10th International Symposium on Practical Design of Ships and Other Floating Structures
Houston, Texas, United States of America

Improving Fatigue Life for Aluminum Cruciform Joints by Weld Toe Grinding

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Abstract

Fatigue improvement by weld toe grinding for aluminum welded joints has been investigated in this paper. Fatigue tests were performed for a number of as-welded and toe-ground non-load carrying cruciform joints. Finite element analyses were carried out to further study the influence of the variation of the main weld parameters such as the weld toe angle, weld toe radius and weld leg length on the stress concentration factors (SCF). Fatigue test results were presented by both a nominal stress based approach and a more refined structural stress based approach for the as-welded joints. Test results show that the weld toe grinding doubles the fatigue life compared to the as-welded joints. It is found that an optimal grinding depth is required to obtain a reasonable fatigue improvement factor.

Keywords

Fatigue; Aluminum; Weld; Toe grinding; Stress concentration.

Introduction

The fatigue life of components is reduced when parts are welded due the presence of weld defects and stress concentrations. Sometimes, often late in the design process or during operation, it is necessary to utilize an increased fatigue life of a particular joint detail by an improvement method. Significant increase in the fatigue life of welded joints has been reported by various kinds of local treatment methods in the steel industry.

Aluminum has been widely used in many areas such as high-speed light crafts (HSLC) in recent years. As the size of vessels becomes larger, fatigue has become a critical design criterion. The possibility of improving the fatigue life of welded joints in fatigue-prone regions is therefore desirable. Weld toe grinding is one of the successful methods in practice for aluminum welded joints (Haagensen et al. 1998; Haagensen and Maddox 2004).

Weld toe grinding technique is a widely accepted fatigue life improvement method due to the reliability and ease by which it can be performed. The main purpose of weld toe grinding is to reintroduce a fatigue initiation period by removing possible defects at the weld toe. The general view today is that a crack initiation period in as-welded steel joints is insignificant due to the existing weld defects (i.e., slag intrusions at the fusion line), which allow the crack growth to initiate very early in the fatigue life. However, the same is not absolutely agreed on for aluminum welded structures, where studies have indicated that the fatigue initiation period may account for a larger portion of the total fatigue life. For this reason, it is argued that the crack initiation period becomes more dominant for aluminum welds than for steel welds. This implies that the weld toe grinding method for aluminum weldments could have a lesser effect on the improvement of fatigue life compared to that of steel joints. In addition, weld toe grinding changes the local weld toe geometry, which alters the local stress concentration. It is therefore an open question whether the weld profile of aluminum and steel welds is comparable so that the modification of the weld notch by the grinding process has a comparable effect on the fatigue life. For example, Tveiten (1999) reported that little improvement was achieved by grinding the weld toe of an aluminum flat bar with a welded bracket while Haagensen and Maddox (2004) pointed out in a summary report that significant improvement could be achieved by using one or a combination of several improvement methods.

A test program was therefore established to investigate the effect of the toe grinding on the fatigue improvement of a non-load carrying cruciform welded joints. Finite element analyses were conducted to calculate different SCFs as well as study the influence of variation of weld parameters on the fatigue behavior of the joints.

Joints Specifications

Specimens and welds

A total umber of thirty-one (31) non-load carrying cruciform welded joints were fabricated, among which the weld toes of thirteen (13) specimens were post-treated by burr grinding while the rest were left in the as-welded condition. The specimens were made from a parent plate 206 mm wide and 12 mm thick. Fig. 1 shows a picture of the tested specimen as fabricated. Fig. 2(a) schematically illustrates the geometrical properties of the specimens. Possible fatigue cracking sites are marked by $C_1 - C_4$. Fig. 2(b) and Fig.2(c) show typical weld toe profiles of the as-welded and toe-ground joints. Some key weld parameters such as the weld toe angle θ, weld leg length λ and weld toe radius ρ are also shown in the same figure. These parameters have been reported to have great influence on the fatigue behavior of welded joints (Engesvik and Moan, 1983; Ye and Moan, 2001)

Fig. 1: Picture of the test specimen

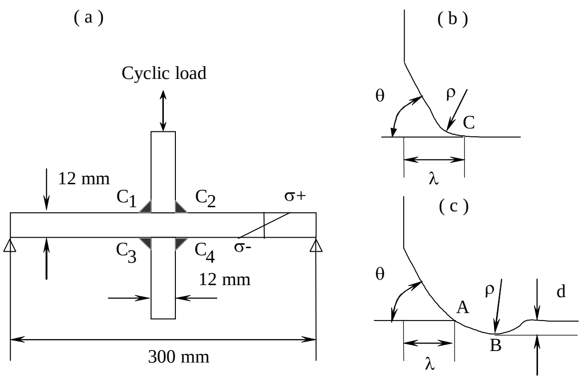

Fig. 2: (a) Geometrical properties; (b) As-welded toe profile; (c) Weld toe profile after grinding

These weld parameters were measured and summarized in Table 1. It is shown in the table that the mean weld toe radius of the toe-ground joints (3.2 mm) is nearly two and half times that of as-welded (1.3 mm). The weld toe angle is increased by grinding; however, the weld leg length is reduced by the material removal at the weld toe. The mean grinding depth is about 0.8 mm into the thickness and this depth is the least requirement in the IIW documentation to assure satisfactory fatigue life improvement (Haagensen and Maddox, 2004).

Table 1: Measured main weld parameters, unit: ρ (mm), θ (deg.), λ (mm), d (mm), STDV=standard deviation

Parameters		Min.	Max.	Mean	STDV
ρ	As-welded	0.1	4.2	1.3	0.90
	Toe-ground	2.5	4.8	3.2	0.38
θ	As-welded	17.0	90.0	52.1	14.40
	Toe-ground	28.0	100.0	72.9	12.92
λ	As-welded	7.2	11.8	9.0	1.05
	Toe-ground	5.9	9.5	7.5	0.81
d	Toe-ground	0.2	1.6	0.8	0.28

Stress analysis

Stress at the weld toe is usually raised by the structural geometry as well as by the weld itself. The structural and notch stresses are correspondingly defined to capture stress raising factors relating to the structural and weld geometry. As a consequence, different fatigue assessment methods have been developed depending on the stress range used in designing SN curves. Fig. 3 schematically illustrates how these stresses are defined for a general joint detail.

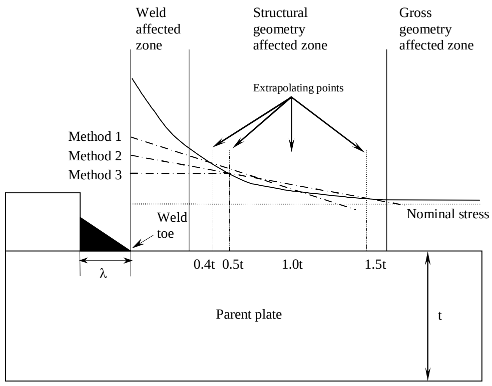

Fig. 3: Stress components near the weld toe

Nominal stress

The failure of the non-load carrying fillet welded cruciform joints occurred at the weld toe. The nominal stress range at the weld toe can be obtained either by simply using elastic beam theory or coarse finite element analysis. For complex joint details, difficulty may arise in calculating the nominal stress and care should be taken to use the calculated nominal stress in the fatigue analysis (Niemi et al., 2006).

For the three point bending load case as shown in Fig. 2(a) in this study, the nominal stress was simply obtained by a beam solution under bending, i.e., $\sigma = My/I$, where M, I, and y represent the bending moment, inertia moment, and the distance of the interested point to the neutral axis of the section, respectively. The difference between the analytical solution and the measured value by strain gauge was less than 2% for both the as-welded and toe-ground joints. The nominal stress applied to the test specimen was 37.7 MPa. It should be noted that the thickness reduction effect of the toe-ground joint was not taken into account while calculating the nominal stress, rather it was reflected in the SCFs.

Structural stress

The nominal stress only reflects the response of the joint to global forces. A traditional fatigue assessment uses this stress as a design stress by including all the other factors, such as the effect of the structural geometry and the weld geometry implicitly in the design of the SN curves. Some more refined fatigue assessment methods have been developed recently based on a deeper understanding of the influence of the structural geometry and weld on the stress at the fatigue cracking area, such as the weld toe. The structural stress range approach has recently been one of the most interesting methods by which structural stress is used to capture the stress raising factor due to structural geometry. However, the contribution of the weld to stress concentration is excluded by performing an extrapolation to the weld toe within the structural geometry affected zone, as shown in Fig. 3. Various methods have been proposed, however, a universal method that can be applied to all kinds of joint types is still needed. The structural SCF can be obtained either by strain gauge measurements or finite element analysis; the latter method was used in this study to calculate the stress concentration. A full model was built in the analysis. However, only a quarter portion of the full finite element models, as well as the sub-models, are shown in Fig. 4 for the sake of symmetry.

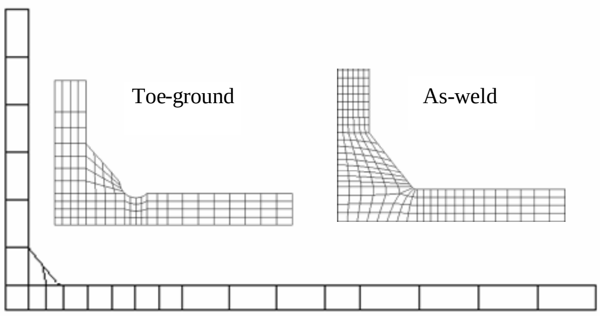

Fig. 4: Finite element model

The structural stress range approach is designed so that the stress raising effects due to the weld can be excluded from the structural SCF. It has been agreed based on experience that the influence of the weld on the stress concentration at the weld toe is confined to a short distance of 0.3-0.5t, i.e., 3.6-6 mm for the specimens studied herein. Three representative structural SCF calculation methods were investigated in this study for the as-welded specimens. Method 1 is a linear extrapolation method in which the stresses at 0.4t and 1.0t were used to perform the extrapolation. Niemi (1995) reported this method after investigating a gusset attachment joint and this is used as a standard method by IIW(2003 ,Hobbacher) . Method 2 is another linear extrapolation method used by DNV (1995, 2000) in which the points 0.5t and 1.5t were used. No extrapolation was required for Method 3, rather the stress value at 0.5t was taken as the structural stress. This method is used by Lloyd's Register. It is seen that in the aforementioned methods, the distance of the leading point is either 0.4t or 0.5t. However, this distance is dependent on the joint type, as reported by Tveiten and Moan (2000).

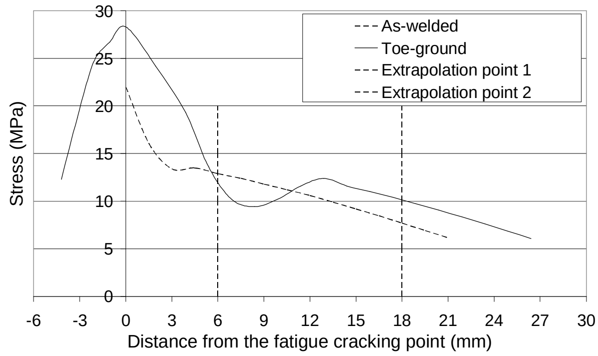

Fig. 5: Stress gradient near the cracking point for the as-welded and toe-ground joints

Fig. 5 shows typical stress distributions near a normal weld toe for the as-welded joint and a "new" toe after grinding based on mean weld parameters in Table 1. It should be noted that different origins were used for the illustration in order to compare the SCFs at the fatigue cracking point. For the as-welded joints, the origin point refers to C in Fig. 2(b), however, the origin refers to B for the toe ground joints, that is, the deepest point B as shown in Fig. 2(c).

The structural stress range approach is based on an assumption and observation that there exists a consistent stress gradient near the weld toe, as shown in Fig. 3. The stress gradient for the as-welded joint, as shown in Fig. 4, reveals the same pattern, therefore it was reasonable to apply the structural stress range approach. However, as shown in Fig. 5, the toe grinding caused redistribution of the stress adjacent to the cracking point B in Fig. 2(c). A consistently increasing stress gradient no longer appeared. This made the application of the structural stress range approach to the toe-ground joint more difficult or even impossible. For instance, a structural SCF of 1.02 was obtained if the stresses at 0.5t and 1.5t were used as the basis for a linear extrapolation. This value was unreasonably small compared to the as-welded cases, which is also in contrast to experience. For instance, a recent IIW documentation pointed out that grinding may introduce further stress concentration at the weld toeHaagensen) (2004 ,and Maddox. Therefore, the structural SCF appears unable to capture the real stress concentration at the fatigue cracking point.

Very little information regarding the influence of weld parameters on structural SCFs is available in the open literature. Moreover, no public literature exists related to the effect of weld parameters for a toe-ground joint when the structural stress range approach is used to present the fatigue test results.

The weld toe radius, weld leg length, and weld toe angle were modeled in the FEM. In each case, the minimum, mean, and maximum values of each of the parameters were chosen to investigate the influence of that parameter, while the mean values of the other parameters were utilized in the model. The results are shown in Tables 2, 3, and 4, respectively.

Table 2: Influence of toe radius on structural SCF

Extrapolation Method	As-welded (λ=9.0, θ=52.1)		
	ρ=0.1	ρ=1.3	ρ=4.2
0.4t/1.0t	1.09	1.09	1.09
0.5t/1.5t	1.08	1.08	1.08
0.5t	1.07	1.07	1.07

Table 3: Influence of leg length radius on structural SCF

Extrapolation Method	As-welded (ρ=1.3, θ=52.1)		
	λ=7.2	λ=9.0	λ=11.8
0.4t/1.0t	1.09	1.09	1.09
0.5t/1.5t	1.07	1.08	1.08
0.5t	1.06	1.07	1.06

Table 4: Influence of toe angle on structural SCF

Extrapolation Method	As-welded (ρ=1.3, λ=9.0)		
	θ=17.0	θ=52.1	θ=90.0
0.4t/1.0t	1.09	1.09	1.09
0.5t/1.5t	1.08	1.08	1.08
0.5t	1.06	1.07	1.06

It is shown in Tables 2, 3, and 4 that, in general, the closer the distance of the leading point in the extrapolation methods to the weld toe, the higher the structural SCF. It can be easily understood that extrapolation points at a short distance from the weld toe may bring the notch effect into the extrapolation procedure and result in a higher stress value at the leading point. The distance necessary to avoid this from occurring has been further clarified by Tveiten and Moan (2000). Extrapolation points must fall within the structural geometry affected zone (Fig. 3) to obtain a reasonable structural SCF. A procedure to calibrate this structural geometry affected zone and the notch affected zone has also been proposed.

The change of weld parameters had little influence on the structural SCFs by all the methods used for the as-welded joint, and the use of different methods did not cause a significant change in the structural SCFs. Therefore, the effect of the weld parameters has been reasonably excluded in the calculation of the structural SCFs.

Notch stress concentration

The notch stress concentration factor included not only the structural geometry related stress raising factors, but also the stress raising factors due to the weld. This factor was assessed by direct finite element calculation by means of the sub-modeling technique (Fig. 4). The notch refers to the weld toe for the as-welded joints (point C in Fig. 2(b)) and the deepest point in the ground profile (point B in Fig. 2(c)). It should be pointed out that no reduction of thickness for the ground joints was applied in the calculation of the nominal stress because it had already been captured in the stresses obtained by the finite element analysis. The results are summarized in Tables 5, 6, and 7. 20-nodes solid elements were used with an element size of 1/16t for weld toe radius larger than 3 mm. However, smaller elements were used for small weld toe radius. The figure below shows the mesh detail for the weld toe radius ρ=0.1 mm. The element size at the weld toe is approximately 0.02 mm.

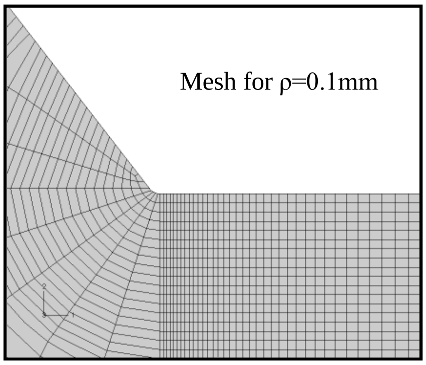

Fig. 6: Finite element model for 0.1 mm weld toe radius

Table 5: Influence of weld toe radius on the notch SCF

As-welded (λ=9.0, θ=52.1)			Toe-ground (λ=9.0, θ=72.9, d=0.8)		
ρ=0.1	ρ=1.3	ρ=4.2	ρ=2.5	ρ=3.2	ρ=4.8
3.78	1.83	1.32	2.01	1.91	1.82

Table 6: Influence of weld leg length on the notch SCF

As-welded (ρ=1.3, θ=52.1)			Toe-ground (ρ=3.2, θ=72.9, d=0.8)		
λ=7.2	λ=9	λ=11.8	λ=5.9	λ=7.5	λ=9.5
1.88	1.83	1.80	1.91	1.91	1.91

Table 7: Influence of weld toe angle on the notch SCF

As-welded (ρ=1.3, λ=9.0)			Toe-ground (ρ=3.2, λ=7.5, d=0.8)		
θ=17	θ=52.1	θ=90	θ=28	θ=72.9	θ=100
1.62	1.83	1.79	1.93	1.91	1.93

It was found, in principle, that notch SCF for the toe-ground joint was greater than those of the as-welded joint when the weld toe radius is larger than 1 mm.

The notch SCF can also be roughly estimated according to the equation $K = 1 + 0.21(\tan\theta)^{1/6}(t/\rho)^{1/2}$ for cruciform joints under bending, in which t represents the parent plate thickness while θ and ρ have the same meaning as indicated in Fig. 2(b, c), as suggested by Yung and Lawrence (1985). For instance, the notch SCF will be 3.38, 1.67 and 1.37 for weld toe radius ρ=0.1, 1.3 and 4.2 mm, respectively (λ=9.0 mm, θ=52.1 degree). The FE results are close to the values obtained by the empirical equation.

Figs. 2 and 4 showed that a "notch" was introduced by grinding that caused more severe stress concentration compared to the as-welded joint. This is revealed in Fig. 5 as well. Moreover, it was also found that the change of weld parameters did not have as significant an influence on the notch SCFs as for the as-welded joint.

Table 5 shows that the increase of the weld toe radius for the toe-ground joint caused a reduction of the notch SCFs for the same reason as the influence of the weld toe radius on the structural SCFs. This also confirms the IIW requirements that the new weld toe radius should not be too small; otherwise a sharp discontinuity may appear accompanied by a high SCF (Haagensen and Maddox, 2004).

The change of the other two parameters, i.e. the weld leg length and weld toe angle had little influence on the notch SCFs for the toe-ground joint, as shown in Tables 6 and 7.

The effect of grinding depth on the notch SCF is further studied by keeping the weld leg length λ=9.0 mm, weld toe angle θ=72.9 degrees and weld toe radius ρ=3.2 mm. Fig. 6 accordingly shows that the notch SCF increases linearly proportional to the increase of the grinding depth.

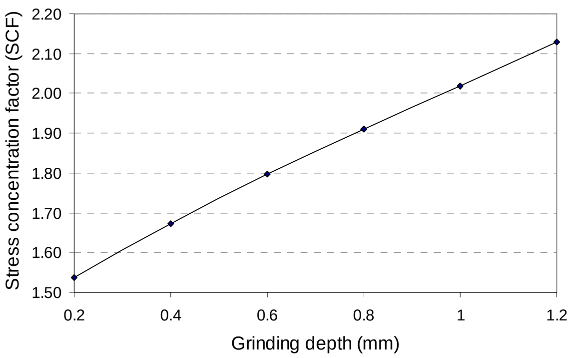

Fig. 7: Influence of grinding depth on notch SCF

Some material including the parent material and weld will be removed by performing the toe grinding. The purpose of the grinding is to take away the small defects introduced by the welding procedure so that the fatigue performance can be improved. However, the removal of the parent material cause a reduction of the thickness of the parent material so as to raise the stress level as it is shown in Fig. 6. Therefore, there exists an optimal grinding depth by which the defects are removed while the stress level is not raised unreasonably high.

Fatigue tests

Test program

Fig. 2(a) is an illustration of the test set-up. The specimens were mounted in a three-point bending test rig under a frequency of 12 Hz. In order to eliminate the compressive residual stress introduced by the welding procedure, a stress ratio of 0.44 was applied to ensure that only tensile stress may occur at C_1 and C_2. All tested joints were cracked from either of these two locations. The fatigue life as number of cycles was recorded when the specimen was fully cracked through the thickness of the plate.

Fatigue behavior of a structural component can be expressed by the equation, $\log N = \log A - m \log S$, in which N represents the fatigue life corresponding to a given stress range S, A is a constant depending on the joint features and load parameters, and m is a statistically obtained parameter. The fatigue strength is usually expressed in terms of the number of cycles at a given level of stress range and the fatigue life is referred to as the number of cycles at a specified stress range. A detail class number assigned to a particular joint type in a design code represents the stress range at the characteristic fatigue life of two million cycles.

Test data

The fatigue life in terms of the number of cycles was recorded when a full thickness crack developed. Eighteen (18) as-welded and thirteen (13) toe-ground specimens were tested and the test data are summarized in Table 8.

Table 8: Recorded fatigue life

No.	Number of cycles to failure	
	As-welded	Toe-Ground
1	930806	2423027
2	1042485	2830036
3	916920	1846428
4	1057019	1421794
5	1774631	2694688
6	1050289	3268021
7	923797	3609481
8	1348637	2765445
9	1051069	3108286
10	1150013	2520398
11	866263	1963157
12	1099022	2262469
13	1041857	2827378
14	1252033	-
15	1063280	-
16	789209	-
17	1202075	-
18	1582690	-
Mean	1119005	2580047
Stdv of logN	0.09	0.11

Fatigue analysis based on nominal stress

The detail classes for the investigated cruciform joints from different codes based on nominal stress are differed in different classifications or standards. The lowest detail class for a non-load carrying cruciform joint was 28, given by Eurocode 9 (1998) and the IIW (Hobbacher, 2003), however, a clear indication of as-welded condition is only specified by the IIW. The highest class, 36, is given by both the IIW and

Aluminum Association(1994) and toe-grinding is clearly indicated by the IIW. It should noted that the IIW is the only code in which the as-welded and toe-ground joints are clearly classified into two detail classes, 28 for as-welded joints, and 36 for ground joints; as a consequence, there is an improvement of approximately 29% in terms of stress range at a given number of cycles. In other words, by applying the above SN curve equation, the fatigue life in terms of cycles at a given stress range level for a toe-ground joint is about twice that of the as-welded joint. Therefore, the IIW SN curves, 28 and 36, were chosen in this study to compare the test data for the as-welded and toe-ground joints in Figs. 6 and 7. The nominal stress applied to the test specimen was 37.7 MPa as can be seen in those two figures.

It seems that that the tested data agreed quite well with the IIW SN curves. The fatigue strength of the as-welded and toe-ground joints was approximately 2.4% and 1.3% below the SN curves, 28 and 36, respectively. The grinding improved the fatigue strength by about 30% in terms of stress range, which was nearly equivalent to a doubling in fatigue life improvement in terms of the number of cycles. This occurred despite the fact that the notch SCF of the toe-ground joint was about 30% greater than the as-welded joint. The contribution of grinding in improving fatigue life is therefore primarily due to the removal of the defects. The grinding depth is therefore the decisive parameter in determining the effect of grinding. This is also reflected by the test data in Figs. 8 and 9 where a rather low fatigue life was recorded and the corresponding grinding depth was found to be the smallest one, i.e. 0.2 mm.

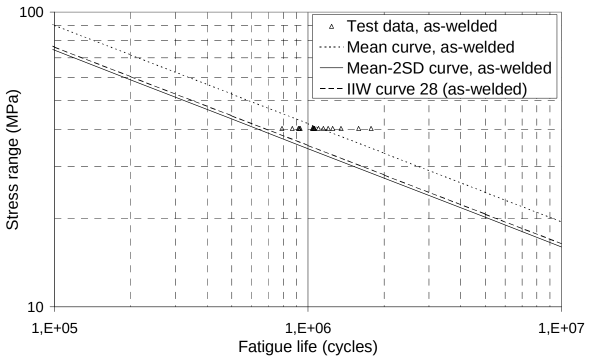

Fig. 8: Test data of as-welded specimens compared with IIW SN curve 28 based on nominal stress

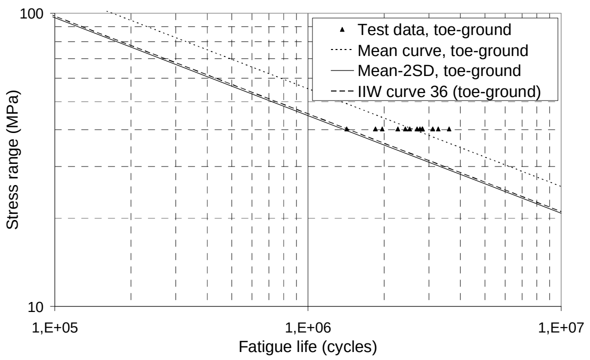

Fig. 9: Test results of toe-ground specimens compared with IIW SN curve 36 based on nominal stress

It should be mentioned that, as indicated in Fig. 2(c), the original weld toe disappeared after grinding and the fatigue cracking was found to be located at point B, which is the deepest point in the ground profile. The effect of the thickness reduction on the determination of the nominal stress was not taken into account when presenting the data against the nominal SN curves. This effect should have been embedded in the specified SN curves for the toe-ground joints. The grinding effect will tend to be more significantly conservative if the nominal stress is corrected by the thickness reduction, i.e., a higher nominal stress was used in the presentation of the test data.

It should also be noted that the standard deviations of logN for the as-welded and toe-ground joints were 0.09 and 0.11, which indicates that the grinding did not reduce the scatter of the test data. Instead, the scatter was slightly expanded. This was probably due to the scatter of the grinding depth, which was from 0.2-1.6 mm, as shown in Table 1. An insufficient grinding depth may cancel off the fatigue life improvement effect compared to those sufficiently ground specimens. As can be seen in Table 8, the lowest fatigue life (cycles to failure 1421794) of toe-ground specimen did not improve significantly compared to the mean fatigue life of the as-welded specimens (cycles to failure=1119005).

Fatigue analysis based on structural stress

Fatigue assessment based on structural stress range has been used in the design of steel tubular joints since the 1970s (HSE, 1996). The structural stress, $\sigma_{structural}=K_g\times\sigma_{nominal}$, is taken as the design stress, where K_g represents the structural SCF. However, the derivation of a universal structural SCF calculation method and consistent design SN curves are still needed for both steel and aluminum plate structures. Moreover, rather limited data for aluminum structures are available up to now.

Eurocode 9 (1998) issued six structural stress design SN curves. The choice of SN curve is dependent on the thickness of the stressed member of the structure, for instance, detail class 35 is proposed for structures with the thickness of a stressed member between 10 and 15 mm. However, no corresponding structural stress calculation process is specified in the code. A detail class of 40 has been accepted, to some extent, as a suitable design SN curve for butt and fillet welded aluminum joints of relatively thin plates (up to 6 mm) failing from the weld toe location ,Partanen and Niemi) (2001 ,Maddox ;1999. A thickness penalty factor was suggested by Niemi(1995) to further apply the detail class 40 to the structures with a thickness exceeding 6 mm. In the case of a 12 mm thickness, a modified detail class will be approximately 35. Tveiten et al. (2002) commented that the use of the penalty factor should be further investigated since the reduction in design fatigue strength would be unacceptably large once the large thickness appears. More description on the choice of a suitable structural stress design SN curve was summarized recently by Tveiten et al. (2002).

The test data of the as-welded specimens are presented against the Eurocode 9 SN curve 35 in Fig. 9. The structural SCFs correspond to the mean weld parameters. The as-welded joint falls quite below the SN curve 35 because the structural SCFs of the as-welded joint is low as shown in Table 2. It should be remembered that the application of the structural stress range approach to the toe-ground joint can bring uncertainties because there is no consistent stress gradient towards the fatigue cracking point.

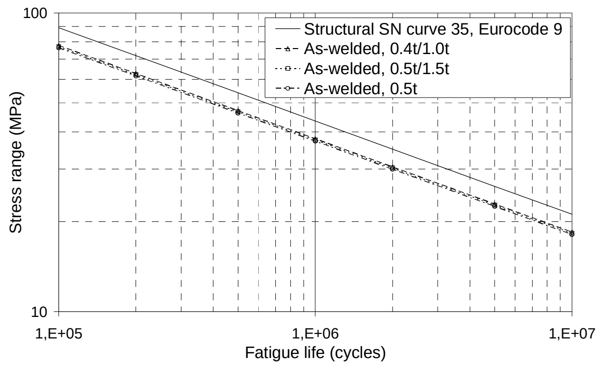

Fig. 10: Test results compared with Eurocode 9 SN curve 35 based on structural stress

Conclusions

The following conclusions can be drawn based on the stress analysis and fatigue tests, which corresponds very well to the IIW recommendation (Haagensen and Maddox, 2004): 1) the weld toe grinding significantly improved the fatigue life of the cruciform joint based on a nominal stress range approach and 2) a near doubling of the fatigue life was observed in terms of the number of cycles for the toe-ground joint.

The test data agreed quite well with the IIW nominal SN curve 28 for the as-welded joints and 36 for the toe ground joints.

The weld parameters had little influence on the structural SCFs for the as-welded joint.

The Eurocode structural SN curve, 35, was found to be non-conservative for the as-welded joints. The structural stress approach appears to be not applicable to toe-ground joints due to the stress redistribution caused by the new weld profile after grinding.

The notch SCFs based on FE analysis of the as-welded joints were generally below those of the toe-ground joints when the weld toe radius is larger than 1 mm, while the latter one had better fatigue performance than the former one. Therefore, the defects introduced by the welding procedure played a decisive role in determining the fatigue behavior of the welded joints. The removal of those defects by grinding significantly improved the fatigue life of the joints.

Larger weld toe radius caused a reduction in the notch SCFs for the toe-ground joints, while other parameters did not affect the value appreciably. It is also important to point out that the grinding depth should exceed a limit, for instance 0.8 mm, for most joints so that the defects can be removed with certainty and to achieve a reasonable fatigue life improvement. On the other hand, excessive grinding reduced the effective plate thickness and, hence, represents a stress raiser.

Acknowledgement

The authors appreciate the financial support of the DASS project that made the experimental study possible. Thanks are also extended to the engineers in the structural laboratory at the Marine Technology Center of NTNU, who contributed to the fatigue testing.

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