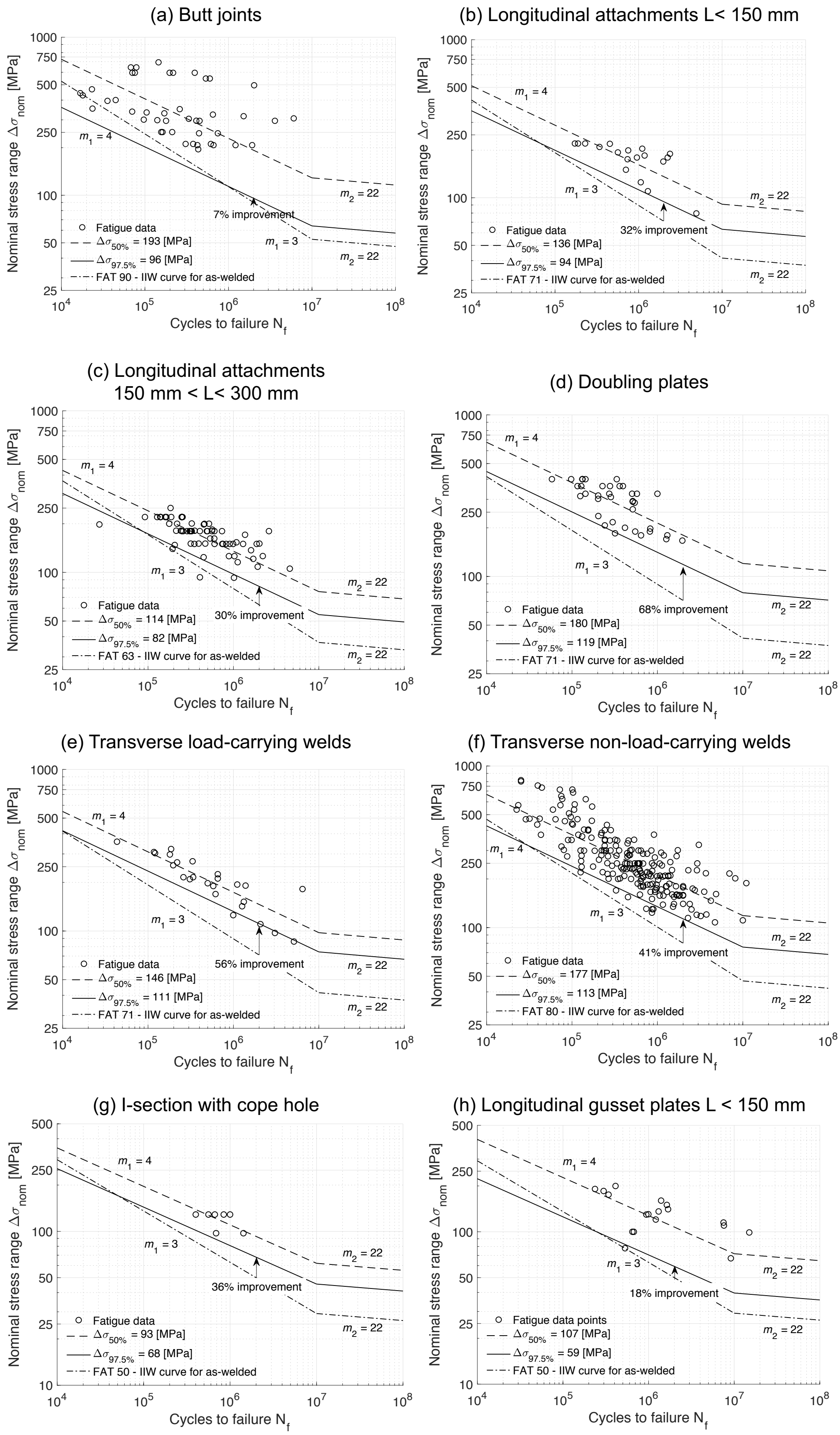


Fig. 13. Comparison of analyzed fatigue data based on a slope $m_1 = 4$ with recommended design *S*–*N* curves for the as-welded state ($m_1 = 3$)

For all weld details, a general increase in fatigue strength after grinding is observed with an average improvement of 36%. Only the assessment of butt joints and longitudinal gusset plates lead to a smaller increase in fatigue strength; this is related to the relatively large scatter and small data sets. In principle, the obtained improvement is in accordance with the IIW recommendations for improvement by burr grinding (i.e. an increase in sustainable stress range corresponding to a factor of 1.3) [24]; however, an increase of more than 40% is observed for the largest data set of all weld details (transverse non-load-carrying welds).

Results for I-section specimens with cope holes and longitudinal gusset plates are represented in Fig. 13(g) and Fig. 13(h). One of the two studies on longitudinal gusset plates applied the improvement technique of disc grinding, which led to a lower increase in fatigue strength as compared to burr grinding. In general, only a small amount of fatigue test data is available for these two weld details. Hence, the effect of grinding on these two weld details cannot be investigated adequately; however, the increase of fatigue strength for I-section of 36% corresponds well to the IIW recommendations.

6.2 Difference in fatigue strength compared to current recommended design curves

In order to generalize the previous findings, the results for the different weld details obtained based on a fixed slope exponent $m_1 = 4$ are summarized in Table 2. To allow for a better comparison with the current recommended improvement of two FAT classes after grinding, the results are rounded to the nearest FAT class. Although five out of nine comparisons yield different results than the current recommended values, the results are generally in line with the current recommendations—especially if the two data sets with small number of specimens are excluded. Interestingly, the results of the doubling plates, which are mainly large-scale specimens, are exceeded by two FAT classes, while the results of the butt joints are two FAT classes below the recommendations; however, the scatter of the butt joints is quite large.

Table 2. Analysis of extracted data using a slope of $m_1 = 4$

	Butt joints	Longitudinal attachments $L < 150$ mm	Longitudinal attachments $L < 300$ mm	Doubling plates	Transverse load-carrying welds	Transverse non-load-carrying welds	I-section with cope hole	Longitudinal gusset plates $L < 150$ mm
FAT class of the as-welded state plus two FAT classes acc. to the IIW	112	90	80	90	90	100	63	63
$\Delta\sigma_{97.5\%}$ for m_1=4	90 [a]	90	80	112	100	112	63	56 [b]

[a] large scatter of data

[b] small amount of test data

The available data of all specimens except for transverse non-load-carrying welds is insufficient to draw final conclusions, but the current recommendation of an improved fatigue strength by two FAT classes after grinding seems reasonable if combined with an *S–N* curve slope of $m_1 = 4$. Thus, all fatigue test results obtained from the literature are plotted in Fig. 14, with the obtained *S–N* curve by enforcing $m_1 = 4$ (solid lines), the current IIW design curves for an *S–N* curve slope of $m_1 = 3$ (dashed lines), and the *S–N* curve for an improvement of two FAT classes and a slope $m_1 = 4$ (dash-dot line). Furthermore, the design curves for weld details of higher fatigue strength are limited by the parent material FAT 160 curve (dotted line).

It can be observed that only five of the test results are below the proposed curves with $m_1 = 4$, which corresponds to an overall survival probability of 98.9%. Compared to the current recommendations, this leads to a more conservative assessment towards the low-cycle fatigue regime and a higher sustainable fatigue strength for large number of load cycles ($N > 10^7$). Moreover, a number of butt-welded joints, longitudinal attachments, as well as non-load-carrying fillet welded joints are safely assessed with a slope $m_1 = 4$ that are below the current design curves for $m_1 = 3$. Finally, the need to limit the curves by the parent material curve FAT 160 is no longer required.

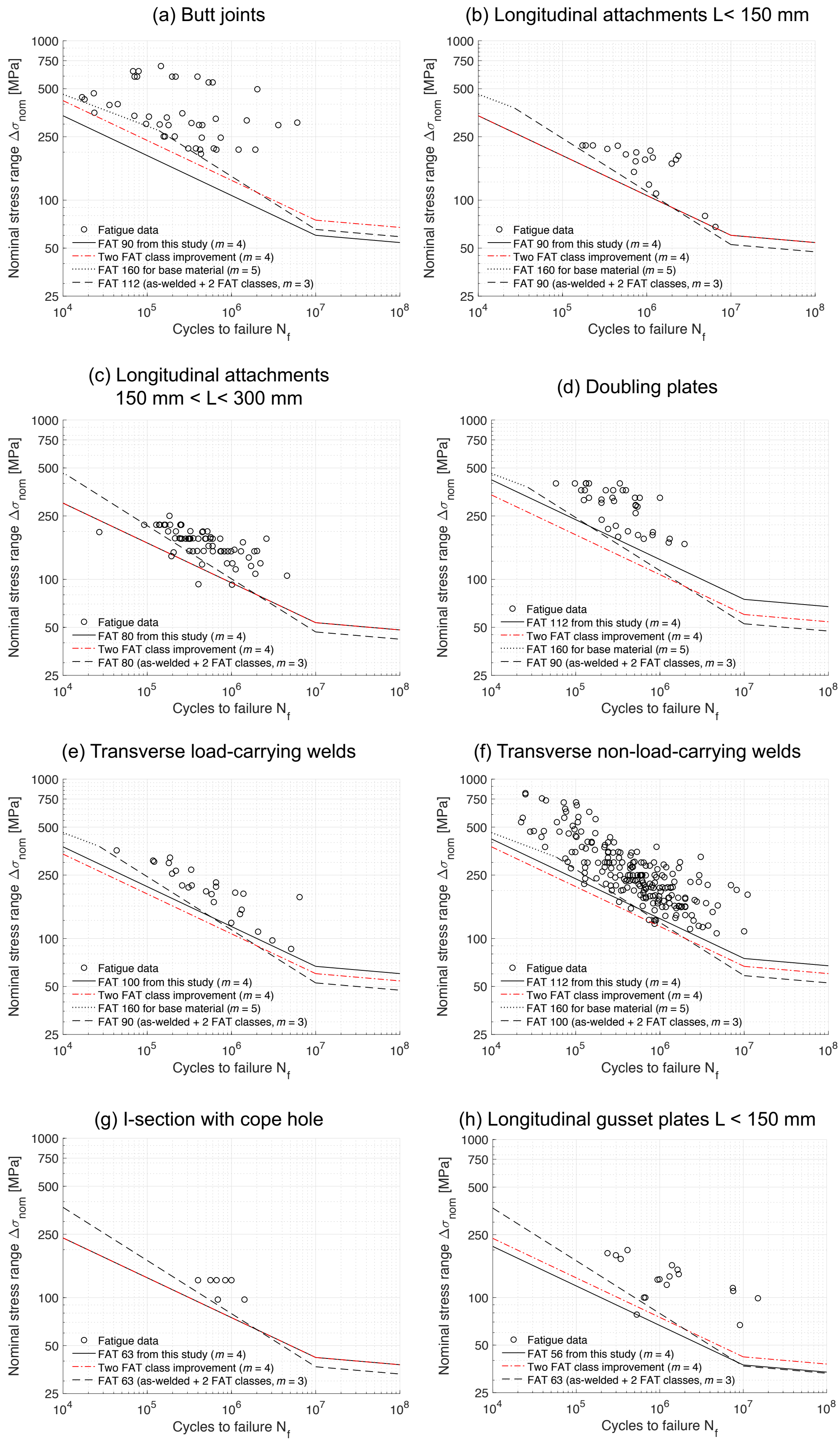


Fig. 14. Comparison of current fatigue design curves with curves obtained in this study and proposed curves for each analyzed weld detail

7 Summary and conclusions

Best-fit *S–N* curves and slope exponents are calculated (according to the IIW and DVS recommendations) for 445 fatigue data points from 33 publications on butt joints, longitudinal attachments, doubling plates, transverse load-carrying welds, and transverse non-load-carrying welds, I-section specimens with cope hole as well as longitudinal gusset plates improved by weld toe grinding and weld profiling. From all best-fit slope exponents, a median slope exponent $m_1 = 4.13$ is obtained. Subsequently, influencing factors on slope exponents and fatigue strength improvement at $N = 2 \times 10^6$ cycles are assessed based on statistical methods. Finally, the fatigue test data for all weld details is assessed based on the currently recommended slope exponent for ground joints ($m_1 = 3$) and the rounded median exponent ($m_1 = 4$). The following conclusions can be drawn from the investigation:

- By comparing the results of welded specimens prior and after grinding, it becomes clear that grinding has a large positive effect on the fatigue strength of welded joints, unless the as-welded quality is already very high. Fatigue strength can be reduced by introducing a deep artificial notch through grinding, or if the cross-sectional area is significantly reduced and thereby the nominal stress increased.
- Grinding is applicable to butt- and fillet-welded joints alike, and a trend towards higher fatigue strength improvement relative to the as-welded state at lower stress ranges is observed for most analyzed weld details.
- An assessment based on the currently recommended slope exponent $m_1 = 3$ led to a number of unconservative fatigue strength assessments for number of cycles to failure $N < 2 \times 10^6$. This supports the assessment based on a slope $m_1 = 4$ for weld details improved by grinding—including large components, such as doubling plates and I-sections with cope holes.
- Weld profiling leads to a greater improvement of fatigue strength than burr and disc grinding, and burr grinding to a greater improvement than disc grinding.
- A slight increase in slope exponent and fatigue strength improvement is observed for high-strength steel joints; however, more test data is required to verify this behavior.
- No correlation is observed between plate thickness and slope exponent as well as fatigue strength improvement.
- A slightly negative effect of increasing stress ratio on fatigue strength improvement was observed; however, the same applied to fully reversed loading. This could be related to residual stresses induced by grinding and subsequent release; however, a systematic investigation into residual stresses due to grinding is required to further analyze this effect.
- Finally, it is recommendable to keep the current bonus on fatigue strength by two FAT classes after grinding, but to change the design curve slope to $m = 4$. This leads to more conservative fatigue strength assessment towards the low-cycle fatigue regime but increases the sustainable stress ranges for load cycles $N > 2 \times 10^6$.

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Appendix of fatigue test results extracted from literature

Table 3. Extracted fatigue data for butt joints improved by weld toe grinding and weld profiling

Reference	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	n	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[43]-1	A515 Grade 70	320[b]	BG	25	2	0	Same stress range			179.9	133.9	34	208.9	70
[33]-1	S355	355[a]	BG	8	8	0.5	3.2	162.8	32	158.8	122.9	29	175.5	43
[33]-2	S355	355[a]	BG	8	8	0.5	4	138.9	13	116.9	117.7	-1	138.9	13
[19]-1	HT50A	382[b]	BG	12.7	11	0	6.12	205.6	67	113.4	95.9	18	151.9	23
[19]-2	HT50B	382[b]	BG	20	2	0	17.12	311.4	153	226.6	146.7	54	249.5	103
[28]	S355	612[b]	BG	diameter 16mm	10	-1	8.3	108.8	-12	38.7	54.1	-28	58	-53
[44]	S600	670[b]	BG	5	10	0	7.55	436.7	255	266.7	165.1	62	327.2	166

[a] nominal σ_{YS}

[b] measured σ_{YS}

[c] Grinding method: burr grinding (BG), disc grinding (DG), weld profiling (WP)

Table 4. Extracted fatigue data for longitudinal attachments improved by weld toe grinding and weld profiling

Reference	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	n	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[36]-1	BS15	278[b]	WP	12.7	10	-1	3.01	75.4	-12	75.5	48.4	56	83.9	-2
[36]-2	BS968	347[b]	WP	12.7	5	0	2.87	120.7	40	122	87	40	129.8	51
[45]-1	Grade A	336[b]	BG	10	11	-1	5.19	165.7	71	149.4	91	64	152.4	57
[27]	S500	633[b]	BG	12	4	-1	5.05	151.2	76	123	70.4	75	139.8	63
[46]-1	S600,960,1100	600-1100[a]	BG	8	6	0.2	2.86	98.8	2	101.2	80.6	26	114.8	18
[46]-2	S600,960,1100	600-1100[a]	BG	8	6	0.2	2.1	69	-20	89.6	63.5	41	104.4	21
[47]	S690QL	819[b]	BG	16	8	0.1	2.15	89.9	5	106.6	91.5	17	118.7	38
[18]-1	SM490YA	418[b]	BG	16	6	0	4.44	124.7	45	104.3	78.3	33	119.6	39
[18]-2	SM490YA	418[b]	BG	16	6	0	4.55	122.1	42	99.6	78.3	27	115.6	34
[18]-3	SM490YA	418[b]	BG	16	6	0	4.42	114.5	33	92.2	78.3	18	109.1	27

[18]-4	SM490YA	418[b]	BG	16	5	0	3.19	104.7	22	100.8	78.3	29	117.8	37
[18]-5	SM490YA	418[b]	BG	16	5	0	4.03	131	52	117.2	78.3	50	130.7	52
[18]-6	SM490YA	418[b]	BG	16	5	0	9.44	161.9	88	108.8	78.3	39	125.9	46

[a] nominal σ_{YS}

[b] measured σ_{YS}

[c] Grinding method: burr grinding (BG), disc grinding (DG), weld profiling (WP)

Table 5. Extracted fatigue data for doubling plates improved by weld toe grinding and weld profiling

Reference	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	n	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[45]-2	Grade A	336[b]	BG	10	14	-1	6.07	156.9	62	127.5	102.9	24	141.3	46
[12]-1	S350	350[a]	DG	16	9	0	5.44	228.4	135	157.3	130.9	20	193.6	100
[12]-2	S350	350[a]	BG	16	8	0	6.37	272.9	181	196.1	130.9	50	229.2	136
[40]-1	-	430[b]	BG	20	4	0.1	4.99	195.2	101	143.2	93.1	54	173.8	79
[40]-2	-	430[b]	BG	20	4	0.1	Same stress range			180.1	93.1	93	201.5	108

[a] nominal σ_{YS}

[b] measured σ_{YS}

[c] Grinding method: burr grinding (BG), disc grinding (DG), weld profiling (WP)

Table 6. Extracted fatigue data for transverse load-carrying welds improved by weld toe grinding and weld profiling

Reference	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	n	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[43]-2	A515 Grade A	320[b]	BG	25	4	0	1.69	69.7	-28	122.9	91.1	35	147.6	52
[20]-1	-	272[b]	BG	10	5	0	3.1	129	33	126.8	79.6	59	145.3	50
[20]-2	-	764[b]	BG	10	5	0	2.45	101.4	5	113.8	80.2	42	129.6	34
[38]-1	-	-	BG	38	5	0.1	2.95	118.1	22	119.3	99.3	20	139.3	44
[38]-2	-	-	BG	38	7	0.1	4.65	174.5	80	144.4	95.7	51	165	70

[a] nominal σ_{YS}

[b] measured σ_{YS}

Table 7. Extracted fatigue data for transverse non-load-carrying welds improved by weld toe grinding and weld profiling

Reference and series	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	n	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[33]-3	S355	355[a]	BG	8	3	0.5	3.81	157.1	43	148.6	127.8	16	158.6	44
[33]-4	S355	355[a]	BG	8	12	0.5	2.42	150.6	37	161.8	131.4	23	174.4	59
[33]-5	S355	355[a]	BG	8	11	0.5	3.38	162.8	48	155.6	120.1	31	172.2	57
[33]-6	S235	235[a]	BG	8	8	0.5	1.01	106.9	-3	151.2	117.2	29	158	44
[37]-1	Grade A	-	WP	10	7	0.1	4.49	216.4	97	190.4	111	72	209.7	91
[37]-2	Grade A	-	WP	10	3	0.1	Same stress range			146.4	98.7	48	163.9	49
[48]	S700	794[b]	BG	8	8	0.2	3.48	205.1	86	191.4	128.3	49	216.7	97
[49]	DH36	375[b]	BG	20	5	0.1	1.09	56.7	-48	135.1	74.5	81	152.8	39
[50]	DH36	375[b]	BG	12.7	10	0.1	5.07	150.7	37	129.9	114.5	13	142.3	29
[51]	S355	406[b]	BG	12.5	2	0.1	2.63	152.7	39	158.6	98.4	61	169.9	54
[52]	S275	275[a]	BG	50	5	0	5.77	178.7	62	137.9	91.3	51	157.8	43
[21]-1	S31803	478[b]	BG	10	11	0.1	3.76	245.7	123	225.5	118.3	91	250.7	128

[21]-2	S31803	478[b]	BG	10	8	0.1	5.25	195.3	78	150.5	107.2	40	175.2	59
[21]-3	Austenitic 304L	256[b]	BG	10	3	0.1	10.25	226.6	106	165	129.6	27	184.6	68
[14]-1	Grade 43A	260[b]	DG	12.5	5	-1	4.41	150.2	37	126.8	106.9	19	144.7	32
[14]-2	Grade 43A	260[b]	DG	12.5	4	0.5	4.57	123.8	13	107.5	94.9	13	119.1	8
[36]-3	BS15	278[b]	WP	12.7	4	-1	2.54	93.3	-15	98.8	63.9	55	107.1	-3
[15]-1	Grade 43A	245[b]	WP	12.5	5	0	6.18	198.7	81	166.4	105.3	58	181.4	65
[15]-2	Grade 43A	245[b]	BG	12.5	6	0	3.45	143.6	31	136.7	105.3	30	150.2	37
[15]-3	Grade 43A	245[b]	DG	12.5	9	0	5.4	153.5	40	121.7	105.3	16	138.7	26
[15]-4	Superiso 70	685[b]	DG	12.5	3	0	3.88	150.1	36	120.1	91.7	31	153.6	40
[15]-5	Superiso 70	685[b]	BG	12.5	3	0	3.91	177.8	62	142.8	91.7	56	180.9	64
[15]-6	Superiso 70	685[b]	WP	12.5	3	0	5.16	260.1	136	203.8	91.7	122	235.8	114
[53]	SUS316L	341[b]	BG	20	7	0.1	3.08	110.3	14	109.2	104.5	4	120.6	24
[22]-1	S355	450[b]	WP	10	15	0	3.33	202.3	84	190.3	110.4	72	222.2	102
[22]-2	F51	608[b]	WP	10	17	0	4.22	260.3	137	223.9	120.2	86	255.1	132

[22]-3	S690	735[b]	WP	10	21	0	5.29	372.2	238	273.2	122.3	123	326.6	197
[35]	S900	972[b]	WP	10	11	0	2.02	127.4	16	192.9	80.9	138	239.1	117
[42]-1	A36	250[b]	BG	20	4	0	1.11	25.6	-77	196.1	232.2	-16	218.6	99
[42]-2	A36	250[b]	BG	20	4	0	1.86	50.4	-54	120.1	232.2	-48	171.6	56
[54]	Low carbon micro alloyed	380[b]	BG	30	6	0.1	5.69	239.2	117	190	116.2	64	204.3	86
[55]	-	420[b]	BG	20	5	0	4.75	232.5	111	181	115.8	56	214.4	95
[56]	S700	700[a]	BG	6	11	0.1	5.03	353.5	221	223.9	168.9	33	297.1	170

[a] nominal σ_{YS}

[b] measured σ_{YS}

[c] Grinding method: burr grinding (BG), disc grinding (DG), weld profiling (WP)

Table 8. Extracted fatigue data for I - section with cope hole improved by weld toe grinding and weld profiling

Reference and series	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	n	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[41]-1	-	-	BG	19	2	0.01	Same stress range			76.9	62.7	23	81.6	20

[41]-2	-	-	BG	19	5	0.01	Same stress range	89	65.3	36	97.5	43

[a] nominal σ_{YS}

[b] measured σ_{YS}

[c] Grinding method: burr grinding (BG), disc grinding (DG), weld profiling (WP)

Table 9. Extracted fatigue data for longitudinal gusset plates improved by weld toe grinding and weld profiling

Reference and series	Steel type	σ_{YS} (MPa)	Method[c]	Plate thickness (mm)	*n*	Stress ratio	Best-fit slope m_1	$\Delta\sigma_{50\%}$ by best-fit slope (MPa)	%imp.at m_1=free to IIW [8]	$\Delta\sigma_{50\%}$ by m_1=3 (MPa)	$\Delta\sigma_{50\%}$ by m_1=3 for as-welded (MPa)	%imp.at m_1=3 to as-welded]	$\Delta\sigma_{50\%}$ by m_1=4 (MPa)	%imp.at m_1=4 to IIW [8]
[45]-2	Grade A	336[b]	BG	10	10	-1	3.25	114.4	68	111.5	73.9	51	121.3	78
[13]-1	S235	235[a]	DG	10	1	>0	Lack of specimens			69.5	46.4	50	76.1	12
[13]-2	S235	235[a]	DG	18	1	>0	Lack of specimens			118.1	53.9	119	122.3	80
[13]-3	S420	420[a]	DG	10	2	>0	Lack of specimens			58.6	48.9	20	64.9	-5

[a] nominal σ_{YS}

[b] measured σ_{YS}

[c] Grinding method: burr grinding (BG), disc grinding (DG), weld profiling (WP)