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Novel method for joining CFRP to aluminium

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Abstract

The current state of the art in joining of carbon-fibre reinforced composites (CFRP) to metals such as aluminium is - for the case of aircraft structures, e.g. - riveting or bolting. However, to reduce structural weight and improve structural performance, integral, load-bearing aluminium-CFRP-structures are desirable. To produce such structures, a novel joint configuration together with an appropriate thermal, laser-based joining process is suggested by the authors.

In this paper, the joint configuration (based on CFRP-Ti-aluminium joints) and the laser beam conduction welding process will be presented, and first specimens obtained will be discussed with respect to their properties. It will be shown that the novel approach is in principle suitable to produce load-bearing CFRP-aluminium structures.

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1. Introduction

Combinations of carbon fibre reinforced composites (CFRP) and metals are increasingly used to adapt local structural properties to specific local requirements. Typical examples for such hybrid structures can be found in products from the aerospace industry (e.g. hull segments), the car industry (e.g. CFRP roof structures), but also in general mechanical engineering (e.g. rotor blade elements). In all these structures, joining of CFRP components to metallic components (mostly made from aluminium) is required.

For joining CFRPs to CFRPs and to metals, both thermal as well as non-thermal processes have been applied so far (see e.g. [1, 2]). In the first group, processes such as bolting or riveting [3, 4] as well as adhesive bonding [3, 5] and loop connections [6] can be found. The industrial use of these processes is widespread (see e.g. [7]), and they have been extensively investigated both experimentally and theoretically with respect to process parameters and properties. In special, both mechanical joining as well as adhesive bonding was already considered for joining of CFRP-metal-structures. As an example, Gross and Schäfer have reported a combined riveted and adhesive bonded CFRP-aluminium joint as early as 1990 [8].

In the second group – welding processes for CFRPs to CFRPs and to metals [5] – vibration [9] or ultrasonic welding (e.g. [10, 11]) are paramount. A combination of both thermal and non-thermal joining is the process vibration welding / adhesive bonding [12]. Jauss et al. are reporting a process utilising microwaves in combination with a filler metal of defined electrical conductivity to achieve local melting of the matrix [13]. More recently, Moser et al. propose an induction welding process for thermoplastic fibre-plastic-compounds, also utilising electrically conductive filler material (wire fabric of stainless steel 1.4301) [14]. Wise [15] is also considering the use of electrically conductive filler materials, in his case applying thermoplastic films with an electrically conductive layer as an intermediate layer between aluminium and CFRP. These films are then molten with the help of an electrical current applied to the joining zone, and an adhesive bond between aluminium and CFRP is formed. However, all these thermal processes share the basic characteristic that, by partially melting the matrix material of the CFRP, a solely adhesive bond to the metal surface is formed.

Taking into account both thermal and non-thermal processes, it can be concluded that all approaches pursued so far for joining of CFRPs to metals do not result in an integral CFRP-metal structure. In special, this means that no joint between the fibres of the CFRP and the metallic structure is obtained, which limits the load-bearing capacity of the joint. Moreover, as both thermal and non-thermal joining concepts normally require an overlap of the joining partners, significant disadvantages with respect to structural weight often have to be taken into account. As a consequence, a novel design together with an appropriate joining process is required to improve this situation especially for CFRP-aluminium structures, which are of greatest industrial interest at the moment.

2. Aim and scope

The investigations reported and discussed in the following were undertaken to demonstrate the principle feasibility of a novel, integral design and joining process for load-bearing CFRP-aluminium structures. To this end, the novel design approach proposed by the authors as well as the joining process and system technology developed to produce these joints according to the proposed design will be reported. Moreover, first experimental results will be reported and discussed, also with respect to joint properties.

3. Description of novel approach

The novel design approach is sketched in figure 1. It is based on the production of a fabric of carbon fibres and titanium wires, which is then thermally joined to the aluminium metallic structure. As a thermal joining process, the authors propose a heat conduction laser beam welding process, operated such that only the aluminium structure is molten in order to create a brazed bond to the titanium wire structure. Subsequently, the fabric is then immersed with the matrix material, and an integral CFRP-aluminium structure is formed [16].
Fig. 1. Principle design approach for integral CFRP-aluminium structures

4. Experimental

4.1. Materials

Alloy EN AW-6056 T6 (Alcan), which is widespread in the aircraft industries, was used for the aluminium side of the structure. The material was milled to obtain a groove with a width of 2 mm and a depth of 1 mm to receive the titanium wire structure, and to obtain an accumulation of aluminium material in the joining zone for wetting the titanium wire structure (see figure 2). The as-milled thickness of the material was 2 mm. Prior to welding, the aluminium surface was pickled.

The titanium wire (ERTi2, Hufnagel GmbH, Bretten) with a diameter of 0.8 mm was cold-formed to obtain a 2-dimensional loop structure with a principal radius of 2.5 mm. The main constituents of the titanium wire are given in table 1.

Table 1. Composition of titanium wire ERTi2 (Hufnagel GmbH, Bretten)

| Element | Al | C  | Fe | H  | N  | O  | Si | Ti |
|---------|----|----|----|----|----|----|----|----|
| weight-% (min) | 0.01 | 0.011 | 0.05 | 0.003 | 0.014 | 0.1 | 0.01 | rest |

For the CFRP side of the structure, a HTS 5631 24k thread (Toho Tenax Europe GmbH) consisting of 24,000 filaments with a diameter of 7 μm was used. After welding, the fibers were immersed by a two-component epoxy resin (Biresin, Sika Deutschland GmbH).
4.2. Experimental set-up for the joining process

For joining the titanium wire structure (2 wires) to the aluminium material, a double-sided laser beam heat conduction welding process was applied (figure 2). The principle of the set-up during joining is given in figure 2.

As illustrated in figure 2, the aluminium and the titanium wire structure were arranged in a vertical position with the aluminium on top. The defocused laser beam (lamp-pumped Nd:YAG laser HL 4006D) was then directed onto the joining zone, simultaneously irradiating both sides of the specimen. During processing, the laser beam was travelling along the aluminium edge, thus creating an aluminium melt pool. Supported by the action of gravity and a certain amount of pre-heating of the titanium wire by the laser beam and by heat conduction from the aluminium melt pool, the aluminium melt wetted the titanium wire structure without melting it. Thus, a brazed bond between the aluminium and the titanium was created.

Figure 3 gives a side view of the gantry-type test plant used for the joining experiments. Two welding heads mounted on the gantry and equipped with a shielding gas chamber flooded by argon were moved along the joining path. The specimens were fixed in a clamping device that consists of two parts. The lower part positions the titanium wire structure. The upper part was designed as a pressure roller head, which is aligned with the laser working heads and exerts a force in horizontal and vertical direction to keep the samples in position during joining.

Fig. 2. Principle of the set-up during joining

Fig. 3. Test plant for the joining experiments (side view)
4.3. Experimental procedure

The experimental procedure was as follows: The aluminium and the titanium wire were positioned and fixed in the clamping device. Then, the titanium-aluminium structure was welded in two steps. In the first step (i.e. the first weld pass), the aluminium and titanium were heated and an aluminium melt pool was formed, resulting in some brazed areas. In the second, immediately subsequent step (i.e. the second weld pass), due to a pre-heating of the materials by the first pass and an increased heat transfer between both materials, a complete wetting of the titanium wire structure in the joining zone was achieved. In both steps, typical processing parameters were a laser power of 1.4 kW at each side at a spot diameter of 8 mm. A typical welding speed was 0.22 m/min. For simplicity, in these experiments the carbon fibres were threaded into the titanium loops after joining. In the final process, it is planned to perform this prior to welding. In the final step, the fibres were immersed with a two-component epoxy resin as matrix material.

4.4. Characterisation of specimens

Aside from a visual examination and evaluation of seam surface quality, cross sections were extracted from all welded specimens and subjected to metallographic analysis. In special, the wetting of the titanium wire structure and the heat-affected zone were investigated by optical microscopy (magnification 20). Moreover, phase layer thickness at the contact zone of the titanium wire to the aluminium alloy was measured by optical microscopy (magnification 12.5, 200 and 500). For etching, a molybdenum-based etchant was used. Additionally, some first specimens were subjected to static tensile testing (specimen dimensions 125 mm x 30 mm), and fracture behaviour was evaluated.

5. Results

5.1. General observations and seam appearance

Figure 4 gives a side view of a welded specimen with a total weld length of approximately 190 mm. The seam itself was smooth and free of ripples and cracks. At a distance of approximately 80 mm from the start (left side), seam width was fairly constant (110 mm). The titanium wires did not exhibit any discoloration.
The top view (figure 5) reveals that the titanium wire regions close to the aluminium were nearly completely wetted by the aluminium melt. However, some irregularities were observed.

![Fig. 5. Top view of welded specimen (aluminium + titanium wire)](image)

5.2. Metallographic examination

A macroscopic cross-section through the joining zone substantiates the good wetting of the titanium wires by the aluminium melt. The overall weld geometry is characterised by an agglomeration of weld metal close to the titanium structure and a relative lack of weld metal close to the solid aluminium, resulting in a seam thickness lower than the aluminium sheet thickness.

![Fig. 6. Macroscopic cross-section of joining zone](image)

A closer look at the interfacial zone between the aluminium weld metal and the titanium wire substantiates complete wetting of the titanium wire by the aluminium melt (Figure 7).

![Fig. 7. Interfacial zone between aluminium weld metal and titanium wire](image)
Further investigations show that between the aluminium weld metal and the titanium wire, an intermetallic phase layer with a thickness of approx. 1.2 μm was formed (figure 8).

Fig. 8. Intermetallic phase layer

In all cross-sections, the aluminium weld metal itself was free of cracks and pores.

5.3. Fracture behaviour

Figure 9 depicts a fractured test specimen (complete test specimen with carbon fibres and matrix) after static tensile testing. The fracture started with delaminations of the matrix at the interfacial zone to the aluminium weld metal. Complete failure of the specimen occurred by subsequent failure of the titanium wires close to the aluminium weld. Only in some cases, the fracture path was through the aluminium weld metal.

Fig. 9. Fractured test specimen with a close-up of fracture zone in the titanium wire (IWT Foundation Institute for Materials Science)

6. Discussion

The investigations reported were aimed at demonstrating the principle feasibility of the suggested novel approach of joining CFRP to aluminium via a titanium wire structure.

With respect to the thermal joining of the aluminium structure to the titanium wire structure using a double-sided laser welding process, we find that a wetting of the titanium wire by the aluminium melt pool without melting the wire can be achieved. While the regularity of the weld seam in the aluminium is satisfactory from a certain distance of the start of the weld (when a stationary temperature field is obtained), wetting still shows some irregularities. Although wetting of the titanium wire region close to the aluminium was complete in most cases, in some areas the cross section of the titanium wire was not completely wetted (see e.g. figure 6). This will require a further
optimisation of the temperature field of the process as well as a positioning of the titanium wire structure with improved accuracy and reproducibility.

The shielding gas supply was apparently excellent, as no discolouration of the titanium was observed. This indicates that it should also be possible to join a titanium/carbon fibre structure (where an excessive heating of the carbon fibre and an access of oxygen to the processing zone have to be absolutely avoided), which is the desired standard procedure.

The microstructural integrity of the weld metal with respect to cracks and pores does not raise any concerns. Intermetallic phases between the aluminium and the steel were observed, however with a thickness of less than 1.2 μm considered being not harmful to tensile properties [17]. However, weld geometry will have to be optimised further (e.g. by optimising the design of the aluminium profile prior to welding) in order to avoid excessive weld sagging, thus weakening the structure.

Static tensile testing illustrated typical potential fracture locations. While delaminations of the interfacial zone may often be associated with failure, the crack location will depend on the final design of the joints. In our first tests, with a relatively small load-bearing cross section of the titanium wire structure, failure in the titanium was to be expected in spite of weld geometry. Further work will therefore have to focus on optimising the design of all elements of the joint in order to obtain optimum fracture behaviour in both static and dynamic tensile testing.

7. Conclusions

The investigations reported and discussed in this paper were undertaken to demonstrate the principle feasibility of a novel, integral design and joining process for load-bearing CFRP-aluminium structures. It was shown that the suggested joint configuration based on CFRP-Ti-aluminium joints can be produced using a laser beam heat conduction welding process. In special, it was shown that regular weld seams in aluminium with a good wetting of the titanium structure can be obtained. Static tensile testing of the complete structure revealed typical fracture paths and indicated potential approaches for design optimisation.

All in all, it should have been demonstrated that the novel approach is in principle suitable to produce load-bearing CFRP-aluminium structures.

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