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Damage Monitoring of Ultrasonically Welded Aluminum / CFRP-Joints during Cyclic Loading via Electrical Resistance Measurements

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Abstract: Aluminum alloys and carbon fiber reinforced polymers (CFRP) are two important materials for lightweight design and the combination of these dissimilar materials becomes increasingly important. Recent investigations have shown that ultrasonic metal welding is a well suited process to realize aluminum/CFRP-joints.The ultrasonic shear oscillation parallel to the welding zone with a simultaneous welding force perpendicular to the aluminum/CFRP-sheets melts the polymer matrix and squeezes the polymer matrix out of the welding zone. This allows a direct contact between the carbon fibers and the aluminum. Beside monotonic properties the cyclic deformation behavior of these ultrasonically welded aluminum/CFRP-joints is essential. Therefore in addition to monotonic shear load tests, fatigue experiments with constant force amplitudes and load-increase-tests were performed on a servo hydraulic test system with a frequency of 5 Hz. The electrical conductivity between carbon fibers and the metal sheet was used to determine changes in the electrical resistance ΔR during cyclic loading.The investigations have proved that in comparison to the measurement of the displacement amplitude, the change of ΔR is much more reliable because of the direct response of the deformation process in the joint.

Keywords: Ultrasonic welding, aluminum, CFRP, hybrid joints, fatigue, electrical resistance

1 Motivation and introduction

Hybrid lightweight constructions become more and more relevant in terms of the shortage of natural resources. In order to select suitable materials for future traffic systems, multi-material concepts are of high interest. The use of dissimilar materials requires appropriate joining techniques. Ultrasonic metal welding is a pressure welding technique which allows to realize various material combinations.

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The formation of the joint occurs as a result of in plane ultrasonic oscillations and a superimposed vertical static welding force. In comparison to other joining techniques like brazing or adhesive bonding, ultrasonic welding is characterized by a very low energy input, consequently low temperatures in the welding zone as well as very short welding times [Graff (2005)]. Ultrasonic welding is currently applied to join plastics or metals to each other by ultrasonic plastic or metal welding [Graff (2005), Greitmann (2003)]. The main difference between both welding techniques is the direction of the oscillation amplitude. For metal welding the amplitude is parallel and in case of plastic welding the oscillation amplitude is perpendicular to the surface of the joining partners. Due to the polymer matrix of fiber reinforced polymers (FRP), at present the ultrasonic plastic welding is typically used to join FRP to each other. But in the case of metal/FRP-joints the ultrasonic plastic welding only enables adhesive bonding between the metal surface and the polymer matrix. Systematic investigations at the Institute of Materials Science and Engineering (WKK) of the University of Kaiserslautern (Germany) have shown that glass or carbon fiber textiles with or even without thermoplastic matrix can be welded to metals by ultrasonic metal welding [Wagner (2004), Balle (2009a)]. In contrast to all plastic welding techniques, the ultrasonic metal welding enables a direct contact between the carbon fibers and the aluminum and results in higher tensile shear strengths and additionally an electrical conductivity between fibers and metal exists which can be used for electrical damage monitoring techniques during mechanical loading of the hybrid welds [Balle (2009b), Balle (2011)]. To ensure hybrid design concepts, like ultrasonically welded joints of aluminum and CFRP, a detailed knowledge of monotonic and cyclic properties of these joints is necessary.

2 Materials, experimental setup and measurement methods

2.1 Base materials

The non-age-hardenable aluminum wrought alloy AA5754 was ultrasonically welded with the carbon fiber reinforced thermoplastic composite polyamide 66 (CF-PA66) based on a satin 5H-fabric of carbon fibers with the trade name “Toray T300J” with a weight per unit area of 285 g/m^2. The tensile tests were performed in rolling direction of the Al-sheet and in filling direction of the carbon fabric in case of the CFRP sheet. The fiber volume fraction of the 2 mm thick CFRP-sheets is about 48 %. It was manufactured at the Institute for Composites (IVW, Kaiserslautern, Germany) with an interval heating process using six layers of CF-fabric. The AA5754-sheets were welded in a work-hardened, thermally-softened and quarter-hard condition (H22). Selected mechanical properties of the materials are summarized in Tab. 1.

Table 1: Monotonic properties of the sheet materials

	Young's Modulus [GPa]	0.2 % Yield Strength [MPa]	Ultimate Tensile Strength [MPa]	Ultimate Elongation [%]
AA5754 H22	70	177	250	13.5
CF-PA66	55	/	580	1.1

2.2 Ultrasonic welding setup for hybrid joints

The AA5754/CFRP-joints, presented in this paper, were welded on a modified and optimized industrial ultrasonic spot metal welding system. The welding setup includes integrated force measuring devices which control the welding force and enable variable force paths during the joining process. In this context a special clamping system was developed at the WKK, see Fig. 1a. he applied LabVIEW-based measuring system enables to control the welding force. Simultaneously a high-resolution measurement of the major process parameters like welding force, welding energy and oscillation amplitude is possible. The specimen geometry of the single overlap joint is shown in Fig 1b. The contact area of the sonotrode is 10 x 10 mm^2. Because it is not possible to determine the exact geometry of the joining area the tensile shear strength was calculated as the ratio of the measured tensile shear force F_Z related to the contact area of the sonotrode.

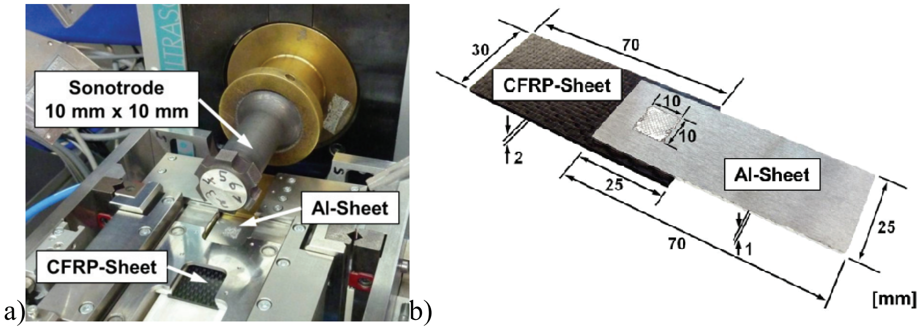


Figure 1: a) Advanced ultrasonic spot welding system (WKK), b) specimen geometry of Al/CFRP-joints

The process parameter triple welding force, oscillation amplitude and welding energy was optimized with a statistical model named "central composite design circumscribed (CCC)" in respect to the maximum tensile shear force F_Z. For joints of AA5754 and CF-PA66 as best process parameters the welding force 160 N, the oscillation amplitude 40 μm and the welding energy 2160 Ws were determined by the CCC-model and proved in tensile shear tests [Balle (2009a)].

In Fig. 2a the cross section of the joining zone of an ultrasonic welded Al/CFRP-joint is schematically shown. Scanning electron microscopic (SEM) investigations show that the mechanical oscillation parallel to the welding area removes the matrix between the carbon fibers and the aluminum. One advantage of this behavior is the possibility to contact the load bearing fibers direct to the aluminum without damaging the carbon fibers of the reinforced composite. In Fig. 2b and 2c two characteristic positions of the welding zone are shown. Fig. 2b is located below the sonotrode mark, where the polymer matrix was squeezed out of the joining zone and the Al-sheet gets locally in contact to the fibers. This generates an electrical contact between fibers and metal sheet [Balle (2011)] and therefore the option for a damage monitoring due to the change in electrical resistivity during mechanical loading [Chung (2001), Schueler (2001), De Baere (2010)]. Fig 2c shows exemplarily an area with pure adhesive contact between the removed polymer of the CFRP and the aluminum.

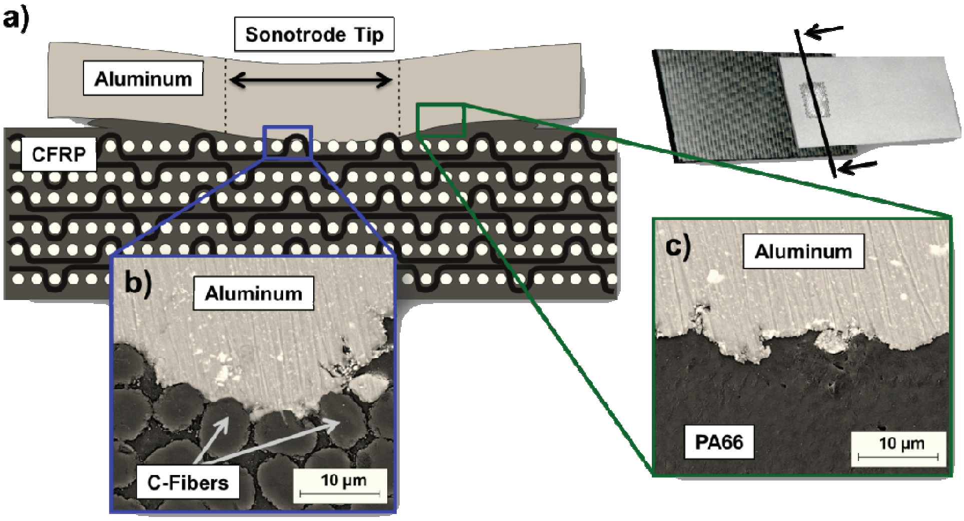


Figure 2: Model of the joining zone and selected micrographs (SEM), a) schematic view of the joining zone in cross section, b) SEM micrograph underneath the sonotrodemark, c) of an area with displaced polymer

2.3 Experimental setup for mechanical loading

The fatigue tests were realized on a servohydraulic test system. Force-controlled load increase tests (LIT) and constant amplitude test (CAT) were performed at a load ratio of $R \approx 0$ with a frequency of 5 Hz at ambient temperature. The measuring setup is shown in Fig 3. The hydraulic grips were adapted to the geometry of the single overlap samples to ensure axial loading conditions. Furthermore, an adjustable bending strut was used to minimize bending stresses. Friction in load direction was prevented by disks made of PTFE positioned between the samples and the strut.

To characterize the cyclic deformation behavior of the aluminum-sheets strain gauges and an electrical resistance measurement systems were used. Furthermore the electrical conductivity between fibers and metal sheet allows to measure the change ofthe electrical resistance ΔR in the joint during monotonic or cyclic load using a DC-power supply. The necessary electric contact between the joining components was realized with a copper clamp applied to the Al-sheet and with a screw in the CFRP-sheet, see Fig. 3. An increasing defect desity due to mechanical loads of the hybrid joint lead finally to a defined change in electrical voltage. The change in electrical resistance ΔR was calculated with Ohm's law. The necessary data recording and evaluation were realized with a LabVIEW-based software module developed at the WKK.

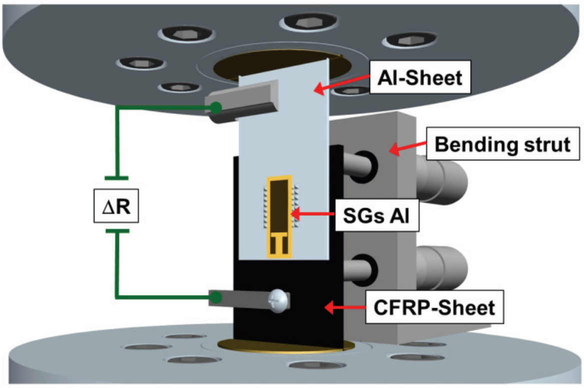


Figure 3: Experimental setup for fatigue tests with single overlap hybrid joints (schematically)

3 Selected results

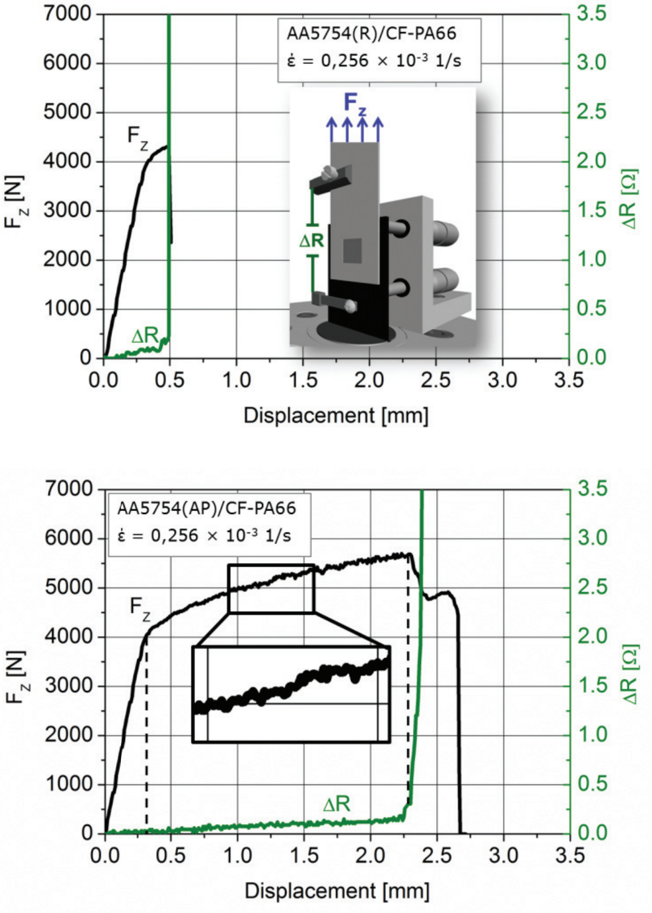
3.1 Monotonic behavior of hybrid aluminum/CFRP-joints

Fig. 4a shows a load-displacement curve of an aluminum sheet in as rolled surface quality welded to a CF-PA66-sheet. The hybrid weld shows an elastic deformation up to $F_Z \approx 4000$ N and fails due to plastic deformation at a load $F_Z$of = 4321 N. Beside the displacement measurement a continuous increase of the electrical resistance ΔR until failure can be observed due to an increasing damage of the welded area between aluminum and carbon fibers. After an etching treatment of the aluminum in concentrated nitric acid (HNO_3) the average tensile shear strength of the joints could be reproducibly enhanced up to $F_Z \approx 5400$ N (54 MPa) [Balle (2009b)]. Moreover a decrease of the standard deviation and a simultaneously improved long-term stability could be observed. Moreover, for welded joints tested after ageing up to four weeks at different temperatures and humidities nearly no decrease of the tensile shear strength for acid-pickled (AP) Al/CFRP-joints was determined [Balle (2009b)].

Fig. 4b illustrates a characteristic load-displacement-curve of AA5754(AP)/CF-PA66-joints. The aluminum sheet was pre-treated in nitric acid as mentioned above before welding. Reaching the yield point of the entire joint again at approximately $F_Z \approx 4000$ N, now pronounced plastic deformation characterized by a discontinuous curve develops. This shape of the load-displacement-curve can be explained by the so called PLC-effect [Robinson (1994)] in the aluminum sheet, see detail in Fig. 4b. The electrical resistance was also measured. During elastic deformation of the joint (Fig. 4a) no change in ΔR was observed. The first slight change of ΔR corresponds to the yield point of the joint, see first dashed line in Fig. 4b. After a linear course of ΔR due to plastic deformation of the aluminum, a pronounced increase of ΔR was measured immediately before final failure of the hybrid weld, see second dashed line in Fig. 4b. The strong increase of ΔR shortly before failure seems to be caused by debonding of the Al-C-Fiber-interface.

3.2 Fatigue behavior of hybrid aluminum/CFRP-joints

Besides monotonic loading, the fatigue behavior of the ultrasonically welded hybrid joints was investigated. First stepwise load increase tests (LIT) were performed for a first estimation of the endurance limit. Beginning at 250 N the cyclic force amplitude F_a was increased stepwise after each 10^4 cycles at 250 N up to the failure. In Fig. 5a the total mean strain $\varepsilon_{Al,m,t}$ of the Al-sheet and the change in electrical resistance ΔR of a AA5754(AP)/CF-PA66-joint are shown. The increase of the total mean strain shows three different areas separated at 4×10^4 and 7×10^4 cycles corresponding to $F_a = 1000$ and 2000 N. A characteristic change in the slope from



a)

b)

Figure 4: Monotonic tensile shear load-displacement- ($\varepsilon = 0{,}256 \times 10^{-3}$ 1/s) and load-resistance curves of a) AA5754(R)/CF-PA66 and b) AA5754(AP)/CF-PA66

linear to nonlinear at point 2, which corresponds to the yield point of the weld, is an indication for the local damage due to cyclic loading.

The course of the electrical resistance includes also a clear indication of the developmentof a fatigue damage in the joint. The first slight increase of the electrical resistance ΔR can be observed at about N = 4 x 10^4 cycles, Fig. 5a, point 1. This change in ΔR correlates with the later on determined endurance limit of the hybrid joints. After N = 7 x 10^4 cycles the ΔR course shows a pronounced increase, Fig. 5a, point 2, until the final fracture occurs at N = 9.7 x 10^4 cycles. The load level of point 2 is equivalent to the yield strength of the Al/CFRP-joint, see Fig. 4b. Hence the electrical resistance is a well suited and high sensitive physical value to describe the actual fatigue state of Al/CFRP-joints. In contrast to conventional strain measurements, which need a defined gauge length, the electrical resistance can be used for direct damage monitoring during mechanical loading of hybrid components. Fig. 5b shows electrical resistance curves of three repeated LIT tests under identical conditions. The experiments indicate thehigh reproducibility of ΔR measurements during cyclic loading of welded AA5754(AP)/CF-PA66-joints. Based on LITs selected constant amplitude tests (CAT) were performed. As ultimate number of cycles $N = 2 \times 10^6$ were chosen. The CAT were summarized in a Woehler-Curve, see Fig. 6. The determined endurance limit (F_a = 1000 N) correlates with the first significant change in ΔR during load-increase tests as mentioned in Fig. 5.

Fig. 7 shows two constant amplitude tests (curves a) and b)) with a force amplitude of F_a = 2250 N. Both curves are characterized by a change in the electrical resistance ΔR during the entire experiment, which was measured with two different experimental setups. The course of point a) was measured with the setup described above with a screw in the CFRP-sheet and a copper clamp attached with a screw to the Al-sheet. The force amplitude of F_a = 2250 N corresponds to an upper force of 4500 N and is slightly above the yield point of the joint. After approximately 85 % of the lifetime, an extreme change of the course of the electrical resistance-curve can be observed as a result of local fracture processes in the joining zone. Curve b) only demonstrates a change of ΔR due to microstructural changes of the cyclically loaded AA5754 sheet. This investigation was carried out with an electrical contact tape on the surface of the Al-sheet below the sonotrode mark and with a copper clamp.

4 Conclusions

Recent investigations have shown that ultrasonic metal welding is well suited to join aluminum alloys with CFRP. With defined pre-treatments of the rolled aluminum sheets like pickling in nitric acid before welding, ultrasonic welded AA5754/CF-

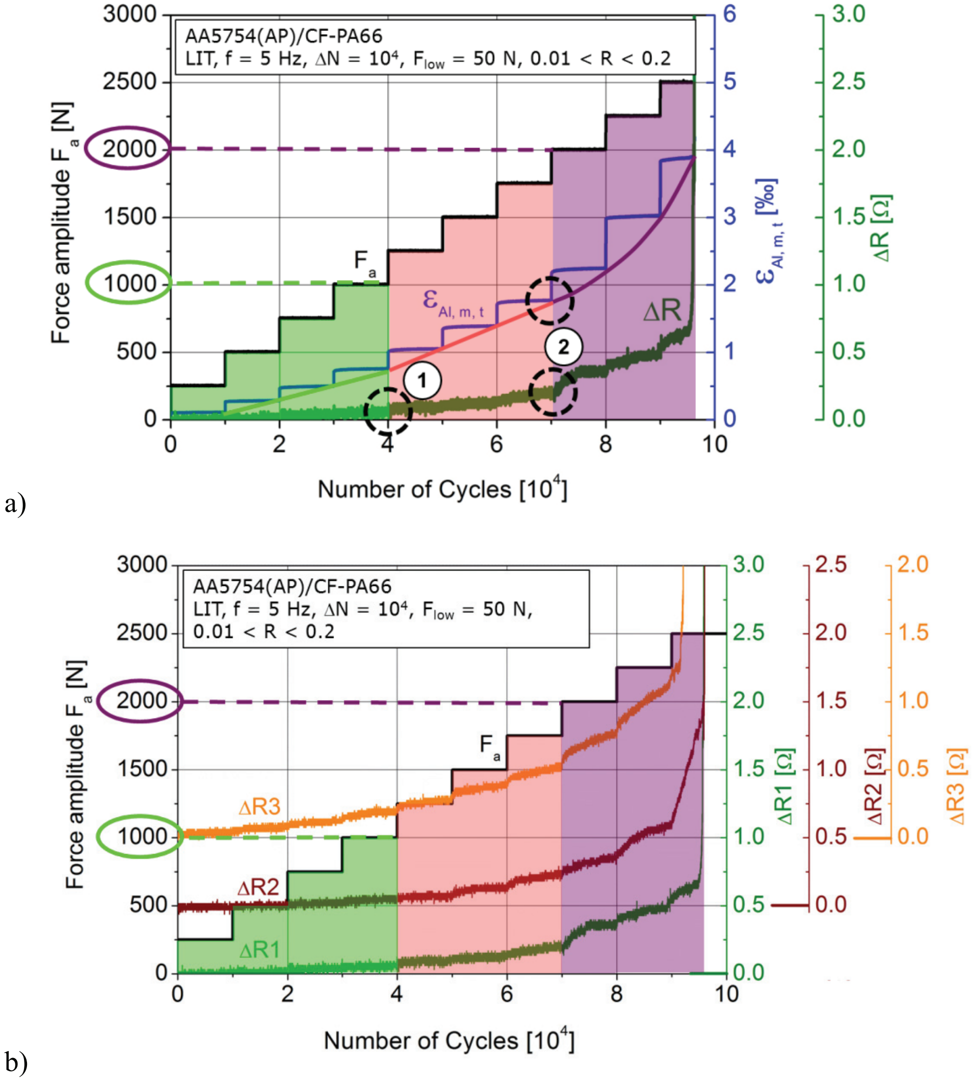


Figure 5: a) Displacement amplitude and change in el. resistance in stepwise load-increase tests of AA5754(AP)/CF-PA66-joints and b) reproducibility of ΔR during cyclic loading

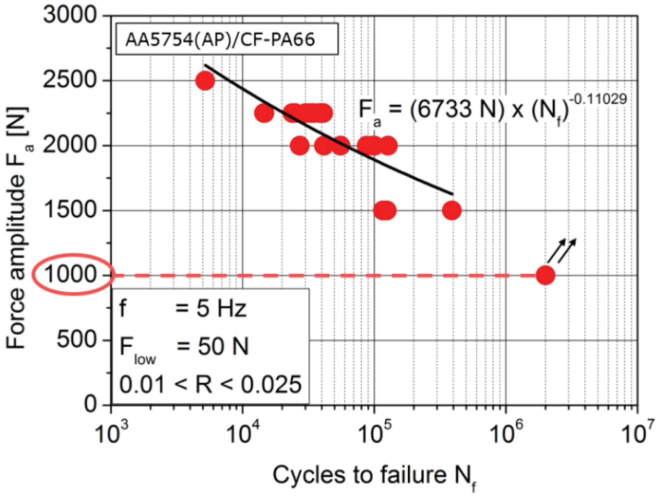


Figure 6: Force-Woehler-Curve of ultrasonically welded AA5754(AP)/CF-PA66-joints

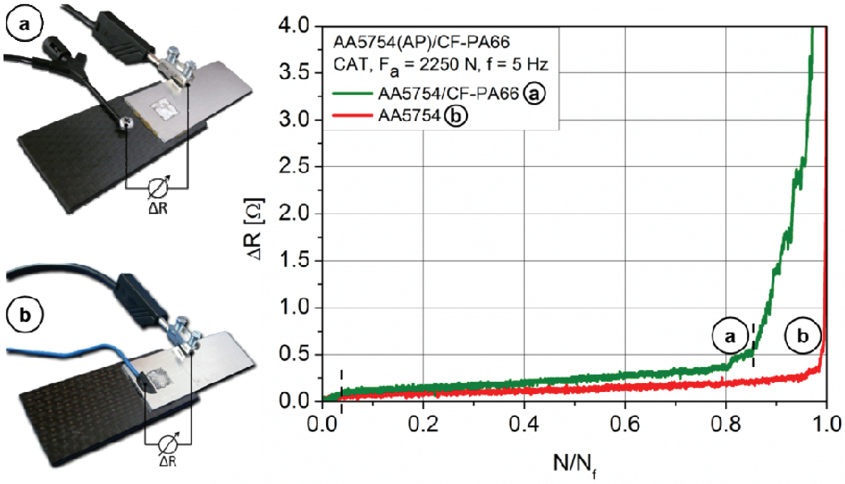


Figure 7: Change in electrical resistance during constant amplitude tests for a) AA5754(AP)/CF-PA66 and b) AA5754

PA66-joints reach a tensile shear strength up to 54 MPa corresponding to an ultimate tensile shear force of $F_Z \approx 5400$ N. The fatigue behavior of the welded hybrid joints was characterized in load increase as well as constant amplitude tests with a servohydraulic test system for single overlap joints at a frequency of 5 Hz. The endurance limit for ultrasonically welded hybrid joints with surface pre-treated aluminum-sheets was determined to be approximately 35 % of the monotonic shear strength. The cyclic deformation behavior of the aluminum was described by load-displacement measurements using a strain gauge mounted on the aluminum in the area of the sonotrode mark. Due to the fact that ultrasonic metal welding is suitable to realize a direct contact between the load bearing carbon fibers and the aluminum it is possible to use the electrical conductivity between the joining partners to characterize fatigue properties. The measurement of the electrical resistance provides in contrast to the strain measurement direct and very sensitive results about damage processes under cyclic loading. The change in electrical resistivity is well suitable for welded hybrid joints and able to monitor the actual damage state during mechanical loading.

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