

Experimental Investigation of the Effect of Different Static Mechanical Properties and Inclined Welding on the Fatigue Strength of Welded Aluminum Details [†]

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Abstract: Civil engineering structures are often loaded cyclically in addition to static loading. For the design of cyclic-loaded aluminum structures, EN 1999-1-3 provides several notch cases for a verification based on the nominal stress concept. These notch cases do not distinguish between the different available alloys exhibiting varying characteristics, such as static mechanical properties in the heat-affected zone. Furthermore, for welded details only longitudinal or transverse welding is covered without the possibility for considering inclined welding with multiaxial stress states. However, load-controlled fatigue testing of two different alloys and specimens out of base material, specimens with 45° welding and transverse welding, respectively, have shown the clear influence of alloy and weld angle on the fatigue strength of welded aluminum details. In this paper, the respective experimental and numerical results of two alloys, EN AW-6082 T6 and EN AW-5754 O/H111, and two weld angles, 45° and 90°, are presented and discussed.

Keywords: fatigue; aluminum alloys; heat-affected zone; inclined welding; multiaxial stress state at weld; fatigue loading; fatigue design



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1. Introduction

In civil engineering, the design of cyclic-loaded aluminum structures is usually based on the nominal stress concept. Respective notch classes are available in the European Standard EN 1999-1-3 (EC 9, Part 1–3) [1] and have been derived from extensive experimental test series [2–4]. In the case of welded joints, notch classes for butt welds and fillet welds are included. Indeed, the welding of aluminum results in a heat-affected zone (HAZ) with reduced strength values for most aluminum alloys. Static mechanical properties for the base material and HAZ are provided in EN 1999-1-1 [5] for the general design of aluminum structures. Yet, this effect is not considered generally in the fatigue design according to EN 1999-1-3 [1]. Even if the HAZ affects the static mechanical properties significantly, no difference between the alloys is made in the notch cases. In fact, ref. [6] has already shown that the alloy influences the fatigue behavior of aluminum structures.

Furthermore, the notch cases only cover longitudinal or transversal welding but no inclined welds with multiaxial stress states (a combination of normal and shear stresses). Harre [7] performed the testing of three different alloys and specimens with transverse welding and welding at angles of 30°, 45° and 60° (butt joints) and found a better fatigue behavior of inclined welding compared to transverse welding. However, the base material was not tested and the focus was not on the difference between the alloys with respect to fatigue performance. These initial results are to be validated and extended as well as complemented by numerical considerations.

In this study, various strain- and load-controlled fatigue testing of butt joints with different welding directions was conducted. Thus, specimens with transversal and 45° welds with respect to the loading direction were investigated. The welding directions

and specimens' geometries for load-controlled fatigue testing are presented in Section 2.2, where one welded specimen of each type is also depicted. For comparison, unwelded specimens were also included in the experimental program. Preceding tensile testing served as the basis for the characterization of the static mechanical material properties. As alloys, EN AW-6082 T6 with obvious HAZ reductions and EN AW-5754 O/H111 with minimum HAZ influence were chosen. Based on the results, a detailed analysis of the fatigue strength of the structural details with inclined welding was carried out. In addition, the influence of static mechanical material properties, especially with respect to the varying exhibition of HAZ, on the fatigue performance of aluminum structures was examined. First numerical results are provided as an outlook for ongoing investigations using the finite element method (FEM).

2. Experimental Investigation

Several experimental investigations were undertaken. Static mechanical properties were determined via tensile testing. For characterizing the cyclic plastic material behavior, strain-controlled fatigue testing was conducted. Furthermore, extensive load-controlled fatigue testing was carried out to investigate the fatigue strength in detail. Results of the latter serve as the main experimental database for this paper. All respective results are presented in the following sections for each type of testing. For the results of strain-controlled fatigue testing and their discussion, though, the reader is referred to [8]. Generally, alloys EN AW-5754 O/H111 and EN AW-6082 T6 were chosen as the alloys to be investigated. The aim was to select two alloys which show different static mechanical properties and especially which behave differently if welded. EN AW-6082 T6 reaches comparatively high static strengths, but significant strength reduction is present for welded details in the heat-affected zone (HAZ). In contrast, alloy EN AW-5754 O/H111 can be characterized by lower static strengths. However, the latter does not exhibit a heat-affected zone when welded. Therefore, no strength reduction for details welded out of EN AW-5754 O/H111 is hypothesized. For examination of base material as well as welded material, specimens solely out of base material and welded specimens were investigated. In addition to the influence of different static mechanical properties and the varying effects of welding, the multiaxial stress states at welds were investigated. For this purpose, specimens with transversal welding and inclined welding (45° with respect to the loading direction) were tested. MIG welding with AlSi5 as welding wire was used. In this section, the testing itself is described while the results are presented and discussed in the subsequent section.

2.1. Tensile Testing

Tensile testing for the specimens out of base material was conducted according to EN ISO 6892-1 [9]. For the butt joints, EN ISO 4136 [10] was consulted. The strains were measured via extensometer using a reference length of $l_0 = 35$ mm. The specimen geometries are shown in Figure 1. For each specimen type (alloy and base material/welding direction) five tests were conducted using a Zwick Z100 testing machine.

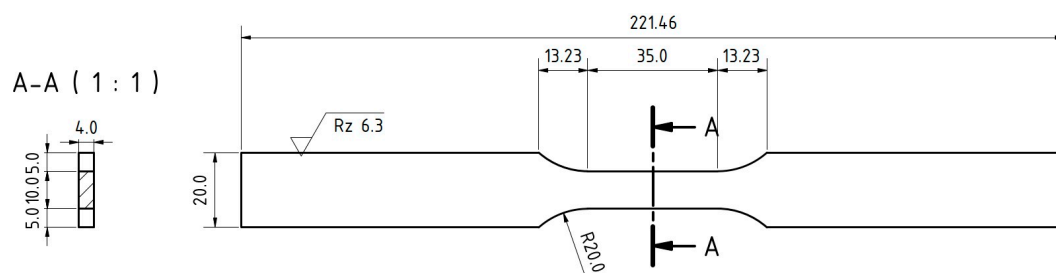


Figure 1. Specimen geometries in mm for tensile testing according to EN ISO 6892-1 [9].

2.2. Load-Controlled Fatigue Testing

Load-controlled fatigue testing and its respective evaluation were conducted according to DIN 50100 [11]. The specimens' geometry was defined according to Figure 2. All load-controlled fatigue tests were conducted at a stress ratio of $R = 0.1$ with a frequency of 12 Hz. For fatigue testing, a servo-hydraulic testing machine Instron 8032 with control 8800 was used. Fatigue-tested specimens without rupture were categorized as the latter beginning from 2.8 million cycles. These were not included in the statistical evaluation. In DIN 50100 [11], a number of cycles of 10^7 is suggested as the limit for fatigue-tested specimens without rupture for aluminum. This study focuses on the finite-life fatigue strength and therefore a smaller limiting number of cycles was chosen. Solely logarithmic normal distribution was applied for evaluation according to DIN 50100 [11].

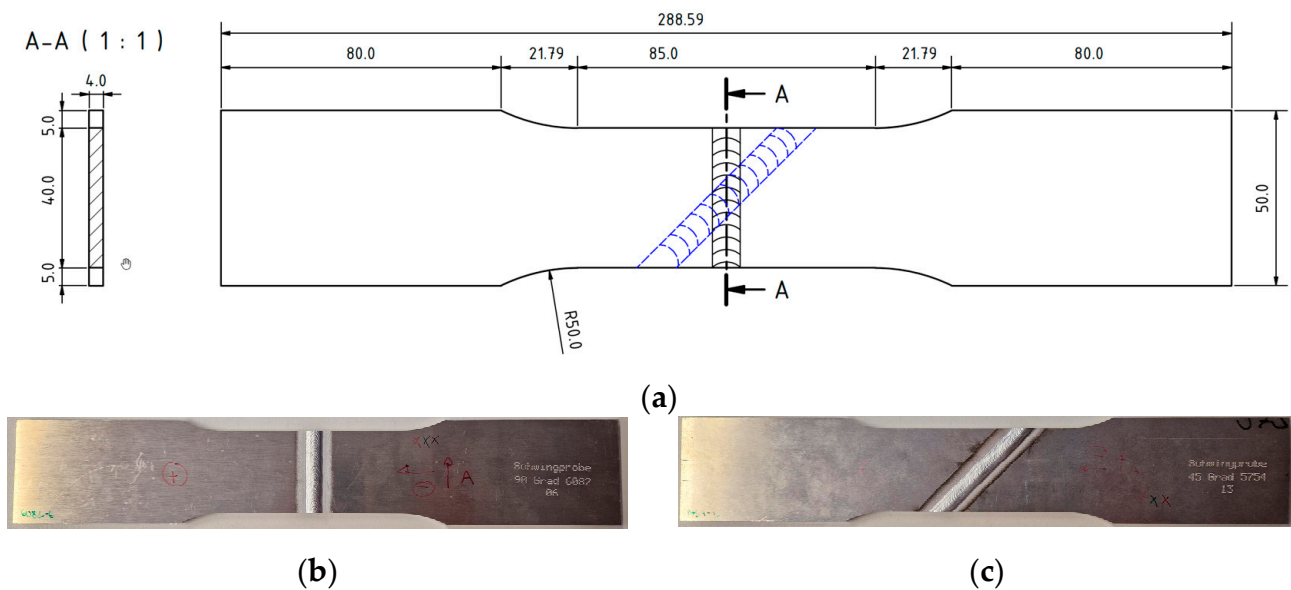


Figure 2. Specimen geometries in mm (a) for load-controlled fatigue testing according to DIN 50100 [11] for base material specimens, transversal welding (black) and 45° welding (blue); and photos of specimen with transversal welding (b) and specimen with 45° weld (c).

3. Results and Discussion

3.1. Tensile Testing

Stress–strain curves for the two alloys and different specimen types are presented in Figure 3. A statistical evaluation as well as a comparison with EN 1999-1-1 [5] are given in Table 1. Characteristic strengths with 95% reliability [12] are calculated with the assumption of known coefficient of variation. The base material specimens show the highest values for both alloys. Analogously to EN 1999-1-1 [5], the specimens of alloy EN AW-5754 O/H111 reach nearly the same strength values for the base material and welded specimens. Still, small differences are present. For the alloy EN AW-6082 T6, a distinct strength reduction due to HAZ is obtained. The tensile strength is reduced to 60% of the base material according to EN 1999-1-1 [5], whereas testing resulted in about a 70% reduction of strength. Elongation at fracture is lower for the welded specimens of both alloys compared to the base material. All test results exceed the values given in EN 1999-1-1 [5] and the respective product code EN 485-2 [13]. Significant differences between the alloys are present with respect to their base material strength and their behavior in the area of the welding. These differences are covered by EN 1999-1-1 [5], however.

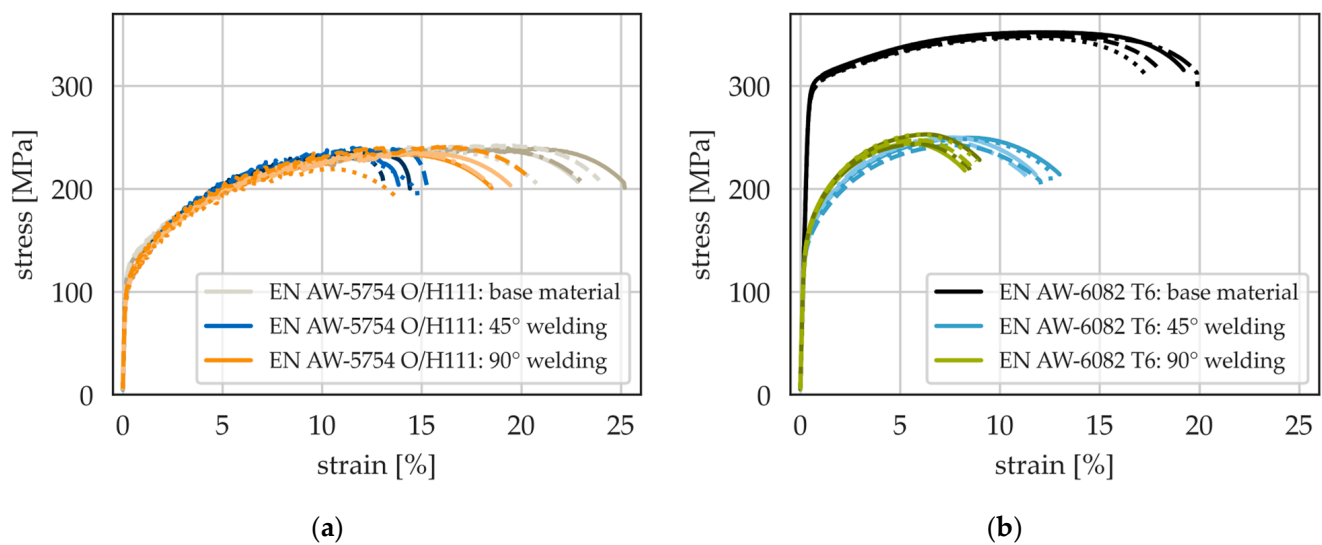


Figure 3. Results of tensile testing for (a) EN AW-5754 O/H111; (b) EN AW-6082 T6.

Table 1. Summary of results of tensile testing in comparison with values in EN 1999-1-1 [5]: proportional limit $f_{p,0.2}$ and tensile strength f_u .

		Base Material		Weld—45° with Respect to Loading Direction		Weld—90° with Respect to Loading Direction	
		EN 1999-1-1 [5]	95% Quantile Tensile Test	EN 1999-1-1 [5]	95% Quantile Tensile Test	EN 1999-1-1 [5]	95% Quantile Tensile Test
EN AW-5754 O/H111	$f_{p,0.2}$ [MPa]	80	124.4	80	109.3	80	106.3
	f_u [MPa]	190	236.6	190	230.1	190	218.7
EN AW-6082 T6	$f_{p,0.2}$ [MPa]	260	298.2	125	145.5	125	153.5
	f_u [MPa]	310	344.8	185	241.9	185	239.9

Harre [7] found a difference in static strength between transverse welding and welding at 45° for EN AW-6082, which is not that distinct in the present results. Harre [7] confirmed the results in [14] qualitatively. The present strength reduction in the HAZ, which is considered as a metallurgical notch in the following, is distributed over the cross-sections for inclined welding with respect to the loading direction. This mitigates the notch and shows the largest impact for decisive metallurgical notches, i.e., the HAZ of EN AW-6082, and large specimen widths. The width of the tested tensile specimens in this study is small (10 mm) compared to the specimens in [7], which reduces or eliminates the effect as the HAZ with a certain width appears in a whole cross-section and therefore explains the minor differences in strength.

3.2. Load-Controlled Fatigue Testing

Based on the pairs of values of applied stress range and endured number of cycles, S-N curves are evaluated. Regression lines with a 50% failure probability are shown in Figure 4 for the base material and welded specimens. Curves for the specimens made out of base material are depicted in grey and black, while results for the specimens with 45° welding are marked in blue and those for the specimens with transverse welding in green and orange.

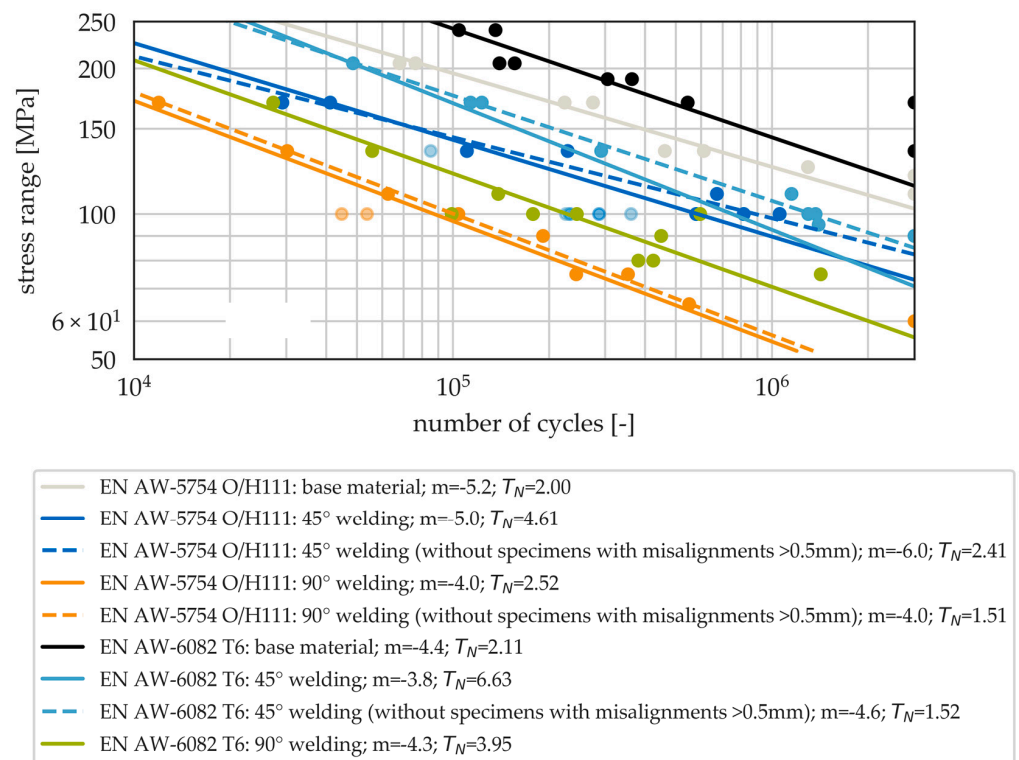


Figure 4. 50% regression analyses of resulting values from load-controlled fatigue testing and respective points of test results (specimens defined as eccentric depicted with more transparent filling).

Generally, as expected, the base material can be assigned a higher fatigue strength compared to the welded specimens in the tested range of up to nearly 3 million cycles. The welded specimens endure fewer cycles compared to the base material due to the stress concentration induced by the weld. The regression curves for welded specimens with welds at 45° with respect to the loading direction lie beyond the resulting curve for specimens with a transverse weld. This is also in accordance with [7]. Furthermore, specimens made from alloy EN AW-6082 T6 endure more cycles compared to alloy EN AW-5754 O/H 111 in the tested range. However, especially for base material specimens and 45° welded specimens the inclination of the regression lines differs between the alloys. The different inclination is also caused, among other things, by the different ratios of the tested stress ranges to the tensile strength of the respective alloys. A separate evaluation without consideration of specimens with larger eccentricity was made; see the dashed curves. Within this evaluation, welded specimens with more than 0.5 mm misalignment, measured via laser scan, were not considered. The results of these eccentric specimens are depicted more transparently.

Concerning the inclination of the resulting S-N curves, the specimens with transverse welding are in very good agreement with EN 1999-1-3 [1]. The regressions have inclinations of $m = 4.0$ and $m = 4.3$ for alloy EN AW-5754 O/H111 and alloy EN AW-6082 T6, respectively. Detail J.7.3.1 in [1], describing one-sided full penetration welds with permanent backing, is characterized by $m = 4.3$. EN 1999-1-3 [1] does not provide a specific notch case for welds at an angle of 45°, so the notch case for transverse welding is the most appropriate. However, it has to be kept in mind that the notch factors are differing, as can be derived from numerical calculations. Besides the notch effect itself (geometrical and metallurgical), a superposition with the multiaxial stress state at the weld is present. Here, [7] describes the division into normal stresses and shear stresses as favorable. Fatigue testing of the specimens with 45° welding resulted in inclinations of $m = 5.0$ for alloy EN AW-5754 O/H111 and $m = 6.0$ for the same alloy without consideration of the specimens with misalignments larger than 0.5 mm. For alloy EN AW-6082 T6 the regressions can be characterized by $m = 3.8$ (all

specimens) and $m = 4.6$ (without specimens with misalignments larger than 0.5 mm). Without consideration of the specimens with larger misalignments, the inclinations are higher for 45° welding than those for specimens with transverse welding. According to EN 1999-1-3 [1], the largest inclination is stated for the base material ($m = 7.0$). From the results of base material testing, inclinations of $m = 5.2$ for EN AW-5754 O/H111 and $m = 4.4$ for EN AW-6082 T6 are observed. These values fall below the standard, but other projects led to similar tendencies concerning the inclinations of S-N curves for the base material of aluminum alloys, see database ALFABET 2.0, which is documented in [15].

The slopes of the resulting curves for the specimen types of alloy EN AW-6082 T6 all show similar values, while the differences in the slopes of alloy EN AW 5754 O/H111 are significantly larger. It should be noted that the tested stress ranges in relation to the characteristic material properties and the related influence of elastic and plastic notch effects play a role in the slopes of the regression lines. For example, the specimens of alloy EN AW-5754 O/H111 were tested in a comparable range in terms of tensile strength, while the welded specimens of alloy EN AW-6082 T6 were tested further into the plastic range than the base material of this alloy, which has a corresponding effect on the results.

The different slope of the regression lines considering all test points compared to the regression lines ignoring the number of cycles of the specimens with axial misalignments greater than 0.5 mm is due to the stress ranges applied to the misaligned specimens. For the series of specimens with 45° welds made of alloy EN AW-5754 O/H111, the stress ranges applied to the specimens defined as misaligned are at the lower limit of the whole tested stress ranges in the project so that these test points rotate the entire 50% regression line and cause a smaller value of the slope. The specimens of alloy EN AW-6082 T6 with 45° welding show the same phenomenon, but rather lower, since the stress ranges applied to the misaligned specimens are also in the lower range, but slightly higher. For the group with transverse welding of alloy EN AW-5754 O/H111, there are no differences in the slopes, since the stress ranges applied to the specimens defined as misaligned are in the middle range of all tested stress ranges in the project. Thus, it is evident for all groups that a uniform distribution of the misaligned specimens over all tested stress ranges only results in a downward shift of the regression line. Without a uniform distribution of the applied stress ranges for misaligned specimens, there is a change in the slope.

Welding at 45° to the loading direction has the advantage that the notch effect of the weld itself does not fall into one cross-section (as in transverse welding), but each cross-section consists of only a small part of the unfavorable notch. The notch effect is related to both the geometry of the weld and discontinuities due to the welding process itself (e.g., pores, inhomogeneities). These factors affecting the cross-section along the weld interact with the multiaxial stress state at the weld and compete with the smallest cross-section perpendicular to the loading direction and starting from the weld ends [7]. Overall, better fatigue performance results and [7] correlates the degree of improvement with the decreasing angle of the loading direction.

3.3. Numerical Results

Within this paper, a short outlook on the currently ongoing numerical investigations is given. In this way, the differences in the geometrical notch effect of transverse welding and 45° welding is illustrated. As already mentioned, a superposition of the geometrical and metallurgical notch effect as well as the geometry effects is observable. For qualitatively comparing the geometrical notch effect due to the welding, a simple bar (thickness 10 mm) with transverse welding (90°) and welding at 45° , respectively is modeled. The notch radius is defined as 1 mm according to [16]. In Figure 5a, the principal stresses at the 45° welding are shown with an applied stress of 1 MPa, which means that stresses are equal to the notch factor. At the beginning of the weld, with an obtuse angle between the welding and loading direction, an increase in stresses is obtained. In Figure 5b, the notch factors in the principal stress direction of 90° transverse welding and 45° welding are compared along the normalized length of the weld. The mean notch factor is significantly reduced

for 45° welding. However, the latter exceeds the notch factor for transverse welding at the beginning of the weld. It has to be kept in mind that influences from the detailed weld geometry, misalignments, etc., are not considered in the presented model. Currently, detailed models of the tested specimens including axial and angular misalignments are in work. Thus, weld geometries at the upper and lower surface of the specimen are modeled according to the real specimen geometries instead of assuming the same weld geometry on both sides. This also results in different trends of notch factor on the respective surfaces. The notch factor at the more narrow but steeper weld at the bottom side, e.g., does not show the reduction of the notch factor at the weld's ends.

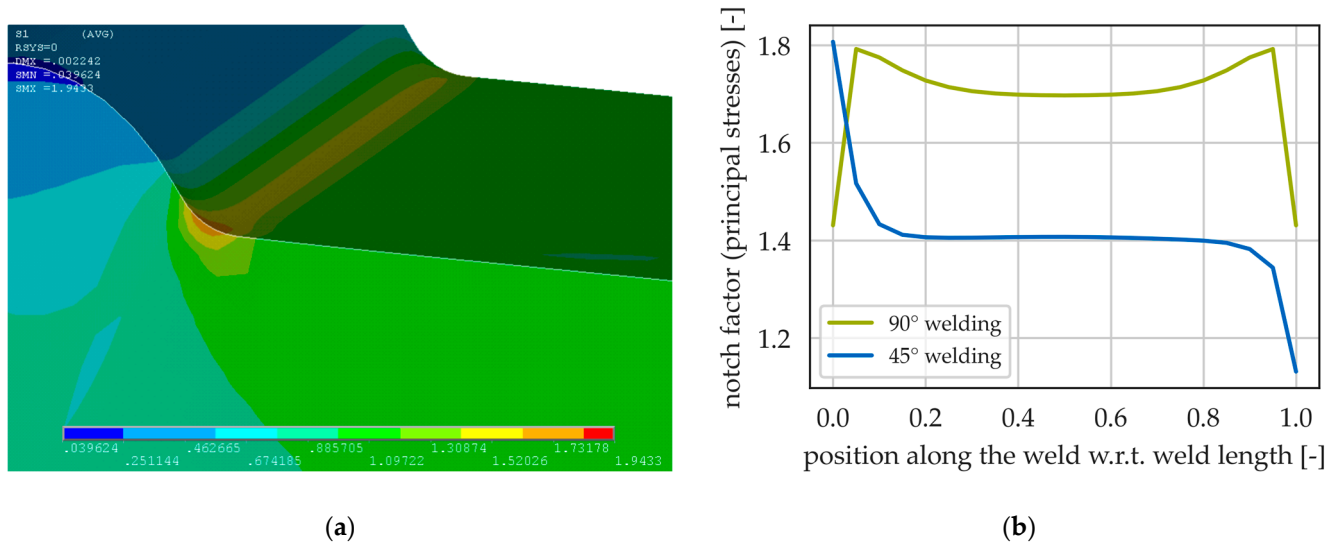


Figure 5. (a) Numerical model with principal stresses (equal to notch factor for applied loading) for 45° welding; (b) comparison of numerically determined notch factor for 45° and 90° welding.

4. Discussion

In EN 1999-1-3 [1], varying static mechanical material properties of available aluminum alloys and the different extent of the strength reduction in the HAZ are not generally considered in notch cases. The only exception is present for material EN AW-7020, where a distinction from other alloys is made in the notch cases for unwelded details. On the other hand, the two alloys considered within this study, EN AW-5754 O/H111 and EN AW-6082 T6, are treated identically, although they reach significantly divergent static mechanical material properties and the influence of welding and the resulting reduction in strength in the HAZ is fundamentally different between EN AW-5754 O/H111 and EN AW-6082 T6.

Tensile testing confirmed the differences in the static mechanical properties of the two considered alloys in accordance with EN 1999-1-1 [5]. Load-controlled fatigue tests were then carried out on unwelded specimens and welded specimens with welding angles of 45° and 90° with respect to the loading direction, respectively, for the two alloys. The alloy and weld angle clearly influence the fatigue performance of the aluminum details. Both parameters affect the respective S-N curves, whereby welding at 45° is more advantageous compared to transverse welds. The results are in accordance with the conclusions by Harre in [7]. Several factors, such as the geometrical and metallurgical notch effect (HAZ) due to welding, the material properties, and the geometrical effects of the welding angle influence the behavior of the specimens and overlap with the resulting number of cycles endured. A clear allocation of the different factors has not yet been entirely made and needs to be further investigated.

Numerical investigations of the corresponding multiaxial stress states are currently being carried out to verify the experimental results. Specifically, experimental and numerical results are compared through detailed recalculation of the fatigue tests performed as described, taking into account the specific geometries (including all offsets, etc.) of the

tested specimens. Initial results indicate a reduced mean notch factor for 45° welding, but at the same time show increased factors at the beginning of the weld. This trend is currently being investigated with a detailed model. A further challenge will be to transfer the results of small-scale tests/investigations to large-scale and thus real structures.

5. Conclusions

Both experimental and numerical results can provide a basis for the adaptation of the existing notch cases. This refers both to the influence of the varying static mechanical properties of the base metal and the HAZ of the different alloys available and to the influence of the welding angle. For example, a differentiation by the alloy used within the notch cases could be made analogous to the alloy EN AW-7020 in EN 1999-1-3 [1].

At the same time, the experimental results allow for detailed numerical investigations and thus support the development of a future design concept taking into account multiaxial stress states at welds. As a consequence of that, a more advantageous design and execution of aluminum structures under fatigue loading can be achieved.

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