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Fatigue assessment of EMPT-welded joints using the reference radius concept

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Abstract

The electromagnetic pulse technology (EMPT) is a joining process similar to the explosion welding. In the process, a flyer-sheet is accelerated towards a target-sheet using electromagnetic fields. During impact high normal and lateral contact forces are generated which join the sheets on an atomic level. This process can be automated for joining thin sheets and is therefore especially suited for mass production, e.g. in the automotive industry. The resulting joints are not comparable to ones made by common MIG/MAG or laser welding processes since no heat is induced. This leads to the question if the standard approaches to assess the weld in terms of their fatigue behavior can be used also and if a reliable fatigue assessment can be achieved. In the paper, the fatigue strength of EMPT-welded connections under constant amplitude loading is presented. Common assessment approaches like the notch stress approach are applied to assess the fatigue life. A comparison between numerically derived fatigue life and experimental tests shows a good agreement and proves the applicability of established approaches.

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Keywords: Fatigue strength; EMPT-welded joints; notch stress approach; aluminum

1. Introduction

Welding is an important joining technique which is commonly used to join two parts of equal material. In common welding technologies, such as GMAW or laser welding, the material is heated above the melting point. During solidification the materials are joined. These most common welding processes come along with some disadvantages. Due to the localized heat input and the yielding of the material during heating and cooling distortion as well as residual stresses may be induced. These implications lead to further problems in the assembling of structures as well as a decrease in the static and fatigue strength. In addition, a heterogeneous material is generated which exists of the weld metal, the heat affected zones and the base metal. Such a joint shows usually a lower strength compared to the

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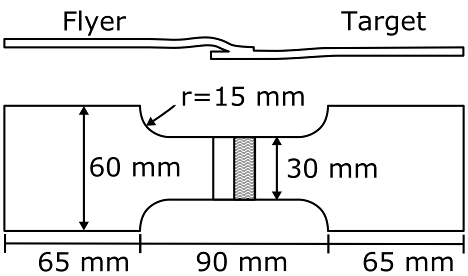

Fig. 1. Geometry of the tested shear specimens

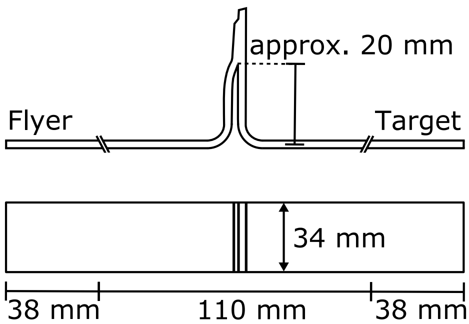

Fig. 2. Geometry of the tested peel specimens

base metal. Further disadvantages of the common processes are the long joining times as well as environmental and health issues due to the welding fumes.

Another way to join two materials but to avoid some of the mentioned side-effects is the welding method called electro-magnetic pulse technology (EMPT) or magnetic pulse welding (MPW). It is based on the very high acceleration of one metal sheet called flyer upon an static metal sheet called target with an electro-magnetic pulse. This joining techniques is from the physical principles closely related to the explosion welding which is a proven and reliable method of joining plates mainly of different materials, e.g. copper to steel [1]. The welding time of EMPT-welding takes place in approximately $T \approx 12\ \mu s$ time. In that time, the flyer hits the target sheet with a velocity of $v \approx 500\ \frac{m}{s}$. At the first contact between the sheets debris is ejected from the surface and an exchange of electrons between the the flyer and the target happens in the joining zone [2]. Because of this exchange of electrons even two different materials can be joint. In contrast to the explosion welding, the EMPT welding can only be used to join thin-walled sheets. Due to the very short joining time the process is also suitable to be used in series or mass production such as in the automotive industry.

In automotive applications joints have to endure high static as well as cyclic loads during service that might lead to a prematurely failure of the joint. In order to assess the strength of the joint, approaches have to be available that can be used to ensure a reliable assessment even during the early development process. For standard joining technologies like GMAW and laser welding fatigue assessment approaches already exists and used in the automotive industry [3, 4]. A common approach is to use the notch stress concept that relies on local notch stresses as a fatigue-relevant value [5]. In this paper it will be investigated whether it is valid to use the notch stress concept also for EMPT-welded joints.

2. Experimental investigations

2.1. Specimen manufacturing and characterization

For fatigue testing two types of specimen were used. So-called shear specimen have been produced in which the load is transferred through the comparatively large joining area, Fig. 1. The second specimens are called peel specimens, Fig. 2. In these specimens, the load is not transferred through the complete joining area but only a small area close to the sharp root notch.

As material the aluminum alloy EN AW 6061 in the condition T4 was used. After the joining a heat treatment for $t = 20\ min$ at $T = 185°C$ and subsequently cooling at room temperature was applied to simulate the heat induced to the cataphoretic painting.

In order to achieve a reliable joint, a distance of $d = 1.5\ mm$ was adjusted between the sheets prior to the EMPT process. This distance is required to reach the high relative velocity necessary for joining. Due to the high welding forces plastic deformations can be identified in the base material close to the joining region that lead to slight deformations in the base material, see Fig. 1 and 2.

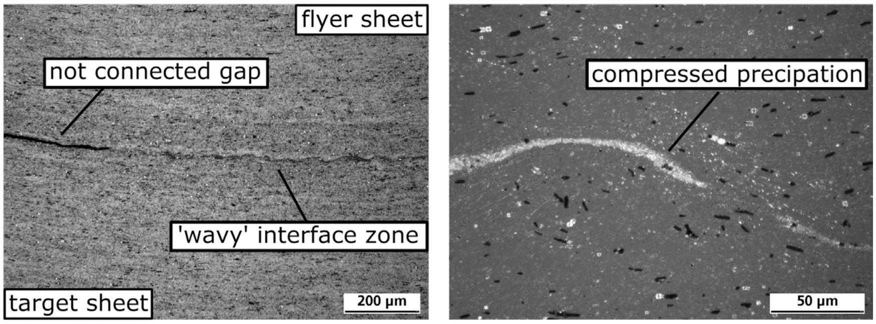

Fig. 3. Left: Joint at the side of failure after welding under polarized light; Right: Detailed view the interface zone

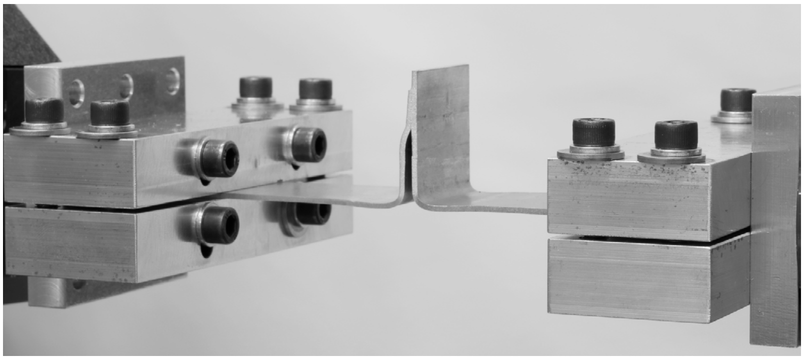

Fig. 4. Peel specimen clamped in the testing rig

The specimens have been produced out of aluminum sheets with a width of $w = 60$ mm, a length of $l = 200$ mm and a thickness of $t = 1.5$ mm. After joining the "weld ends" have been removed to focus on the continuous weld region. The net width of the shear specimen was reduced to $w_n = 30$ mm, the one of the peel specimen was reduced to $w_n = 34$ mm .

Microsections have been prepared from the cross section of the weld to examine the joint region in detail, Fig. 3. As it is characteristic for EMPT- or explosion-welded joints a 'wavy' interface zone can be identified. In the microsection a width of the weld zone of $w_{wz} = 5.8$ mm could be measured.

2.2. Fatigue tests

For the fatigue tests a clamping length $l_c = 65$ mm for the shear specimen and $l_c = 38$ mm for the peel specimen was used, Fig. 4. This lead to a free length (distance between the clamps) of $l_f = 90$ mm for the shear specimen and $l_f = 110$ mm for the peel specimen. The axial offset between the clamps was set to $off = 3.5$ mm for the shear specimen but $off = 0$ mm for the peel specimen in consequnce of the given specimen geometries after the welding process. With this constellation minimal clamping loads have been induced in the specimen.

In the fatigue tests a cyclic axial load was applied to the specimen with a load ratio $R = F_{min}/F_{max}$ of $R = 0$ using load control. For the peel specimens a second load ratio of $R = 0.5$ was used to investigate the sensitivity to mean stress. The testing frequency was set to $f = 20$ Hz. All tests are performed until rupture of the specimen or until a maximum number of load cycle $N = 10^7$ cycles was reached.

For all fatigue test series S-N curves were evaluated using statistical methods according to [6]. The S-N curve of the shear specimens was determined to have a slope of $k = 3.08$ and an endurable load of $F_a = 155$ N at $N_k = 10^6$ load cycles, Fig. 5. The statistical derived scatter of $T_S = 1 : 1.08$ is small

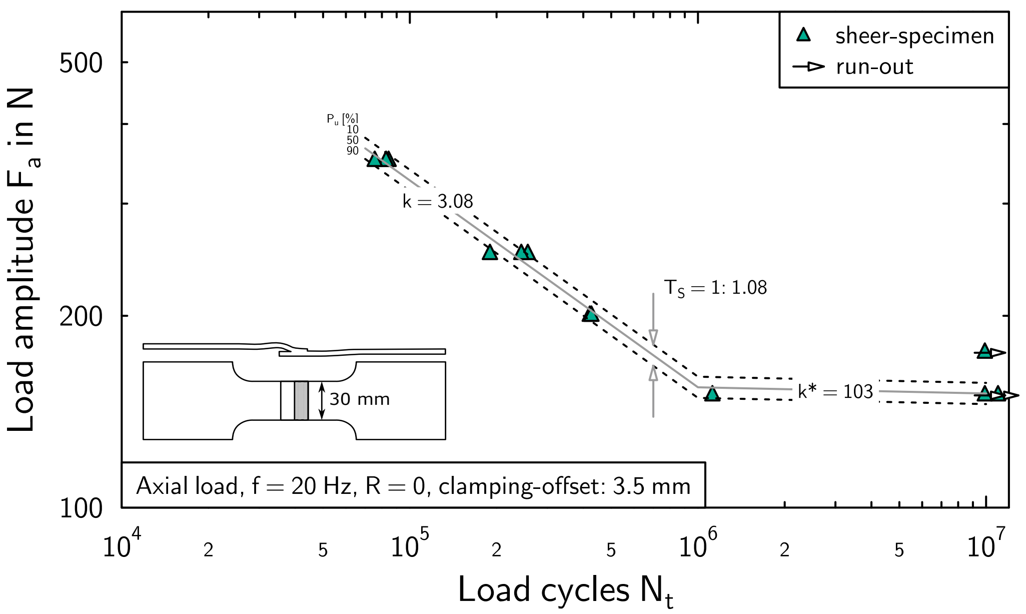

Fig. 5. S-N curve of the shear specimens

compared to standard GMAW welded joints [4]. In the long life regime ($N \geq N_k$) a slope of $k^* = 103$ was preset on the basis of [7].

For the peel specimens a shallower slope of $k = 4.3$ was determined, Fig. 6. In the long life regime ($N \geq N_k$) a slope of $k^* = 12$ was used in order achieve a best fit to the experimental data. The load amplitude at the knee point $N_k = 10^6$ was determined to $F_a = 40.10\ N$. The scatter is identified as $T_S = 1 : 1.10$ and is a little bit greater than for the shear specimens. In the fatigue tests with $R = 0.5$ a lower endurable load amplitude of $F_a = 26.75\ N$ was determined. For peel specimen it should be taken in mind that the bearable stresses are directly addicted to the lever arm which is the distance between the joint and the line of action of the force. For the evaluation the same knee point and the same slope as identified for the tests with $R = 0$ was preset for the statistical evaluation. With both tests at $R = 0$ and $R = 0.5$ am mean stress sensitivity M [8] of

$$M = \frac{F_a(R=0) - F_a(R=0.5)}{F_m(R=0.5) - F_m(R=0)} = 0.18 \quad (1)$$

was derived.

In all tests, the failure starts at the sharp notch between flyer and target sheet. In case of shear specimen the crack propagation continues through the base metal of the target sheet. In case of peel specimen the crack propagation continues through the base metal of the target sheet but also through the flyer sheet.

3. Numerical investigation

In order to perform a fatigue assessment with the notch stress approach, FE-models of both specimen types have to be generated which represent the realistic behavior during the fatigue tests.

For this two contour scans of the specimens have been used as basis to build the FE-models. In these scan, the local geometry of the weld region could be recorded and included within the FE-model. Since the shear specimen had a significant angular misalignment, the global distortion of the whole specimen was considered additionally. The local features in the weld region, the width of the weld,

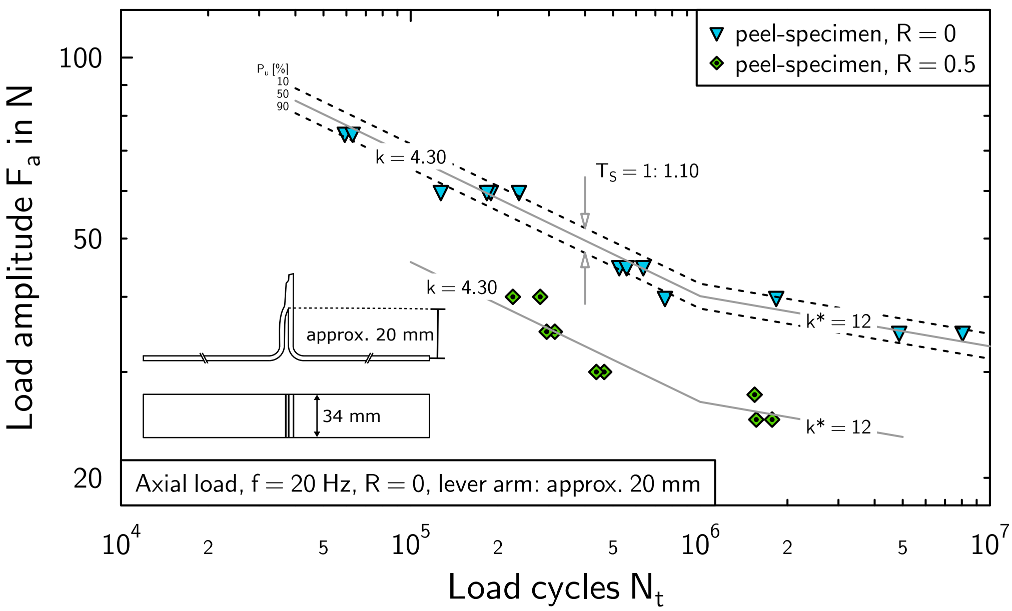

Fig. 6. S-N curves of the peel specimens with $R = 0$ and $R = 0.5$

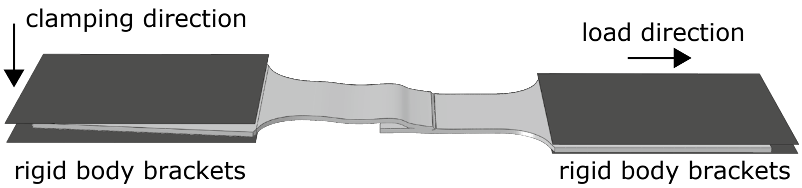

Fig. 7. FE-model of the shear specimen

the geometry of the sharp crack-like gap in the non-joined region and the local deformation of the base material, was adapted to fit the geometry identified from the micro-sections. A reference radius of $r_{ref} = 0.05$ *mm* was included in both models to derive notch stresses for the fatigue evaluation. The meshing of the models was realized with hexahedron elements with second order approach. The local notch region was discretized according to [9] in order to achieve converged notch stresses. The Young's modul was set to 72 *GPa* and the Poission ratio was set to 0.33. All calculations were linear elastic with a nonlinear displacment approach.

Due to the weld distortion of the shear specimens stresses are induced during the clamping process since only the offset of the clamps was adjusted in the test rig and not the angular misalignment. To capture the influence of the clamping process two calculation steps were used. First, the clamping was simulated by using four analytical surfaces to describe the clamping process, Fig. 7. Second, the axial load was applied. A comparison between numerically derived and experimental measured strains shows a high degree of deviation. This deviation was mainly caused by the finite stiffness of the test rig compared to the infinite stiffness (rotation and displacement set to zero) used in the first FE-model. The deviation in strains was reduced significantly by replacing the rotation and displacement boundary conditions by springs in the FE-model.

The peel specimen had only minor global distortions. Here, the clamped region was modeled with a kinematic coupling considering the free clamping length of 110 *mm*, Fig. 8. A good agreement was identified in a comparison between measured and numerically derived strains.

From the FE-calculation the notch stresses were calculated in the fatigue critical crack-like notches

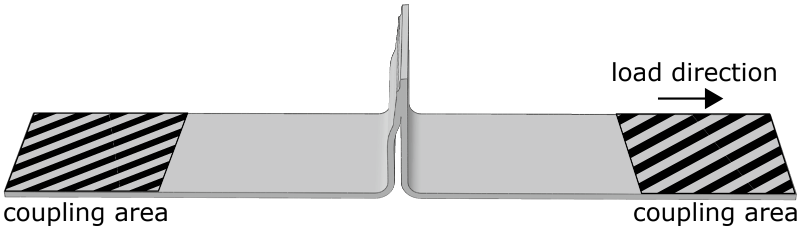

Fig. 8. FE-model of the peel specimen

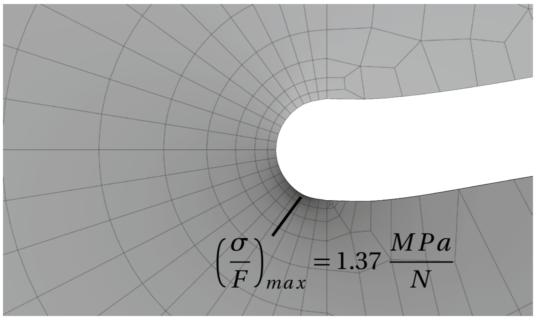

Fig. 9. Stress inside the notch of the shear specimen

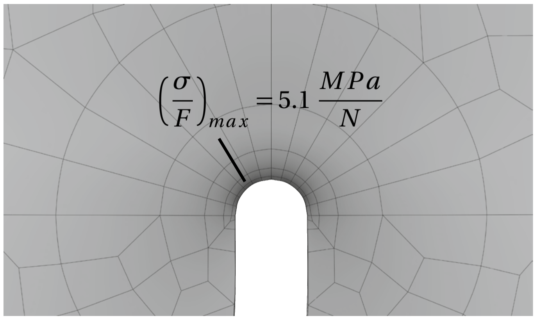

Fig. 10. Stress inside the notch of the peel specimen

of the joint, Fig. 9 and Fig. 10. At the shear specimens a notch stress of $\sigma_e = 1.37\ \frac{MPa}{N}$ was calculated. The notch stress at the peels specimens is with $\sigma_e = 5.1\ \frac{MPa}{N}$ around four times higher. This is due to the long lever arm and the induced bending stresses.

4. Evaluation

With the derived notch stresses an evaluation of the fatigue strength can be performed for both specimens. For this the endurable loads from the fatigue test results are transformed to local endurable stresses using the results from the FEA, Fig.11. A comparison of the endurable notch stresses from both specimen types shows a good agreement. This demonstrates the principle validity of the notch stress approach for the fatigue assessment of EMPT-welded joints.

In a second step, a comparison was made between the endurable notch stresses of EMPT- and conventional welded joints. For this the endurable notch stresses derived from a laser-welded overlap joint made from aluminum with the same thickness $t = 1.5\ mm$ as well as the reference S-N curve consisting of overall 18 test series tested at $R = 0$ from [10] ($\sigma_{e,2e6} = 166.5\,MPa,\ k = 5.4$) have been included for comparison, Fig.11. The comparison shows quite a good agreement. The endurable notch stresses at the laser-welded joint with the same geometrical features are in the same range as the ones of the EMPT-welded joints. In addition, the EMPT-welded joints are positioned in the scatter band of the reference S-N curve. This indicates that also for EMPT-welded joints the same characteristic values, i.e. endurable notch stresses, can be applied for a fatigue assessment.

A comparison with the design S-N curve recommended in [11], modified to fit the slope ($k = 5.0$) of welded thin sheets [12], shows that a safe design of EMPT-welded joints with design values based on conventional welding processes is going to be achieved.

5. Conclusions

The fatigue strength of EMPT-welded aluminum joints was investigated and assessed with the notch stress approach. From the evaluation following major conclusions can be drawn.

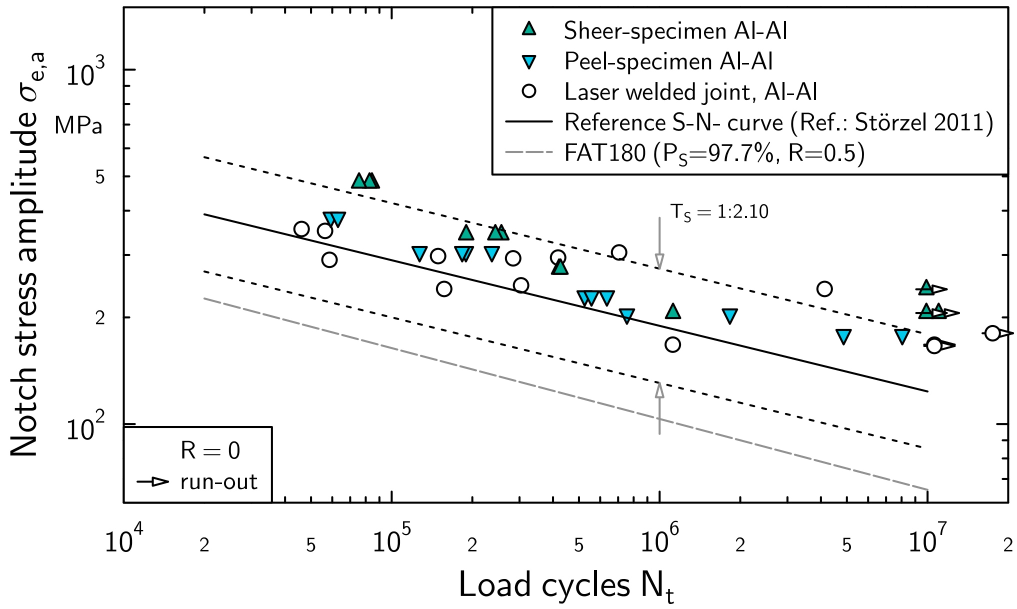

Fig. 11. Notch stress amplitude

- The course of the S-N curve, i.e. knee point N_k and slope k, of the EMPT-welded joints is similar to the one of conventional welded joints.
- With the notch stress approach the fatigue strength of both EMPT-welded specimen types, peel and shear specimen, can be described using same characteristic values.
- A comparison of endurable notch stress between EMPT- and conventional welded joints shows no significant difference. This indicates, that a fatigue assessment can be performed with known design values for conventional welded aluminum joints.

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