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Assessment of alternative joining techniques for Ti–6Al–4V/CFRP hybrid joints regarding tensile and fatigue strength

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ABSTRACT

CFRP and titanium joints are used in the aerospace industry. These materials are usually joined by titanium rivets which are inserted into holes drilled through both materials. Conventional riveted hybrid joints of CFRP and titanium parts fail under quasi static loading due to the uneven load distribution at the titanium rivets. Under cyclic loading, the fatigue failure occurs mainly in the titanium part because of the higher notch sensitivity. The aim of this work is the comparison of different joining concepts in terms of stiffness, strength and fatigue limit. First, laser riveting, here titanium pins are Nd:YAG laser beam welded to the Ti–6Al–4V parts. Second, conventional riveted hybrid joint is combined with adhesive bonding. Third, surface structuring of the Ti–6Al–4V parts is used to enhance friction in the riveted joint. Tensile and fatigue tests as well as fractographical examinations are performed to establish the process–property–performance relationship of the hybrid joints. Laser riveting leads to higher stiffness but equal strength, when compared to conventional riveted joints. Fatigue life is improved by the implementation of adhesive bonding and surface structuring.

1. Introduction

New joining concepts and manufacturing technologies have been developed by the transportation industries to permit the use of lightweight structures to reduce carbon dioxide emissions and fuel consumption. To fulfil these goals, materials with a high strength-to-density-ratio, such as carbon fibre reinforced plastic (CFRP) and titanium are extensively used in modern aircraft structures [1,2]. The titanium alloy Ti–6Al–4V possesses high strength, sufficient ductility, low density and high corrosion resistance. Titanium is the only lightweight metal that can be directly attached to the CFRP structures without risking the development of corrosion defects [3].

The current overlap joining method for CFRP and titanium is still based on classical riveting technology. There are only few publications about alternative joining methods for titanium with CFRP available [4–12]. Adhesive bonding as direct alternative to riveting has been used for aircraft primary structures [4,13]. However, the bonding of CFRP to titanium has still some obstacles to overcame due to the realization of proper and repeatable surface preparation of titanium and not controllable alteration of adhesive bonded joints [5,13]. Syassen et al. patented the method for joining of titanium alloys to CFRP by ultrasonic welding [6]. The ultrasonic welded bonds should have good properties with regard to the resistance to shear forces, corrosion resistance and durability and should be suitable for use in aircraft or spacecraft. Altmeyer et al. described the feasibility study of application the friction riveting for joining of grade 3 titanium with a short carbon fibre-reinforced polyether ether ketone [7]. The mechanical performance of the joints was only investigated in a tensile pull-out force test. Kocian et al. described hybrid structures of composites with integrated titanium layers, namely Ti-CF/PEEK laminates [8]. The hybrid structures can be adhesive bonded to titanium and composite and serve as a transition part between titanium and composite. Similar approach investigated by the researcher group named "Black-Silver" [9]. The purpose of realization of hybrid structures by integration of titanium wires and titanium foils in the composites is to create the transition structures in fibre reinforced plastic aluminium compounds. However, the alternative joining techniques mentioned above were not investigated for joining of titanium with high strength duroplast CFRP materials that are typically used for primary airframe structures, where the behaviour of hybrid joints with regard to the residual strength and fatigue is of the great importance.

The objective of the research was the development of alternative joining methods to achieve improved strength and fatigue limit properties for the hybrid joint zone (HJZ) between titanium and CFRP. One approach is using laser beam welding (LBW) as a

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joining technology [10–12]. LBW (denoted also as laser riveting of Ti–6Al–4V/CFRP lap joint) process was developed and optimised in terms of the temperature distribution to avoid thermal damage of CFRP structure, the interface properties and the mechanical structure of the hybrid joint zone. Further approaches investigated in this study included the combination of an adhesive film, rivets and the use of a surface structured Ti–6Al–4V part to obtain a reinforcing pinning effect. Both a classical riveted joint and the modified hybrid joint zones were tested in standard tensile and fatigue tests to understand and compare their properties and failure mechanisms.

2. Experimental

2.1. Materials

A 2.5 mm thick Ti–6Al–4V sheet (grade 5, annealed) was lap joined to the CFRP material using different modified joint types to improve the load distribution compared with a conventional Ti–6Al–4V/CFRP rivet lap joint (reference joint). Additionally, the lap joint was used to assess changes to the tensile strength and fatigue life. The CFRP material consisted of M21E/34%/134/IMA-12K laminate with 20 ply layups of 25-mm × 200-mm plates that were 2.5 mm thick. The layup orientation is shown in Table 1. The layup with the highest ultimate tensile load for the three different orientations was chosen for use in these experiments. Titanium rivets (HI-LITE–EN6115 T3-4) with shaft diameters of 4.8 mm and with protruding heads were used for the reference joint. Seven different Ti–6Al–4V/CFRP lap joint configurations were investigated. Three conventional HI-LITE rivets were used for a reference joint and were manually fastened to join a CFRP sheet to a Ti–6Al–4V plate (Fig. 1(a)).

Pins with diameters of 4.8 mm and 2.0 mm used for the laser riveting were fabricated from annealed Ti–6Al–4V titanium alloy rods. The heads of the pins were 9.0 mm and 4.0 mm in diameter, and the shafts were 4.8 mm and 2.0 mm in diameter, respectively.

Three types of laser riveted Ti–6Al–4V/CFRP lap joints were produced. The first type used 3 × 4.8-mm pins and was geometrically similar to a conventional lap joint. For other types of joints, the pin diameter, number and arrangement were modified to achieve a more even load distribution within the lap area. An array of 18 × 2.0-mm pins was implemented, which led to the second type of laser riveted Ti–6Al–4V/CFRP lap joints. The number of 2.0-mm pins (18) was set to realize an equivalent total area that is comparable to the reference joint with 3 × 4.8-mm rivets.

The CFRP material can be affected by the heat imparted into the materials during laser beam welding. A reference sample containing the same array of 18 × 2.0-mm pins was produced, whereas another sample used steel 42CrMo4 QT screws that were substituted for the Ti–6Al–4V pins. Steel 42CrMo4 QT screws were chosen because of their low cost and high shear strength compared to Ti–6Al–4V titanium alloy pins. Additionally, this choice was made to show that the heat input did not influence the mechanical behaviour of laser riveted Ti–6Al–4V/CFRP lap joints when subjected to static and cyclic load. The third type of specimen used a combination of 2 × 4.8-mm pins and 11 × 2.0-mm pins to additionally reinforce the lap joint.

An alternative approach for improving the load distribution was employing adhesive bonded Ti–6Al–4V/CFRP lap joints, which were drilled and fastened with HI-LITEs to create a reinforced bonded joint (adhesive bonded and joined with 3 × 4.8-mm conventional rivets). Cleaning and an abrasive treatment with a plastic blasting media of medium hardness were applied as a surface pre-treatment for CFRP parts before adhesive bonding. Based on a study published by Kwakernaak et al. [13] a promising surface treatment consisted of cleaning, grit-blasting with an aluminium oxide and cleaning followed by a sol–gel treatment was chosen for Ti–6Al–4V parts. The bonding agent was made of the BR 127 primer and FM 73 epoxy. As shown in Fig. 11 the thickness of the adhesive layer was about 160 μm.

By way of substitution for adhesive bonding, the Ti–6Al–4V part was surface structured with a number of pyramids machined into the surface to obtain a reinforcing pinning effect (Fig. 1(b)). This approach is similar to the work of Ucsnik et al. [14] and Parkes et al. [15]. The surface structured Ti–6Al–4V parts were milled out of 4.0 mm Ti–6Al–4V parts. Curing of the pressed together Ti–6Al–4V and CFRP parts was accomplished in the autoclave. The cross section of Ti–6Al–4V/CFRP joints shows a good penetration of the pyramid into the CFRP material (Fig. 12). After curing the joints were drilled and fastened with HI-LITEs (surface structured and joined with 3 × 4.8-mm conventional rivets).

The overlapping area for all of the investigated titanium-CFRP specimens subjected to mechanical testing was 77 mm × 25 mm.

2.2. Laser riveting

The Ti–6Al–4V sheet and CFRP specimen were match-drilled together and dried cleaned afterward joining. The Ti–6Al–4V pins were cleaned in an alcohol solution prior to being placed in an ultrasonic bath and pushed through the holes of the plates with the head on the free surface of the CFRP plate. The parts were then clamped to the working table under the laser and welded via laser beam, as shown in Fig. 2(a). To ensure a tight joining via laser riveting, a pneumatic system was used to preload the CFRP part to the Ti–6Al–4V part. Standard pneumatic cylinders were used to realize a simple but effective clamping system: by a central argon pressure of 0.0, 1.5 and 8.0 bar applied to the cylinders a blank holder consisting of two parts was pressed downward on the CFRP part, keeping the CFRP and the Ti–6Al–4V part in a fixed position during the laser riveting process. By the use of an argon driven pneumatic system no oxygen contamination could occur.

The Ti–6Al–4V sheet and CFRP specimen were lap joined by a continuous wave 3.3 kW Nd:YAG laser. A six-axis robot (KUKA KR 30 HA) was used to move the approximately 0.4 mm diameter laser beam. The specimens were fixed in an open box filled with Ar shielding gas to protect the Ti–6Al–4V weld bead from ambient air during the LBW process. Fig. 2(b) shows a macrograph of a laser riveted specimen with 11 × 2.0 mm pins and 2 × 4.8-mm pins.

The fixed laser riveting process parameters included the welding speed, Ar shielding gas and the clamping system. The parameters optimised for the laser riveting of the hybrid joints were the laser beam power, the structure preloading, the welding start and end points and the welding sequence.

2.3. Microstructural and mechanical characterization

The microstructure of joints was studied using an optical microscope and SEM with electron back-scatter diffraction (EBSD). The EBSD measurements were performed for a specimen area of

Table 1
Fibre orientations of the CFRP laminate layups.

Ply	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Direction	45	−45	0	90	−45	45	0	0	90	0	0	90	0	0	45	−45	90	0	−45	45