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Failure behavior of aluminum-titanium hybrid seams within a novel aluminum-CFRP joining concept

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Abstract

Modern light weight designs include various materials to create specific local properties. Hence, joining of dissimilar materials is an important task, especially the combination of carbon fiber reinforced plastics and aluminum alloys is a favored choice. In this paper, investigations on a novel joining concept for these materials are shown carried out within the DFG research group "Schwarz-Silber" at the University of Bremen. A titanium transition structure consisting of a foil laminate is applied. On the aluminum side joining is realized by a simultaneous double-sided laser process. In the results the failure behavior of this joint is characterized.

Keywords: laser joining; titanium; CFRP; aluminum; failure behavior

1. Motivation / State of the Art

Multi-material design is applied in an increasing number of constructions. It enables the adaptation of material properties to specific local requirements (Kocik et al., 2006). Product examples can be found in the automotive industry, the aerospace industry, or generally in mechanical engineering (Schumacher et al., 2007). Especially, combinations of carbon fiber reinforced plastics (CFRP) and aluminum alloys (Al) offer high potential for light weight components. Typical joining methods are riveting, bolting, and screwing (Bashford, 1986). Di Franco et al. investigate adhesive bonding, riveting, and a combination of both

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joining techniques (Di Franco et al., 2012 and Di Franco et al., 2012a) in a recent research project. Furthermore, an ultrasonic welding process is described in literature for joining CFRP and Al by Balle et al., 2011. Usually, an adhesive bond is created between the Al surface and the CFRP matrix. In this case, a direct connection of the fibers and the aluminum can be achieved additionally.

However, techniques like riveting determine a weakening of the CFRP by drilling on the one hand. Due to these interruptions of the load path the components have to be strengthened in the joining zone. On the other hand, the drilling of CFRP itself is still a challenge because, for example, high cutting speeds lead to increasing surface layer damages in the CFRP material (Brinksmeier et al., 2011). All techniques like riveting or adhesive bonding require an overlap of the joining partners which causes additional weight. Moreover, contacting carbon and aluminum directly features a high risk for contact corrosion (Köhler et al., 2012).

Thus, the research group “Schwarz-Silber” at the University of Bremen investigates novel joining concepts. Transition structures made of titanium (Ti) having high specific strength and corrosion resistance (Neugebauer et al., 2010) shall connect the two base materials to enable an integral connection and to improve corrosion behavior (Fig. 1). As a result, two hybrid joints Al-Ti and Ti-CFRP have to be developed and analyzed. The so-called “foil concept” realizes the connection using a titanium foil laminate. Kreimeyer and Vollertsen have shown for different joint configurations that dissimilar metals having significant different melting temperatures like Al-steel or Al-Ti can be joined using a laser process (Kreimeyer and Vollertsen, 2005). In this case, a heat conduction laser beam process melts the aluminum. Subsequently, the molten aluminum wets the titanium surface.

In this paper first results with respect to the failure behavior of the Al-Ti joint within the novel foil concept for connecting Al and CFRP parts are presented.

2. Experimental

2.1. Materials

The titanium laminate consists of three foils of pure titanium (grade 2) having a thickness of 0.6 mm each. The aluminum sheet (EN AW-6082 T6) has a thickness of 4 mm. A single-mode fiber laser with a laser output power of up to 1 kW (YLR-1000-SM by IPG Laser) and a lamp pumped 4 kW Nd:YAG laser (HL4006D by Trumpf) are used. The CFRP part is made of 0.3 mm thick CFRP-prepreg layers (CYCOM 977-2 by Cytec). The tensile tests have been performed on an electro-mechanical test machine Z020 from Zwick/Roell.

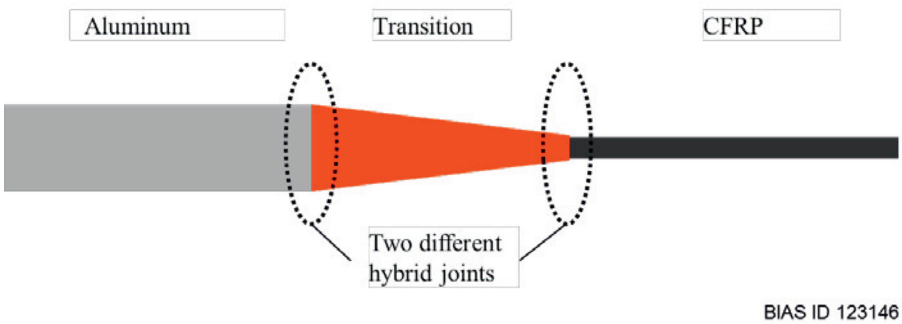


Fig. 1. Principle of integral joining of CFRP and aluminum components by integrating a transition structure

2.2. Methods

Fig. 2 illustrates the manufacturing of the foil concept. First, titanium foils and CFRP-prepreg layers are alternately assembled to create a hybrid laminate connection (step 1). Afterwards, a laser weld seals off the pure titanium side of the laminate from the Ti-CFRP hybrid zone (step 2) to avoid an infiltration of the complete interspaces between the titanium foils during curing (3 h / 180 °C) and compression (step 3) which is necessary to finish the CFRP part. Otherwise, resin in the joining zone could generate seam defects during the last step in which the laminate is joined to the aluminum sheet by a simultaneous double-sided laser process (step 4). In this step, the pure titanium side of the laminate is positioned into a milled groove having a depth of 2 mm at the face side of the aluminum sheet. In addition, it is possible to integrate another weld (cf. step 2) near the Al-Ti fusion zone to reinforce the titanium laminate.

The quasi-static mechanical properties of the specimens are determined on an electro-mechanical tensile test machine with test speed of 0.5 mm/min. The seam strength R_{Seam} being the maximum tensile force normalized to the specimen width is calculated for every specimen to enable a comparison of different specimen geometries. For a mathematical description of the scatter of the seam strength values a two parametric Weibull distribution is used (Eq. 1). With this function the probability P can be calculated that the seam stress σ exceeds the seam strength of the specimen. $R_{Seam,50}$ is the median of the seam strength values and the parameter m is an indicator of the scatter. For adaption of the distribution function a probability P_i has to be assigned to the N experimentally obtained strength values.

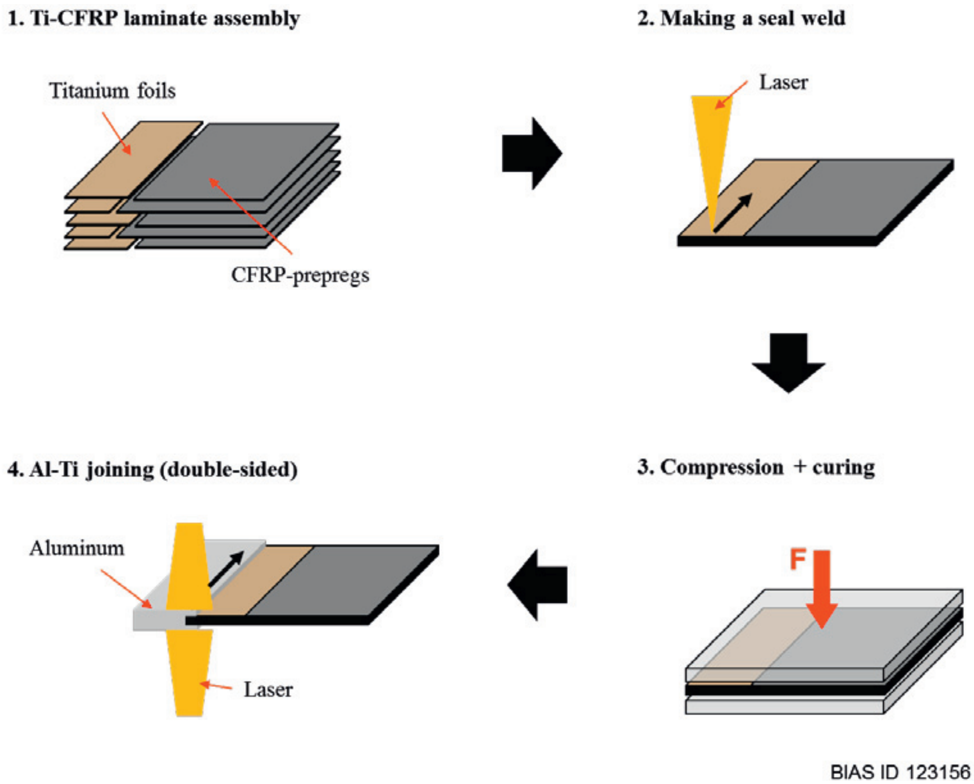


Fig. 2. Procedure of the foil concept to join CFRP and aluminum structures by laser beam processes

For that purpose the values have to be arranged by size starting with the smallest value numbered i = 1 to the biggest value i = N. A probability is assigned to each measured strength value by the following estimation function (Eq. 2). The Weibull distribution is adapted to experimentally obtained fracture probabilities by least square minimization.

$$P(\sigma) = 1 - 2^{\left(\frac{\sigma}{R_{Seam,50}}\right)^m} \tag{1}$$

$$P_i = \frac{i}{N+1} \tag{2}$$

2.3. Program

Fig. 3 shows a sketch of the cross section of an Al-Ti-CFRP specimen. A wetting of the laminate front side by molten aluminum occurs during the simultaneous double-sided laser process. In addition, the melt wets the external faces of the laminate by two overlaps. In this paper two kinds of specimens are investigated: complete Al-Ti-CFRP specimens (set A) and modified Al-Ti specimens (set B). The modification of set B includes an additional weld in the fusion zone to reinforce the connection between the foils. The failure behaviors of five complete Al-Ti-CFRP (set A) and nine modified Al-Ti (set B) specimens are analyzed with results of tensile tests. Specimen widths are 15 mm and 30 mm for the Al-Ti-CFRP and the Al-Ti specimens, respectively.

3. Results and Discussion

Tensile tests were performed to characterize the failure behavior and to determine the joint strength of complete Al-Ti-CFRP specimens (set A) as well as modified Al-Ti specimens (set B). Fig. 4 shows fracture probabilities of the specimens in dependence of seam strength. The median seam strength $R_{Seam,50}$ determined at five Al-Ti-CFRP specimens is 308 N/mm. In case of the modified Al-Ti specimens a median seam strength of $R_{Seam,50}$ = 346 N/mm in company with a higher scatter has been measured.

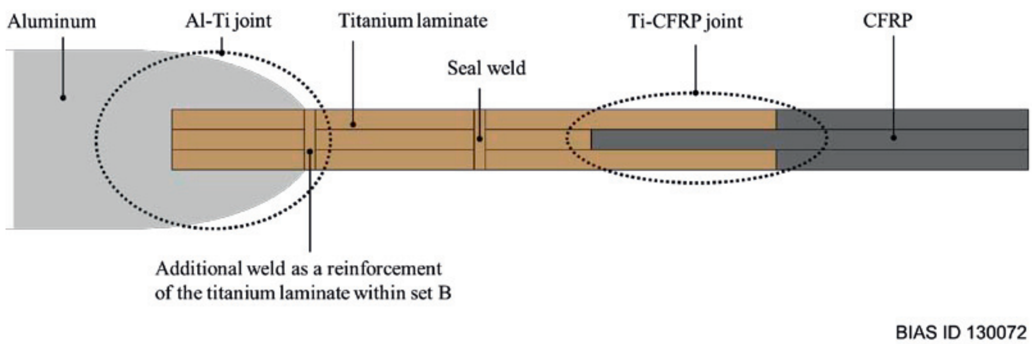


Fig. 3. Sketch of the cross section of an Al-Ti-CFRP specimen

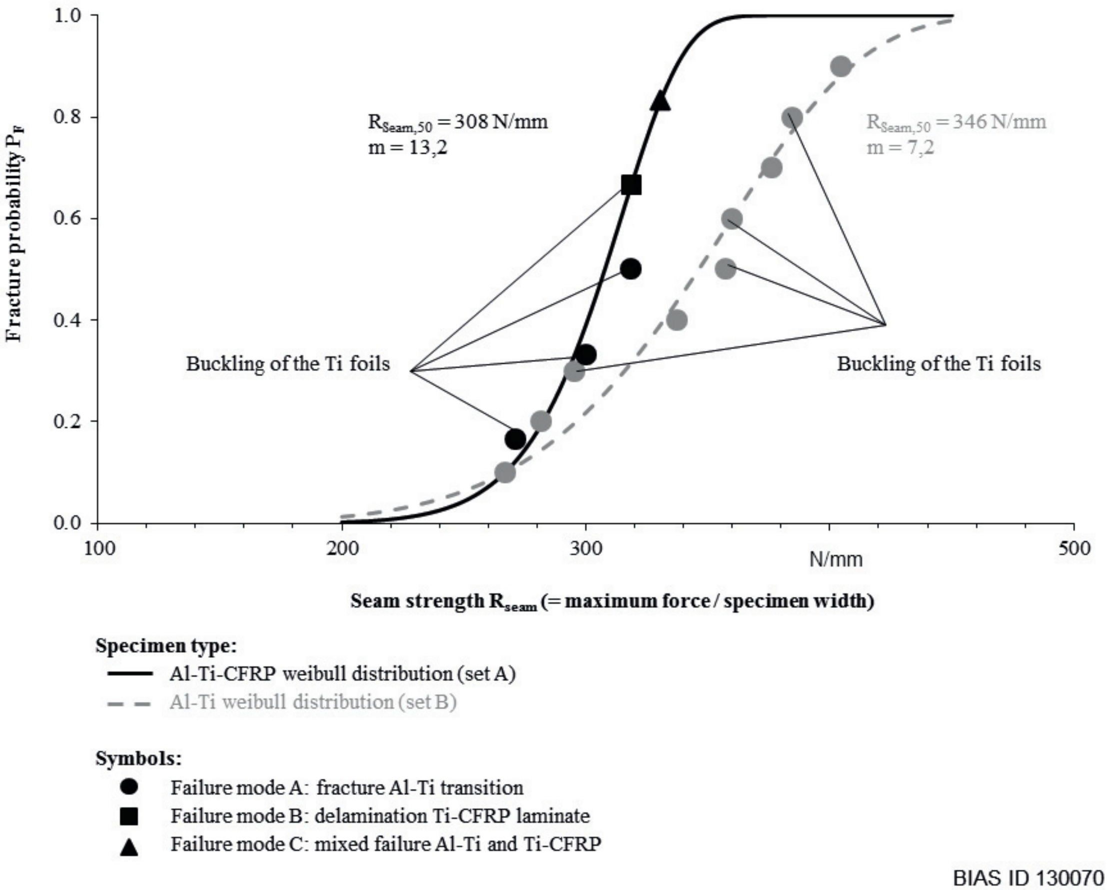
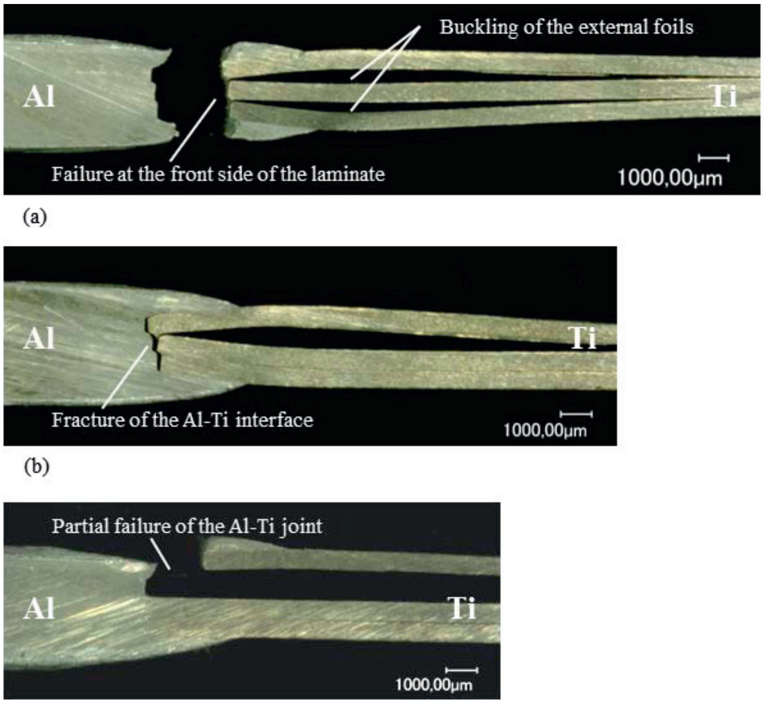


Fig. 4. Joint strength values of Al-Ti-CFRP (set A) and modified Al-Ti (set B) specimens (laser power P_L=3.6 kW, speed v_L=0.22 m/min)

Within the set of five Al-Ti-CFRP specimens three different failure modes occurred. Fig. 5a illustrates fracture within the Al-Ti fusion zone (failure mode A). The failure is located at the front side of the titanium laminate. The path of crack follows the laminate front side orientation within the aluminum overlaps. A deformation of the outer foils can be observed which is caused by bending moments due to asymmetrical force transmission of the aluminum overlaps. Three of five Al-Ti-CFRP specimens failed that way. In contrast, one specimen failed at the Ti-CFRP interface by delamination in the end (failure mode B). However, the Al-Ti part of the joint is also damaged as seen in Fig. 5b. The Al-Ti interface is fractured at the front side of the laminate. A separation of the foils due to buckling is only observed between the first and the second foil. Potentially, a connection between the second and the third foil exists caused by a partial infiltration of the interface between the foils by aluminum during the manufacturing process. Fig. 5c shows a failure in both partial joints Al-Ti and Ti-CFRP (failure mode C). The connection of one titanium foil and the aluminum sheet has failed and a delamination between the other titanium foils and the CFRP part occurred.



(c)

BIAS ID 130071

Fig. 5. Al-Ti part of the complete Al-Ti-CFRP specimens after loading: (a) fracture within the Al-Ti transition (failure mode A); (b) fracture of the Al-Ti interface at the front side of the laminate in case of a total failure of the Ti-CFRP connection in the end (failure mode B); (c) mixed failure of Al-Ti and Ti-CFRP joints (failure mode C)

Fig. 6 displays the load-displacement curves of complete Al-Ti-CFRP specimens (set A) having the three different failure modes. Linear slopes of the load-displacement curves change after a displacement of approximately 0.25 mm. This point correlates with snaps which have been heard during the tensile tests. The snaps are presumably caused by crack propagation in the intermetallic layer at the front side of the titanium foils. Hence, this loss of stiffness could explain the lower slopes of the load-displacement curves afterwards. At a displacement of approximately 1.14 mm a load drop appeared in case of failure mode A and B which might be caused by the abrupt fracture of the residual Al-Ti interface at the laminate front side. The final failure of the intermetallic phase layer at the front side of the laminate could be influenced by the buckling of the external foils because the bending of the foils result in additional stress at the Al-Ti-interface at the front side of the titanium laminate. After an additional elongation the aluminum overlaps of the specimen shown in Fig. 5a with failure mode A failed completely at a seam stress of 300 N/mm. In case of the specimen with failure mode B the final failure is caused by a complete delamination of the Ti-CFRP interface at a seam stress of 319 N/mm. The specimen with failure mode C failed within the Al-Ti and the Ti-CFRP interfaces at a seam stress of 330 N/mm.

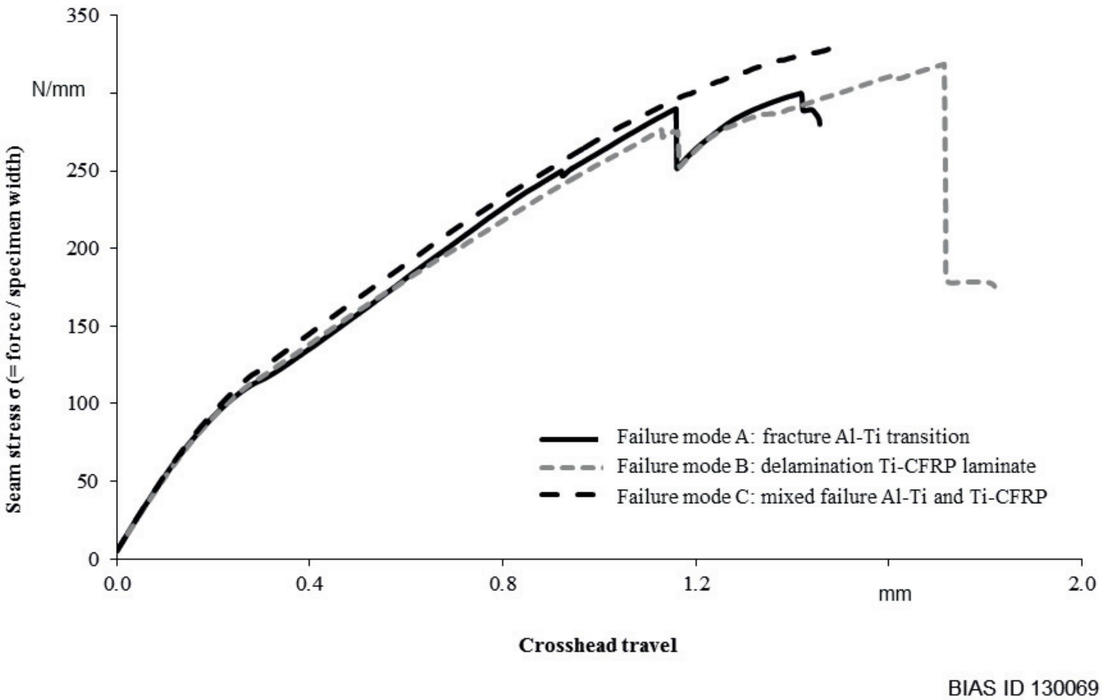


Fig. 6. Load-displacement curves of the complete Al-Ti-CFRP specimens having the three different failure modes

The modified Al-Ti specimens (set B) were manufactured with an additional weld near the Al-Ti fusion zone. However, four of nine specimens have shown a buckling of the foils after tensile tests as demonstrated in Fig. 5a. This indicates that the seam width of this additional weld connecting the foils with each other is too small to reliably avoid separation. Five specimens fractured without buckling at the same load level. Thus, an effect of the foil bending on the seam strength cannot be determined. The difference between the seam strength median values of set A and set B might be caused by the additional failure modes B and C in case of complete Al-Ti-CFRP specimens.

Conclusion

Within the aluminum-CFRP joints of the novel "foil concept" competing failure modes appeared. However, failing of the Al-Ti interface at the front side of the titanium laminate has been detected at all specimens. Hence, a modification of the Al-Ti joining zone would be necessary to make the entire specimen suitable for higher seam loads. Additionally, a buckling of the external titanium foils of the laminate occurred next to the Al-Ti transition at several specimens. Prospectively, such local plastic deformations of the joint should be avoided at an early stage of loading, even though the buckling has not shown significant influence on the seam strength in this investigation.

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References

Kocik, R., Vugrin, T., Seefeld, T., 2006. Laserschweißen im Flugzeugbau: Stand und künftige Anwendungen, 5. Laseranwenderforum (LAF'06), eds.: F. Vollertsen, T. Seefeld. BIAS-Verlag Bremen, Bd. 28, p. 15-26.

Schumacher, J., Irretier, A., Kocik, R., Tinscher, R., Kessler, O., Sotirov, N., Bomas, H., 2007. Investigation of Laser-Beam Joined Titanium-Aluminum Hybrid Structures Applied Production Technology (APT'07), eds.: F. Vollertsen, C. Thomy. BIAS-Verlag Bremen, p. 149-160.

Bashford, D.P., 1986. Basic Aspects of Joining Technology for Fibre Reinforced Plastics, in: G. Pritchard (Ed.), Developments in Reinforced Plastics 5 – Processing and Fabrication, Elsevier, London, p. 205-232.

Di Franco, G., Fratini, L., Pasta, P., 2012. Analysis of the mechanical performance of hybrid (SPR/bonded) single-lap joints between CFRP panels and aluminum blanks, International Journal of Adhesion and Adhesives, http://dx.doi.org/10.1016/j.ijadhadh.2012.10.008

Di Franco, G., Fratini, L., Pasta, P., 2012. Influence of the distance between rivets in self-piercing riveting bonded joints made of carbon fiber panels and AA2024 blanks, Materials and Design 35, p. 342.

Balle, F., Huxhold, S., Wagner, G., Eifler, D., 2011. Damage monitoring of ultrasonically welded aluminum/CFRP-joints by electrical resistance measurements, Procedia Engineering 10, p. 433.

Brinksmeier, E., Fangmann, S., Rentsch, R., 2011. Drilling of composites and resulting surface integrity, CIRP Annals – Manufacturing Technology, Volume 60, Issue 1, p. 57-60.

Köhler, J., Grove, T., Maiß, O., Denkena, B., 2012. Residual Stresses in Milled Titanium Parts, 1st CIRP Global Web Conference: Interdisciplinary Research in Production Engineering (CIRPE2012), Procedia CIRP, Volume 2, p. 79-82.

Neugebauer, R., Meyer, L. W., Halle, T., Popp, M., Fritsch, S., John, C., 2010. Manufacture of a β-titanium hollow shaft by incremental forming, in: Prod. Eng. Res. Devel. 4.

Kreimeyer, M., Vollertsen, F., 2005. Processing titanium-aluminum hybrid joints for aircraft applications, Proc. 3rd International WLT-Conference on Lasers in Manufacturing 2005, eds.: E. Beyer, AT-Fachverlag Munich, p. 73-78.