JOINING OF LIGHT METALS TO FIBER REINFORCED POLYMER COMPOSITES BY POWER ULTRASONICS

Frank Balle[1], Florian Staab[2] and Johannes Born[3]

[1;2]University of Kaiserslautern, Institute of Materials Science and Engineering (WKK)
P.O. Box 3049, 67653 Kaiserslautern, Germany
[1]Email: balle@mv.uni-kl.de, Web Page: www.uni-kl.de/WKK
[2]Email: staab@mv.uni-kl.de, Web Page: www.uni-kl.de/WKK
[3]Composite Technology Center GmbH, Stade
Email: johannes.born@airbus.com, Web Page: http://www.airbus.com

Keywords: Ultrasonic welding, Hybrid joining, Multi-material design, Aircraft industry, Light metals

Abstract

The application of joining techniques like ultrasonic welding allows a very efficient design of multi-material-components to enable a saturation of material-specific advantages and mechanical properties. Multi-material concepts offer highest potentials for weight saving and optimization of lightweight structures but inherit challenges as well.
The Institute of Materials Science and Engineering of the University of Kaiserslautern (WKK) has a long-time experience on ultrasonic welding of dissimilar materials, for example different kinds of CFRP, light metals or steels. The process parameters are optimized by statistical test planning methods and the validation via related mechanical properties.
This gained knowledge is now to be transferred to applications in aviation industry in cooperation with CTC GmbH (Stade) and Airbus Group (Bremen, Hamburg). Therefore aircraft-related materials are joined by ultrasonic welding. The applied process parameters are recorded and analyzed in detail to be interlinked with the resulting mechanical properties of the hybrid joints. Aircraft derived multi-material demonstrators will be designed, manufactured and tested with respect to its monotonic and fatigue properties as well as its resistance to aging.

1. Introduction

After the consequent evolution of CFRP usage in primary aircraft structures Airbus settled the A350XWB as the first composite aircraft within the Airbus family. Starting with military and secondary structure applications the utilization of CFRP in Airbus products steadily increased and will reach a next step with the introduction of the A350XWB-1000 in 2017. But reviewing the material breakdown of the aircraft with a structure weight share of 47% for titanium alloys, aluminium alloys, steel alloys and other material it can be concluded that the A350 aircraft is also one of the most sophisticated multi-material structures in aerospace so far [1].
Some of the key challenges of this hybrid aircraft are the joining of hybrid material stacks, the tolerance and gap management, stress optimized designs, robustness of joining method, automation and process costs [2]. Thus one of the main driver and key technologies for the development of next generation hybrid aircraft structures are suitable and new joining methods. The state of the art methods are mechanical fastening as well as bonding for metallic and composite structures. Regarding performance, costs and certification limits these methods open up potential for alternative joining techniques such as ultrasonic welding especially for hybrid structures. These could enable new disruptive structural concepts based e.g. on new integration sequences, design principles for structural mechanics and efficient joint geometries.
In the framework of a new research project, supported by the German Research Foundation (DFG), hybrid welds out of aluminium and titanium alloys to different carbon fiber reinforced thermoplastic

Excerpt from ISBN 978-3-00-053387-7

composites will be investigated from a basic point of view. Some selected results as well as future steps are presented in this paper as well as during the talk during ECCM17.

2. The technology of ultrasonic welding – main principle and process characteristics

The possibility to weld metals by ultrasonic energy was randomly discovered in the early 1930s in the United States. The original aim was to reduce the electrical contact resistance between metals during resistance welding by superimposed transversal ultrasonic oscillations. Thereby it was discovered that a joint can also be realized only by ultrasonic oscillation and without any weld current. Some years later ultrasonic metal welding was established for industrial productions. At the same time also many applications for ultrasonic plastic welding have been opened up, a welding variant which is characterized by an oscillation amplitude perpendicular to the welding zone [3]. Today both ultrasonic welding techniques have reached a significant relevance in industry. The ultrasonic plastic welding method is applied for thermoplastic packages of food and beverage. It is also established to join toys or housings of electronic components. For example ultrasonic metal welding is used to join cable harnesses of cars or multi-layer stack for batteries as well as for the production of airbag cap detonators [3, 4].
Ultrasonic metal welding is a solid state welding technique, where the formation of the bond occurs as a result of a moderate static pressure and a superimposed ultrasonic oscillation, which is parallel to the interface between the parts to be welded without fusion of the metals. In comparison to fusion welding or even 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 as well as moderate investment costs. The high frequency relative motion between the parts forms a solid state weld through progressive shearing and high plastic deformation between surface asperities that disperses oxides and contaminants. Consequently an increasing area of pure metal contact and finally bonding of the adjacent surfaces will be realized. The process is excellent for joining foils, thin to thicker sheets as well as joining wires to connectors in circuit boards. Most metals and their alloys can be ultrasonically welded. Various weld geometries like spot, torsion or roll seam welds can be realized by an adapted arrangement of the machine components and an appropriate design of the welding tool, called sonotrode, Figure 1a. Furthermore dissimilar metal combinations are easily welded with high power ultrasonics. Regarding the efficiency, automation capability, achievable mechanical and technological properties ultrasonic metal welding is a very attractive alternative to existing joining techniques for multi-material systems. The main influencing parameters can be split into process-related as well as materials induced limits of ultrasonic welded joints, see Figure 1b.

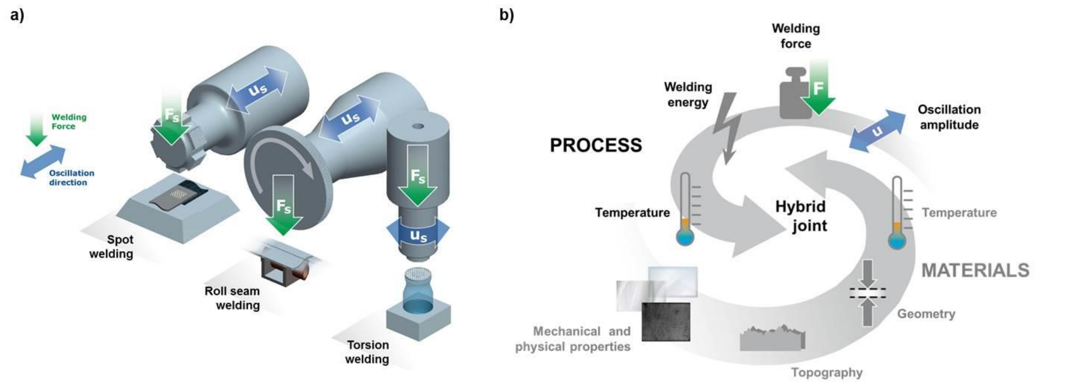

Figure 1. a) Variants of ultrasonic metal welding, b) significant influencing parameters

From a process view welding force, welding energy and oscillation amplitude should be optimized by statistical test methods (DoE), see also [5]. Besides chemical, physical and mechanical properties of the used materials the geometry of the upper joining partner is one of the most influencing factors due to the energy absorption in the material. Welds can be realized for a material thickness of up to 3 mm in case of aluminum. The geometry of the lower joining partner is less critical, whereas the topography of the specimen surface becomes important. The achieved temperatures during ultrasonic welding are

Excerpt from ISBN 978-3-00-053387-7

typically well below the melting points of the metals. A higher temperature can enhance the pressure welding process due to improved ductility, but is not required, see also [7].

3. Ultrasonic welding of light metals to fiber reinforced polymers – selected results

Ultrasonic (US) spot welding is the most common variant of US metal welding and was investigated to join different aluminum alloys (AA1050, AA5754 and AA2024) to carbon fiber reinforced polymers (CFRP). A constant thickness of 1 mm for all aluminum sheets and 2 mm for the carbon fiber fabric reinforced polymer with PA66 matrix and a fiber volume fraction of 48% were chosen.
In case of joining metals to reinforced polymers, ultrasonic plastic as well as ultrasonic metal welding was considered in general. The optimized process parameters for both variants and the related achievable tensile shear strengths of AA5754/CFRP-joints are summarized in Figure 2a. Ultrasonic plastic welding is characterized by ultrasonic oscillations perpendicular to the sheet surface to be welded. So this welding method only realizes adhesive bonds between the polymer matrices of the CFRP and the aluminum surface corresponding to lower strengths in comparison to ultrasonically metal welded joints, see Figure 2b.
In difference to plastic welding, ultrasonic metal welding is characterized by ultrasonic oscillations parallel to the metal surface. As a result the polymer matrix is softened and squeezed out of the welding zone underneath the sonotrode. For ultrasonic metal welded joints it could be proven that both an intermolecular contact and a mechanical interlocking of the load bearing carbon fibers of the CFRP and the aluminum surface developed during ultrasonic metal welding, see Figure 2c. Furthermore, no damage of the carbon fibers was observed in the cross section. Based on this experience, only ultrasonic metal welding has been pursued for joining light alloys like AA1050, AA5754 and AA2024 to fiber reinforced polymer composites.

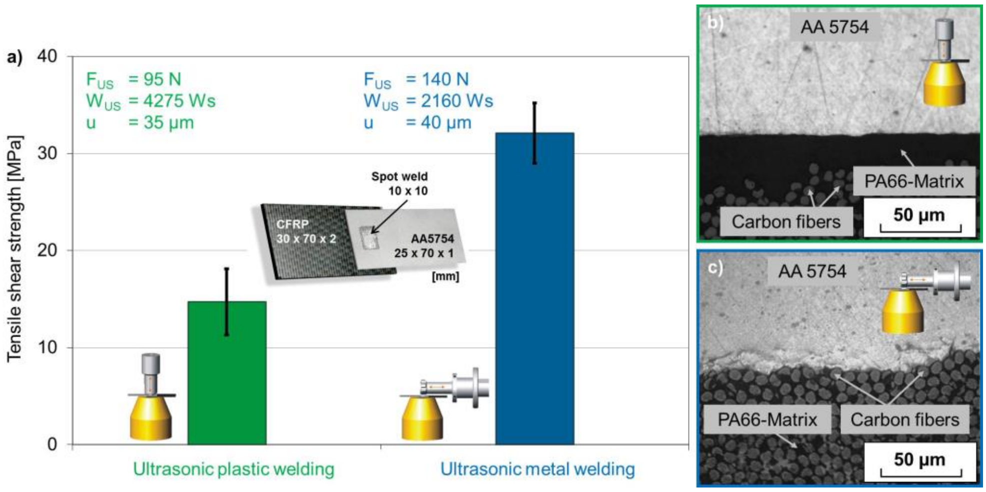

Figure 2. a) Comparison of ultrasonic plastic and metal welding for AA5754/CF-PA66-joints, b) Cross section of plastic welded joint, c) Microstructure of metal welded Al/CFRP-joint

In case of AA1050/CF-PA66 the calculated and experimentally approved process parameter triple realized the best possible interface properties: The failure under tensile shear loading occurs in the aluminum sheet outside the joining area and not at the interface, see Figure 3. So the ultimate tensile strength (UTS) of the AA1050 sheet limits the achievable strength of the hybrid joints, see also [6]. To increase the entire strength of Al/CFRP-joints the UTS of the aluminum base materials has to be increased. So the self-hardening aluminum alloy AA5754 as well as the precipitation hardening aluminum alloy AA2024 was taken into account to achieve a much higher joint strength. All Al/CFRP-joints were optimised using identical statistical test procedures. For AA1050/CF-PA66-joints the appropriate parameters lead to tensile shear forces up to 2460 N corresponding to tensile shear strength of 25 MPa [6].Since it was 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 related to the squared sonotrode contact area with 100 mm². By using AA5754 the tensile shear strength can be improved up to 32 MPa without surface pre-treatment and up to 54 MPa using chemical surface pre-treatment of the aluminum AA5754 surface in nitric acid, see Figure 3.

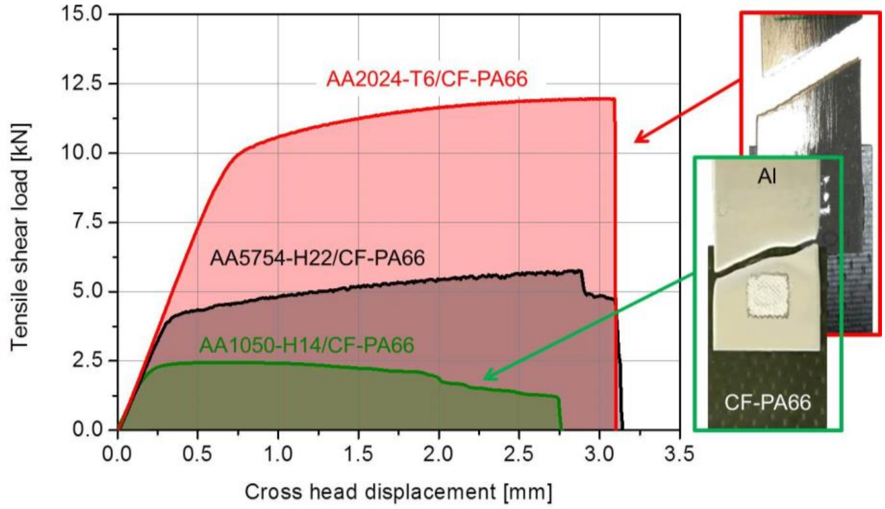

Figure 3. Tensile shear behavior of AA1050, AA5754 and AA2024/CF-PA66-joints

The surface finish of the aluminum sheets strongly influences the formation of the hybrid interface. Acid pickling of AA5754 leads to microstructural surface roughness corresponding to mechanical interlocking with the thermoplastic matrix [8]. Ultrasonically welded AA5754/CF-PA66-joints achieve joint strengths, which are above the yield strength of the aluminum, see Figure 3. However, the plastic deformation of the AA5754 sheets leads to a proceeding damage in the interfacial area followed by final fracture. The higher yield strength of the precipitation hardening aluminum alloy AA2024 offers higher strengths. But for joining AA2024 with CFRP by ultrasonic metal welding a sufficient deformation capability is necessary. For this reason an adapted coupled welding process has been developed. In a first step the AA2024 sheet was solution annealed at 500°C for 60 minutes [9]. After water quenching, the ductile aluminum sheet was promptly welded to the CFRP within 15 minutes and finally artificial aged. As a result the maximum improvement of the strength was realized for AA2024/CF-PA66-joints with up to 113 MPa. The real interfacial strength could not be determined due to failure of the AA2024 itself, see Figure 3.
Beside the ultrasonic spot welding approach first welding experiments by the use of torsional modes and a ring-shaped sonotrode have been realized, see Figure 4.

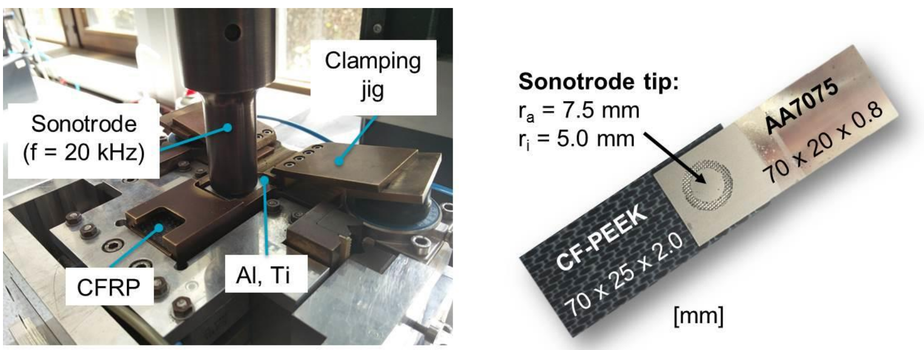

Figure 4. Used ultrasonic torsion welding system and torsion welded Al/CFRP-joint

In this case the necessary welding energy is introduced as a transversal wave into the upper joining partner. The torsional ultrasonic welding process possesses the advantage that highest generator power up to 10 kW is accessible. The aerospace Al alloy AA7075 in condition T6 (solution annealed and artificially aged) was chosen as the upper joining partner with a thickness of 0.8 mm. The lower

Excerpt from ISBN 978-3-00-053387-7

joining partner was a carbon fiber satin fabric reinforced PEEK sheet with a thickness of 2 mm. The experimental setup of the ultrasonic torsion welding system (TSP 3000, Telsonic Ultrasonics, 6.5 kW) and a successfully welded AA7075/CF-PEEK-joint is shown in Figure 4. Further results and information will be given during the talk at ECCM17.

3. Final remarks and future steps

Ultrasonic metal welding is one promising technique to realized hybrid joints. Possible applications fields can be seen in future vehicles and aircrafts concerning multi-material concepts. Besides the discussed Al to CFRP joints ultrasonic metal welding is well suited to realize welds of ductile to brittle materials like metal to glasses or metals to ceramics. Further details are described in [7].
With increasing possibilities in material design, the material-related challenges raise as well. Due to a critical electro-chemical potential, a direct contact of aluminum based metals with CFRP structures has to be avoided, especially for aerospace applications. With a potential difference of 0.9 V in a 3% salt solution, the combination of Al/CFRP must be regarded as critical for galvanic corrosion. Therefore two corrosion resistant multi material concepts were drafted and will be studied in future. On the one hand a CFRP with an isolating glassfibre fabric will be examined. Furthermore commercially pure titanium (cp-Ti grade 1) interlayers will be examined to realize robust CFRP to Al-based structures. Finally ultrasonic welding experiments will be performed to join aerospace titanium alloys to aerospace thermoplastic composites (CF-PPS and CF-PEEK) in a direct and robust manner.

Acknowledgments

We thank the German Research Foundation (DFG) for financial support in the framework of the research project BA 4073/9-1 as well as the project partners CTC (Stade) and Airbus Group (Bremen, Hamburg) for the support of metal sheets and composites as well as fruitful discussions.

References and further reading

[1] T. Stöven, Bonded Airframe Structures; *„TechnoBond“,Memmingen*; Airbus Materials & Processes, Oral presentation, 2013
[2] B. Knickrehm, J. Jendrny, A brief story of technical challenges in the aerospace industry – Of rates and reach; *18. Paderborner Symposium Fügetechnik*; Oral presentation, 2013
[3] K. Graff, *New developments in advanced welding*, chapter 9, Woodhead Publishing, 2005
[4] J. Rotheiser, Ultrasonic Welding, In: *Joining of Plastics*, Carl Hanser Verlag, Munich, 2004
[5] F. Balle, D. Eifler, Statistical test planning for ultrasonic welding of dissimilar materials using the example of aluminum-carbon fiber reinforced polymers (CFRP) joints, *Mat. Sci. and Eng*. Techn., 43(4), 286-292, 2012
[6] F. Balle, G. Wagner, D. Eifler, Ultrasonic Spot Welding of Aluminum Sheet/Carbon Fiber Reinforced Polymer Joints”, *Mat. Sci. and Eng. Techn.*, 38(11), 934-938, 2007
[7] G. Wagner, F. Balle, D. Eifler, Ultrasonic Welding of Hybrid Joints, *Journal of the Minerals, Metals and Materials Society (JOM)*, 64(3), 401-406, 2012
[8] F. Balle, S. Emrich, G. Wagner. et al., Improvement of ultrasonically welded aluminum/carbon fiber reinforced polymer-joints by surface technology and high resolution analysis”, *Adv. Eng. Mat.*, 15, No.9, 814-820, 2013
[9] F. Balle, S. Huxhold, S. Emrich et al., Influence of Heat Treatments on the Mechanical Properties of Ultrasonic Welded AA2024/CF-PA66-Joints, *Adv. Eng. Mat.*, 15, No.9, 837-845, 2013

Excerpt from ISBN 978-3-00-053387-7