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A strength-model for laser joined hybrid aluminum–titanium transition structures

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ABSTRACT

Besides aluminum (Al) and titanium (Ti) alloys carbon fiber reinforced plastics (CFRP) are increasingly demanded for modern aircraft structures. Therefore, suitable Al–Ti and Al–CFRP joining techniques are of great interest. A novel concept for Al–CFRP joints uses titanium laminates as transition elements. In this paper, the tensile strengths of double-sided laser beam joined hybrid structures of aluminum sheets and single-layer as well as multi-layer titanium parts are investigated by varying the edge shape and the laminate build-up. The full-double-15°-scarf-edges produce the maximum strength. It is shown that a model can explain and predict the different failure behaviors and strengths.

1. Introduction

Multi-material-design is an approach of great and currently increasing interest for the aircraft industry to fulfill the requested reduction of fuel consumption in terms of transportation means in the future. The material mix in aircraft structures includes, especially, aluminum (Al) and titanium (Ti) alloys as well as more and more carbon fiber reinforced plastics (CFRP). However, the benefit of multi-material designs can only be granted by realizing suitable transitions. Thus, understanding of joining technologies plays a key role for multi-material manufacturing [1].

State of the art technologies for such hybrid joints are adhesive bonding or mechanical joining. Both require the overlapping of the joint partners resulting in additional weight. Thus, frontal joints would be preferable. A successful approach for hybrid Al–Ti butt joints was found in thermal processes in which only the aluminum is molten. The titanium remains solid and is wetted by the aluminum melt. High joint strength due to resulting thin interfacial intermetallic compound layers and good surface quality have been reported for a simultaneous double-sided laser beam process which enables fluxless Al–Ti joining [2]. Currently, novel light thin, so-called integral, Al–CFRP joints are under investigation using titanium laminates as transition structures [3]. The afore-mentioned process approach is applied for the sub-joint between aluminum sheet and titanium laminate.

Though bevel edges [4] or chamfers [2] were exemplarily used to improve the joining process, the interfacial compound layer structure and/or the seam strength of hybrid joints, no systematic investigation about the influences of geometrical parameters on the joint strength is known. The different stiffness of aluminum and titanium results in a heterogeneous stress field.

In this paper, a model is described and validated which allows a fast prediction of the joint strength depending on the joint design. Especially, the sensitivities of a joint strength against variations of the material properties, the interfacial strength and the edge design as well as against dimensional deviations due to preparation and/or process tolerances are of great interest. In addition, the hypothesis that the area of the vertical front-face of the titanium part determines the joint strength of the Al–Ti seams is investigated. It is suggested that the local stress in the vertical front-face interface increases with the decreasing titanium front-face height. The front-face height is originated by the edge design of the titanium part, see designation in Fig. 1b.

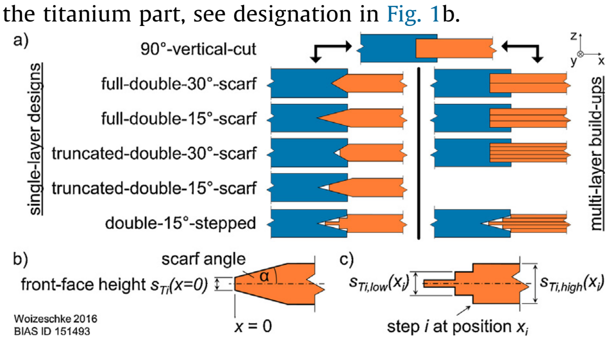

Fig. 1. (a) Joint designs prior to the process; illustration of (b) front-face height and (c) the two local thicknesses of the titanium part at a step.

2. Experimental

In this study, the Al–Ti joints have been produced by a simultaneous double-sided laser beam process. The joints consist of aluminum sheets of the alloy EN AW-6082 (AlSi1MgMn), heat treated in T6 standard, and titanium parts of the alloy Ti6Al4V (Grade 5). The seam thickness is equal or less than the thickness of the aluminum base sheet. The joining experiments have been

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carried out with 2×2 kW laser power (Nd:YAG laser with a wave length of 1064 nm) and 3.7 mm/s joining speed. Laser beam axes were positioned 2.5 mm above the face side of the aluminum sheet. During the joining process, the aluminum edge is molten while the titanium edge is only heated up and remains solid.

In order to identify and understand the influence of the titanium front-face height on the joint strength, titanium edge designs with different heights have been selected. All configurations are illustrated in Fig. 1a. Besides comparatively standard vertical-cut edges, having the maximum front-face height of 2.6 mm corresponding to the sheet thickness, so-called truncated (Fig. 1b) and full double-scarf designs with decreased heights of 0.8 mm and 0 mm are investigated for two different scarf angles. In addition, a stepped design with five steps in total and a front-face height of 0.5 mm is considered in this study, see Fig. 1c. Besides monolithic single-layer titanium structures also multi-layer variants are investigated. Effects of the laminate build-up are evaluated by comparing laminates with different numbers of layers (2, 3 and 5 layers) in case of the vertical-cut edge design and exemplarily a five-layer variant for the stepped design. Overall, titanium sheets with the thicknesses 2.60 mm, 1.22 mm, 0.77 mm and 0.53 mm are used. All titanium edge and aluminum notch designs were manufactured by milling. The aluminum notches are adapted to the titanium edge designs in order to reduce the gap volume between the parts prior to the process. Rectangular shaped notches of 3 mm depths have been used for vertical-cut edges, V-shaped notches for double-scarf edges with the angles of 15° (4 mm deep) and 30° (2 mm deep) as well as for the double-15°-stepped variant (4 mm deep).

Three tensile test items for the experimental evaluation of the joint strength and one item for the microscopy analysis of the seam cross-section were extracted from each produced joint specimen. A minimum of three joint specimens were produced per edge design. Thus, the joint configurations are compared by the medians and the averaged deviations of at least nine test items per edge design. Within the test set, a maximum tilt of 2° between the central axes of the aluminum and titanium parts occurred. The quasi-static tensile tests were carried out with the crosshead speed of 5 mm/min after at least 80 days of natural aging. The experimental joint strength R_j is calculated by dividing the measured breaking force F_b by the multiplication of the test item's width (b = 15 mm) and the thickness of the aluminum base sheet ($s_{\mathrm{Al,base}}$ = 4 mm).

The experimentally determined joint strengths are compared to values predicted by a strength-model. Input data for the model are on the one hand the seam geometries, the elastic moduli and the Poisson's ratios to calculate local stress distributions within each cross-section along the x-axis beginning at the titanium front-face (x = 0). On the other hand, the strengths of the titanium material, the aluminum weld material and the interface are needed to predict the joint strength. Any seam geometry, namely the local thicknesses of the aluminum and titanium part along the x-axis, is taken from a minimum of 20 measurements within the cross-section micrograph. Based on the measurements, the aluminum seam surface and the titanium edge path (=interface), see Fig. 2a, are approximated by polynomial functions and linear interpolation, respectively, providing the angles of the interface and the seam surface, $\alpha(x)$ and $\beta(x)$, as functions of x. The elastic moduli were measured to 113.8 GPa for the 2.6 mm thick titanium sheets and to 74.1 GPa for the aluminum sheets. The Poisson's ratios of 0.346 for aluminum and 0.31 for titanium are taken from [5] and [6], respectively. The tensile strength of the used 2.6 mm thick titanium sheets is 1052 ± 10 N/mm^2. For the aluminum weld material strength a value of 249.5 ± 6.0 N/mm^2 is used. It has been determined by comparatively small tensile test items with an average cross-section of 5.1 ± 0.9 mm^2 which had been extracted from the aluminum fusion zone of vertical-cut-edge specimens. In order to determine a characteristic interfacial strength for the applied process and material combination, test items of the standard vertical-cut edge design have been modified for preliminary tensile tests. As modification, the aluminum overlaps on both titanium sides were locally removed by milling to create a pure butt joint with a remaining interface which is perpendicularly oriented to the tensile load. As input parameter for the model an averaged interfacial strength of 227.1 ± 17.0 N/mm^2 has been determined in a set of 15 modified test items. The standard deviations of the interfacial and the aluminum weld material strength are included in the error bar of a predicted Al–Ti joint strength determined by additional calculations.

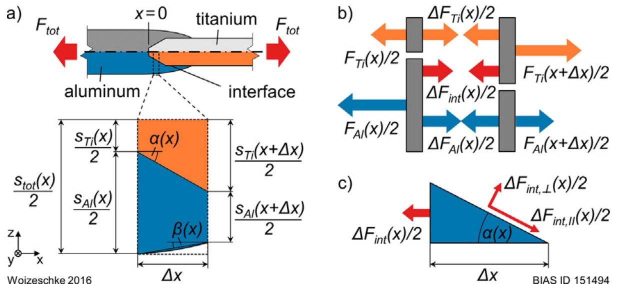

Fig. 2. Derivation of a model for calculating the interfacial stress based on the changing force fractions: (a) exemplary section; (b) assumed bar model of the force distribution and (c) interfacial force components.

3. Strength-model

3.1. Local stresses

In order to predict the strength of hybrid Al–Ti seams, the local stresses within the aluminum and titanium parts of the seam as well as the interfacial stress are needed. The calculation is based on the geometrical measurements of the seam geometries. Symmetry of the joint design is assumed. The total force F_{tot} of quasi-static tensile loading is partitioned within the seam into a local aluminum force fraction $F_{\mathrm{Al}}(x)$ and a local titanium force fraction $F_{\mathrm{Ti}}(x)$, see Eq. (1). It is assumed that the strain within a cross-section is constant, see Eq. (2). Additionally, the simplification of solely elastic behavior is applied according to Eq. (3). As a result, the force fraction of the titanium part can be calculated by Eq. (4). The equation shows that the force distribution depends on the local aluminum and titanium thicknesses as functions of the x-position, $s_{\mathrm{Al}}(x)$ and $s_{\mathrm{Ti}}(x)$, whose sum is the total seam thickness $s_{\mathrm{tot}}(x)$, as well as by the ratios of the elastic moduli, E_{Al} and E_{Ti}, and the Poisson's ratios, ν_{Al} and ν_{Ti}, which are summarized in C_E. Start of the x-axis orientated in load direction is set to the titanium front-face in each case.

The calculation of the interfacial stress can be explained by an exemplary section, see Fig. 2a. According to Eqs. (4) and (1), any change of the thickness ratio between the aluminum and the titanium parts leads to a changed force distribution. Furthermore, any change of the force distribution causes an amount of force $\Delta F_{\mathrm{int}}(x)$, which has to be transferred trough the interface within this section. As a result of a bar model (Fig. 2b), this amount of force is determined by the difference of the titanium force fraction between two x-positions x and $x+\Delta x$, see Eq. (5) and after insertion (6). The changes of s_{tot} and s_{Ti} are described by the interface orientation $\alpha(x)$ and the surface angle $\beta(x)$, respectively, in conjunction with the step width Δx.

$$F_{\mathrm{tot}} = F_{\mathrm{Ti}}(x) + F_{\mathrm{Al}}(x) \quad (1)$$

$$\epsilon_x(z) \overset{\mathrm{def}}{=} \mathrm{const.} \Rightarrow \epsilon_{x,\mathrm{Ti}}(x) = \epsilon_{x,\mathrm{Al}}(x) \quad (2)$$

$$\sigma_i = \epsilon \cdot \frac{E_i}{1-\nu_i} = \frac{F_i}{b \cdot s_i} \Rightarrow \epsilon = \frac{F_i \cdot (1-\nu_i)}{b \cdot s_i \cdot E_i} \quad \text{with } i = \{\mathrm{Ti}, \mathrm{Al}\} \quad (3)$$

$$F_{\mathrm{Ti}}(x) = F_{\mathrm{tot}} \cdot \left[1 + C_E \cdot \left(\frac{s_{\mathrm{tot}}(x)}{s_{\mathrm{Ti}}(x)} - 1\right)\right]^{-1} \quad \text{with } C_E = \frac{E_{\mathrm{Al}}}{E_{\mathrm{Ti}}} \cdot \frac{(1-\nu_{\mathrm{Ti}})}{(1-\nu_{\mathrm{Al}})} \quad (4)$$

$$\Delta F_{\mathrm{int}}(x) = F_{\mathrm{Ti}}(x + \Delta x) - F_{\mathrm{Ti}}(x) \quad (5)$$

$$\Delta F_{\mathrm{int}}(x) = F_{\mathrm{tot}} \cdot \left[\frac{1}{1 + C_E \cdot \left(\frac{s_{\mathrm{tot}}(x) - \tan\beta(x) \cdot \Delta x}{s_{\mathrm{Ti}}(x) + \tan\alpha(x) \cdot \Delta x} - 1\right)} - \frac{1}{1 + C_E \cdot \left(\frac{s_{\mathrm{tot}}(x)}{s_{\mathrm{Ti}}(x)} - 1\right)}\right] \quad (6)$$