Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 10 (2011) 433–438
Engineering Procedia

ICM11

Damage Monitoring of Ultrasonically Welded Aluminum/ CFRP-Joints by Electrical Resistance Measurements

Frank Balle*, Stefan Huxhold, Guntram Wagner, Dietmar Eifler

Institute of Materials Science and Engineering, University of Kaiserslautern, P.O. Box 3049, 67653 Kaiserslautern, Germany

Abstract

Ultrasonic metal welding is well suited to realize aluminum alloy/carbon fiber reinforced polymer (CFRP) – joints. Beside monotonic properties the cyclic deformation behavior of ultrasonic welded aluminum/CFRP-joints was investigated. Load increase as well as constant amplitude tests were performed with a servohydraulic testing system at a frequency of 5 Hz. The joints are realized by temperature induced softening and mechanical replacing the polymer out of the welding zone as a result of the ultrasonic shear oscillation. In contrast to conventional joining procedures this is the pre-condition, which allows a direct contact between the carbon fibers and the aluminum. By the fact that the carbon fibers are welded directly onto the aluminum it is possible to use the hybrid welds as their own fatigue damage sensors. Therefore additional to standard mechanical data, the change in the electrical resistance ΔR is monitored during the fatigue tests and used to describe the actual fatigue status in detail. The evaluation of the fatigue results shows that the change in ΔR is much more reliable than the change in the displacement amplitude measured by strain gauges mounted on the surface of the Al- and CFRP-sheets because of the direct response out of the joining zone itself.

Selection and peer-review under responsibility of ICM11

Keywords: Ultrasonic welding, Hybrid joints, Fatigue, Monitoring, Electrical Resistance

Nomenclature

F_z: Tensile shear force	ΔR: Change in electrical resistance	$\dot{\varepsilon}$: Strain rate
F_a: Cyclic force amplitude	AP: Acid pickled	R: Rolled

* Corresponding author. Phone: ++49 (0) 631-205-3942; Fax:++49(0) 631-205 2137.
E-mail address: balle@mv.uni-kl.de.

1877-7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.074

1. Motivation and introduction

For the development of new hybrid lightweight products appropriate joining techniques are necessary. To ensure hybrid design concepts a detailed knowledge of monotonic and cyclic deformation behavior of joints made of dissimilar materials is essential.

Ultrasonic welding is a pressure welding technique, whereby the formation of the bond occurs as a result of a ultrasonic oscillation and a superimposed static welding force. In comparison to other joining techniques like adhesive bonding or brazing, ultrasonic welding is characterized by a low energy input, consequently low temperatures in the welding zone and very short welding times [1]. Current applications of this technology are plastic as well as metal welding [1, 2]. Until now ultrasonic plastic welding is typically used to join FRP to each other, but in the case of metal/FRP-joints the ultrasonic plastic welding method only enables adhesive joints between metal and polymer matrix and not directly with the load bearing fibers of the FRP, resulting in lower strength and stiffness of the joints. Recent results at the Institute of Material Science and Engineering (WKK) of the University of Kaiserslautern show, that carbon fiber textiles with or even without thermoplastic matrix can be welded to metals by ultrasonic metal welding [3, 4]. In contrast to all plastic welding techniques a direct contact between the carbon fiber reinforcement and the aluminum surface is realized by ultrasonic metal welding. Due to this fact it is possible to use the electrical conductivity between carbon fibers and metal for direct damage monitoring during mechanical loading of the hybrid welds. First the experimental setup for the production and testing of ultrasonically welded aluminum/CFRP-joints will be introduced followed by selected results of the mechanical behavior of the joints.

2. Materials, experimental setup and measurement methods

2.1. Base materials

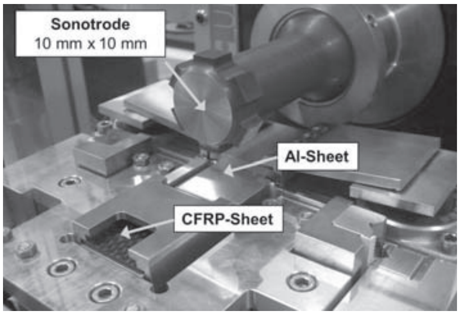
The non heat treatable aluminum wrought alloy (AA5754) was ultrasonically welded onto the carbon fiber reinforced thermoplastic composite made of polyamide 66 (CF-PA66) with a satin 5H-fabric of carbon fibers (Toray T300J) and a weight per unit area of 285 g/m². The tensile tests were performed in rolling 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 organic sheets is about 48%. It was manufactured in an autoclave process using six layers of CF-fabric at the University of Kaiserslautern in the framework of the research unit 524 supported by the German Research Foundation (DFG). The AA5754-sheets were welded in a work-hardened, thermally-softened and quarter-hard condition (H22). Selected mechanical properties of the base materials are summarized in table 1.

Table 1. Monotonic properties of the base 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

In this paper only modified and optimized industrial ultrasonic spot metal welding systems were used to join AA5754 and CFRP. One essential requirement for hybrid joints is to control the welding force during the joining process accurately by an integrated force measuring device. For this reason a special clamping system was developed at the WKK, see Fig. 1a. Furthermore, the welding system is equipped with several measuring devices to enable a high-resolution measurement of the main process parameters like welding force and welding energy. The specimen geometry is shown in Fig. 1b. The welding area of the sonotrode is 10 x 10 mm². Since it is not possible to determine the exact geometry of the joining area the shear strength is calculated by the ratio of the achieved tensile shear force F_Z related to the nominal sonotrode contact area.

(a) 

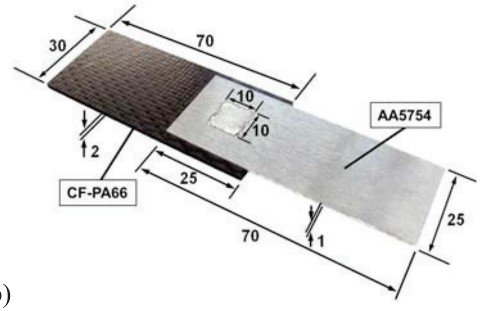
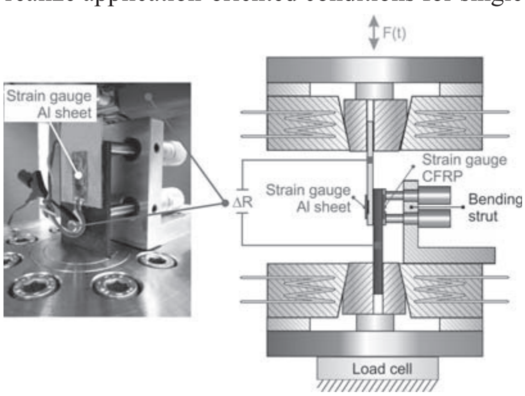
(b) 

Fig. 1. (a) Advanced ultrasonic spot welding system (b) Specimen geometry for Al/CFRP-joints

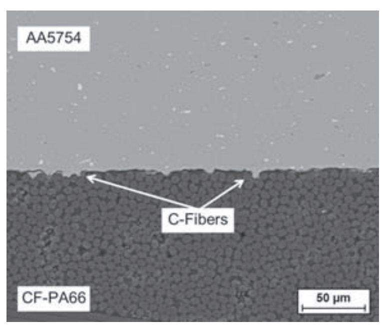
A statistical model named "central composite design circumscribed (CCC)" was used to find optimized process parameter combinations to weld the Al/CFRP-joints. For joints of AA5754 and CF-PA66 composites the following process parameters were systematically calculated and verified in tensile shear tests: Welding force of 160 N, oscillation amplitude of 40 µm and welding energy of 2160 Ws [3].

2.3. Experimental setup

Force-controlled fatigue tests were performed at ambient temperature with a frequency of 5Hz on a servohydraulic testing system MTS 858 with the experimental setup shown in Fig. 2a. For single overlap samples the hydraulic grip was modified and adjusted by a bending strut to avoid bending stresses. A constraint in loading direction is prohibited by the use of disks made of PTFE. A stress ratio of R > 0 was selected to realize application-oriented conditions for single overlap joints.



(a)



(b)

Fig. 2. (a) Fatigue testing setup for single overlap joints (real and schematic), (b) Cross section of the joining zone (SEM)

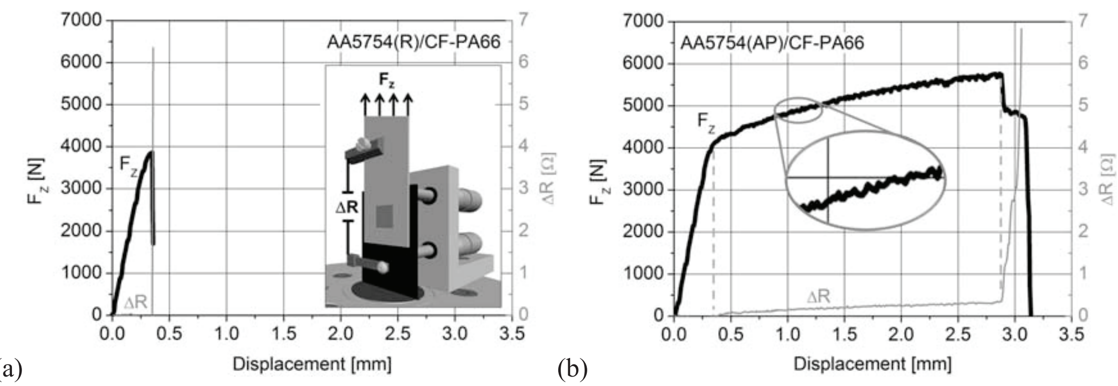
One intrinsic advantage of an ultrasonic oscillation parallel to the surface of the joining partners, which is typical for ultrasonic metal welding, is the possibility to realize a direct contact between the metal and the load bearing fibers of the reinforced composite. Thereby the welding process does not damage any fibers and electrical conductivity between fibers and metal sheet is generated. Scanning electron microscopic (SEM) investigations of the welding zones show that the ultrasonic metal welding process removes the matrix between the fiber reinforcement and the aluminum surface and allow the metallic surface to get into direct contact to the fibers [3], see Fig. 2b. Due to this fact the change in the electrical resistance ΔR is monitored during monotonic and cyclic loading additional to standard mechanical data. A DC-power supply enables reproducible electrical resistance measurements. The electric contact is applied by a screw into the CFRP-sheet and by a copper clamp with the Al-sheet. The electrical voltage is changing under mechanical load of the whole hybrid joint. Using Ohm´s law, it is possible to calculate the change in electrical resistance ΔR. Data logging and evaluation were realized with a LabView-based software module developed at WKK.

3. Results

3.1. Monotonic behavior of hybrid aluminum/CFRP-joints

Fig. 3a shows a load-displacement curve of an aluminum sheet in as rolled surface quality welded with a CF-PA66-sheet. The hybrid weld fails without any preliminary warning after purely elastic deformation at a load of $F_Z \approx 3860$ N [4]. Beside distance measurement also the change in electrical resistance is reflected by a prompt failure due to a sudden fracture in between aluminum and carbon fiber composite.

With chemical surface pre-treatments of the aluminum sheets, in nitric acid the tensile shear strength of the joints can be increased up to 54 MPa in average [4]. Furthermore the long-term stability can be improved significantly. The ultrasonic spot welded joints were tested after ageing of one and four weeks at different temperatures and humidities. Nearly no decrease of the tensile shear strength was determined and the mechanical properties of these joints are not affected by ageing effects at the chosen testing conditions [4].



(a) (b)

Fig. 3. Monotonic Load-Displacement- ($\dot{\varepsilon} = 0{,}2 \times 10^{-3}$ 1/s) and Load-Resistance Curves for (a) AA5754(R)/CF-PA66 and (b) AA5754(AP)/CF-PA66

Fig. 3b illustrats a characteristic load-displacement-curve for AA5754(AP)/CF-PA66-joints. After reaching the yield point of the entire joint at approximately 4000 N, plastic deformation occurs characterized by a flat discontinuous shape of the curve. This shape of the load-displacement-curve can be attributed to the so called PLC-effect [5] in the aluminum sheet, see detail in Fig. 3b.

In this test the electrical resistance was also measured. During elastic deformation of the weld no change in ΔR was observed. The first change of ΔR corresponds to the yield point of the joint, see first dashed line in Fig. 3b. After a linear course of ΔR due to plastic deformation and first Al-C-Fiber debonding a pronounced increase of ΔR was measured immediately before final failure of the hybrid weld, see second dashed line in Fig. 3b.

3.2. Fatigue behavior of hybrid aluminum/CFRP-joints

Besides monotonic loading, cyclic loading of ultrasonically welded hybrid joints was investigated. Stepwise load increase tests (LIT) were performed for a first estimation of the endurance limit and to determine appropriate stress amplitudes for constant amplitude tests. Beginning at a value of 250 N the cyclic force amplitude F_a was increased stepwise after 10^4 cycles at 250 N up to the failure. The maximum number of cycles was 2×10^6. Based on LIT selected constant amplitude tests were performed with the same test conditions to evaluate the endurance limit. In Fig. 4a the total mean strain $\varepsilon_{Al, m, t}$ of the Al sheet, the total mean strain $\varepsilon_{CFRP, m, t}$ of the CFRP sheet as well as the change in electrical resistance ΔR for a chemical pre-treated AA5754/CF-PA66 - joint are shown. The total mean strains don´t give an early indication of imminent fracture of the specimen. Due to the direct response out of the joining zone the course of the electrical resistance includes a clear indication of a developing fatigue damage in the joining zone. A first slight increase of the electrical resistance ΔR can be observed for more than $N = 4 \times 10^4$ cycles, Fig. 4a, point ❶. This first pronounced change in ΔR correlates with the observed endurance limit of these joints, see Woehler-curve in Figure 4b.

After $N = 7 \times 10^4$ cycles the course shows a pronounced increase, Figure 4a, point ❷, until final fracture occurs at $N = 9.5 \times 10^4$ cycles. The load level of point ❷ is equivalent to the yield point of the Al/CFRP-joint, see Figure 3b. Therefore the electrical resistance is a well suited and high sensitive physical value to determine the actual fatigue state of Al/CFRP-joints. In contrast to conventional strain measurement methods, which need a defined gauge length, the electrical resistance can be used for direct damage monitoring during mechanical loading of hybrid components.

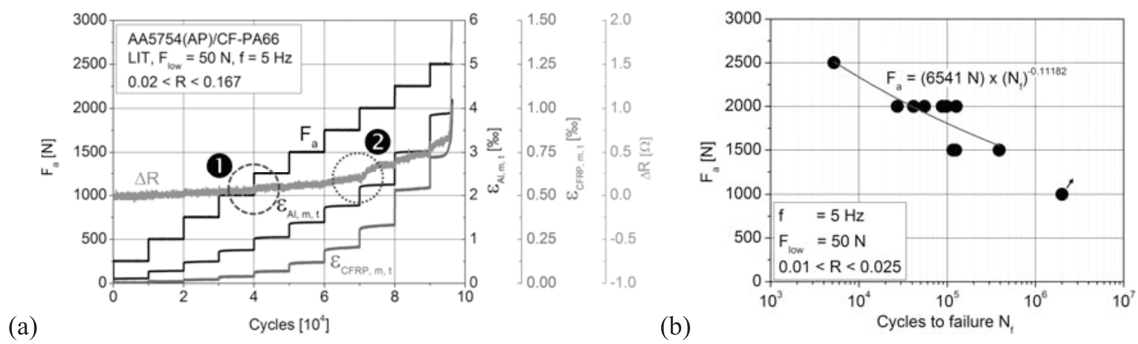


Fig. 4. (a) Displacement amplitude and change in el. resistance in stepwise load-increase tests for AA5754(AP)/CF-PA66-joints (b) Load-Woehler-Curve of ultrasonically welded AA5754(AP)/CF-PA66-joints

4. Conclusions

For the first time the ultrasonic metal welding technique was successfully applied to join metal sheets with CFRP. Using statistical test planning tensile shear strengths of more than 30 MPa were realized for suitable process parameters with AA5754/CF-PA66-joints [3]. This value can be increased up to 54 MPa by adapted surface pre-treatments of the aluminum sheet like pickling in nitric acid. Furthermore the long-term stability can be significantly influenced by this procedure [4]. The fatigue behavior of welded hybrid joints was investigated in load increase as well as constant amplitude tests at a servohydraulic testing system for single overlap joints at a frequency of 5 Hz. The cyclic deformation behavior was described with load-displacement measurements with strain gauges on the surface of both joining partners. The endurance limit for ultrasonically welded hybrid structures was determined to be approximately 35% of the monotonic strength of surface pre-treated joints.

During the ultrasonic welding process the polymer matrix is removed out of the welding zone. This allows a direct contact between the load bearing carbon fibers and the Al-sheet metal without any damage of the carbon fiber reinforcement. Due to the realized electrical conductivity between Al-sheets and carbon fibers it is possible to measure the change in electrical resistance ΔR during cyclic loading. In contrast to the strain measurement a direct answer out of the joining zone itself is realized by ΔR. This method is much more sensitive in respect of microstructural changes in the joining zone during mechanical loading than the strain gauges mounted on the surface of the joining partners.

The feasibility to join aluminum sheets to CFRP with high monotonic and cyclic strength allows a considerable extension of the application fields of ultrasonically welded components. With a detailed knowledge of the mechanical behavior and the possibility of an online health monitoring system, ultrasonic welding of hybrid structures is an attractive alternative to existing metal/polymer joining techniques like adhesive bonding or riveting.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for the financial support in the framework of the research unit 524. They further thank the state research “Center for Mathematical and Computational Modeling $(CM)^2$” at the University of Kaiserslautern for the financial co-support.

References

[1] Graff, K. *Ultrasonic metal welding.* In: New developments in advanced welding, Woodhead Publishing, 2005, p. 241-269

[2] Greitmann M.J., Adam T., Holzweißig H.G., et. al., *Techn. J. of Welding and all. Proc.*, DVS-Verlag GmbH, Düsseldorf 2003; Issue 5: 268-274

[3] Balle, F., Wagner, G., Eifler, D. Ultrasonic Metal Welding of Aluminum Sheets to Carbon Fiber Reinforced Thermoplastic Composites*. Adv. Eng. Mat.* 2009; **11**, No.1-2:35-39

[4] Balle F., Wagner, G., Eifler, D. *Joining of Aluminum 5754 Alloy to carbon fiber reinforced polymers (CFRP) by ultrasonic welding*. In: Aluminum Alloys: Fabrication, Characterization and Applications II, TMS (The Minerals, Metals & Materials Society), USA, 2009, p. 191-196

[5] Robinson, J. M., Serrated flow in aluminum base alloys. *Int. Mat. Reviews* 1994, **29**: 217-227