ANALYSIS OF INTEGRAL TRANSITION STRUCTURES FOR FRP-ALUMINIUM COMPOUNDS

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Abstract

The demand for weight saving in aerospace leads to increasing numbers of applications of fibre composites for primary structural components. In consequence the use of FRP-metal compounds is necessary. In load application zones the joints are often accomplished by conventional conjunctions like riveting. Disadvantages are the interrupted load path due to destroyed fibres by drilling and the bulky design due to rivets. The need of lean, weight-minimised and composite optimized hybrid compounds in lightweight design is obvious.

Within the investigations of the researcher group "Schwarz Silber" (FOR 1224) founded by the DFG (German Research Foundation) novel interface structures for advanced CFRP-aluminium compounds are currently being studied. Altogether, five interdisciplinary projects are carried out at the University of Bremen. Considering textile, welding and casting techniques novel, integral joint concepts will be designed, dimensioned and produced with the objective to avoid the above mentioned disadvantages and to fulfil requirements like minimum weight for a lightweight design as well as corrosion resistance. Experimental and numerical investigations support the validation and enhancements of the developed solutions. Within their work the researcher group focussed on three concepts realizing the transition structures: the usage of wires (titanium), foils (titanium) and fibres (glass fibre) as transition elements between CFRP and aluminium. The joint between CFRP and the three mentioned transition elements is realized by different textile, casting and welding technologies are used for the connection between transition element and aluminium.

Regarding the wire concept combining textile and welding techniques basic investigations have been done. This concept envisages the coupling of FRP with Al sheets by using Ti wire loops at the materials interface. It is intended to join the wire loops by textile techniques on the CFRP side and on the Al side by laser beam welding. First investigations on the wire concept show, that the chosen interface structure between CFRP and aluminium is a failure critical element. After failure of the bonding layer between aluminium and resin the Ti-wires transmit the introduced forces. This can be derived from the stepwise failure and decrease of the tensile force. Running investigations on wire concept concentrate therefore on the design of the Ti-wires. Investigations of the microstructure and the mechanical behaviour of Ti-wires have been done.

This paper presents the first results of the correlation between the microstructure and the fracture behaviour of Ti-CFRP joints under static tensile loading. Furthermore, first design principles for advanced CFRP-Al compounds with Ti-wire interface structures are discussed, which were supplemented by simulations.

1. INTRODUCTION

The overall demand for ecological efficiency requires weight saving even in lightweight design. This leads to increasing applications with combined fibre and metal components in a structure. Typically applications with these combinations of materials exists in aerospace (mounting for vertical stabilizer rudder, segment of fuselage), in automotive (axle guide, CFRP-roof) and in general mechanical engineering (hydraulic elements, hinged brackets).

Connections of components are implemented by adhesive or mechanical joints [1-5]. A joint, which is often realized by riveting or bolting, has to withstand the load transmission. But the application of joining technology is not always appropriate to the material, which means not in the sense of lightweight requirements. Since the joint’s influence on efficiency of weight for the whole design, the joint’s design is essential.

In load application zones the joints are often accomplished by conventional conjunctions like riveting. Due to bypass and transfer loads the carrying capacity of bolted joints is depending on bearing and shear stress. Since laminates posses low properties against bearing and shear stress the coupling efficiency is not optimized. To enhance the grade of connection for bolted joints in FRP components FML (fibre metal laminates) are applied, where CFRP (carbon fibre reinforced plastic) laminates are stiffened by titanium foils [6,7]. This technology causes other challenges like bonding between titanium foils and CFRP layers and risk of delaminating due to drilling process for riveting. For solving these challenges big efforts are necessary. But at the end main disadvantages still remain: the interrupted load path due to destroyed fibres by drilling and the bulky design due to rivets.

Even if many investigations have been done and are currently being under study, bolting and riveting are not optimised joining technologies for FRP structures. The need of lean, weight-minimized and composite appropriate hybrid compounds in lightweight design is obvious.

FIG 1 compares a conventional riveting joint to a lean CFRP-Al joint. In accordance with design principles of HSB [8] geometrical dimensions for the influenced area by riveted joints are determined. Joints with lean, integral transition zones are derived from these dimensions. To avoid the contact of CFRP with aluminium, titanium is implemented. Hence, the risk of corrosion is reduced. By usage of certain surface treatments for the chosen transition structure it is intended to minimize the galvanic corrosion. As a result of a lean joint the weight is reduced about 50 %. The potential of weight saving by means of a FRP optimised joining technology is obvious.

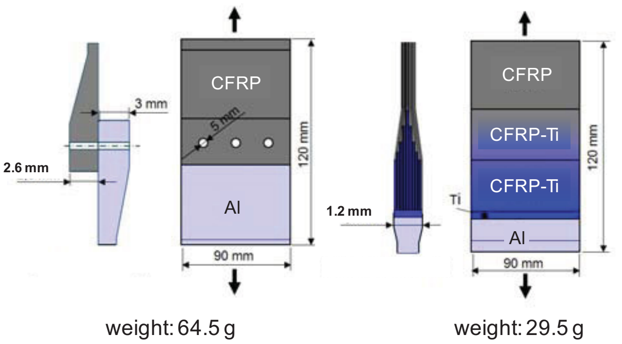


FIGURE 1. Potential of an integral CFRP-Aluminium joint (b) compared to a conventional riveted joint (a)

Within the investigations of the researcher group "Schwarz Silber" (FOR 1224) founded by the DFG (German Research Foundation) novel interface structures for advanced CFRP-aluminium compounds are currently being studied with five interdisciplinary projects at the University of Bremen. Considering textile, welding and casting techniques novel joint concepts will be designed, dimensioned and produced with the objective to avoid the above mentioned disadvantages and to fulfil requirements like minimum weight for a lightweight design as well as corrosion resistance.

2. DESIGN CONCEPTS

For the development for integral CFRP-Al transition structures approaches like material closure or frictional connections are possible. In terms of these approaches three different concepts combining textile, welding or casting techniques are currently being under study (FIG 2-4). Concept "wire" and "fibre" represent a parallel arrangement of miniaturised loop connections, which can be found for high punctual load applications in FRP structures [9, 10]. The foil-concept is based on comprehensive investigations of CFRP-Ti-laminates [6, 7, 10, 11].

WIRE CONCEPT

This concept represents a parallel arrangement of miniaturised loop connections. It is characterized by joining a CF-Ti-textile to an aluminium sheet. A carbon fibre loop is threaded through a titanium wire loop by textile technologies on one side. On the other side the titanium wire loops of the CF-Ti-textile were joined to an aluminium component by welding or casting.

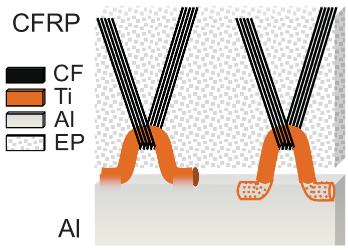


FIGURE 2. Wire concept

FOIL CONCEPT

The foil-concept is based on hybrid laminates. Considering the integration of titanium foils in CFRP for bolted joints comprehensive investigations had been done [12]. This concept is characterised by joining a Ti-CFRP laminate on an aluminium sheet. A hybrid laminate, in which all CFRP-layers will be replaced stepwise by titanium foils, has to be fabricated. The laminate existing only of Ti-foils is welded on aluminium.

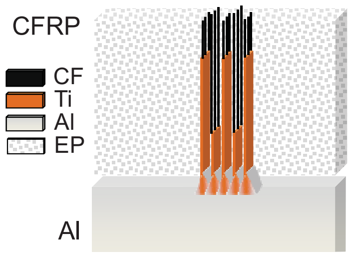


FIGURE 3. Foil concept

FIBRE CONCEPT

The fibre-based concept is in principle similar to the wire concept but the titanium wires are replaced by glass fibre loops. It is characterised by joining a glass fibre-CF-textile on aluminium. The glass fibre roving loops were bonded to an aluminium sheet by pressure casting technologies.

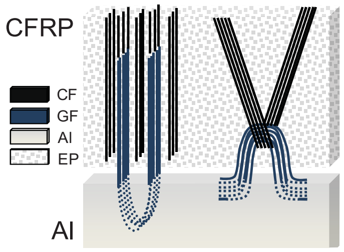


FIGURE 4. Fibre concept

In contrast to the conventional riveted joints all these novel concepts are characterized by a lean and integral construction. Hence the advantages are smaller cross-section and less weight and no need for installation space.

The challenges of these CFRP-aluminium compounds are versatile. Neither the design of these kinds of interface structures, the determination of failure criterions nor production technologies for the joining methods have been investigated before. In the first three years of the interdisciplinary project the concepts will be produced, analysed and optimised in view of quasi static tensile loading**.** The most promising design will be developed further concerning compression loads and bending within the second phase of the project.

3. EXPERIMENTAL

To be able to interpret and understand results of an investigation of a CFRP-Ti-loop reference values for comparison are advantageous. Hence the loop connection CFRP-Ti was reduced to a loop existing of two materials. A carbon fibre loop and a titanium wire without a resin matrix represent the “dry” loop.

Quasi static tensile tests are carried out for these “dry” single loop connections. Results are interpreted to determine the correlation between different material parameters and the strength. Additionally the influence of the welding process on the mechanical performance was investigated for selected Ti wires.

3.1. Materials

The specifications of the Ti wires (Ti2) are listed in TAB 1. A dry carbon fibre roving (HTS) with 24,000 filaments were chosen to ensure the failure of the Ti-wires [13, 14]. The Ti-wires were characterised by tensile tests as well as by metallographic methods.

Name	Material/Condition	Diameter
Ti-1	Ti2 / ~160 HV0.025	0.8 mm
Ti-2	Ti2 / ~255 HV0.025	
Ti-3	Ti2 / ~200 HV0.025	1.0 mm

TABLE 1. Specifications of Ti wires and carbon fibres

3.2. Experimental Setup

For the investigations on the performance of the dry loops Ti wires ~10 cm in length were bent to 180° around a bolt with a diameter of 8 mm. After clamping the Ti-wires in the jig for tensile test (clamping length ~ 4.5 cm) the carbon fibres were threaded through the Ti-wire loop (FIG 5).

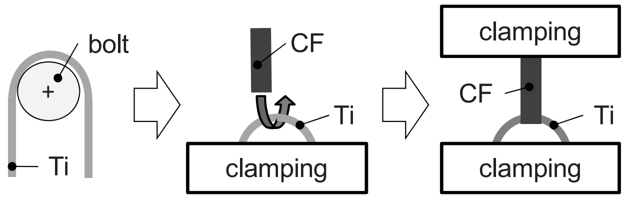


FIGURE 5. Procedure for testing dry CF-Ti loops

Regarding the influence of the welding process Al-sheets (thickness ~5 mm) were prepared with a notch (4 mm depth, ~1 mm width) wherein continuous Ti-wire loops placed (FIG 6). The carbon fibre was threaded through the Ti wire like in the earlier experiments, but in contrast to the prior procedure the Al-sheet was clamped into the test device.

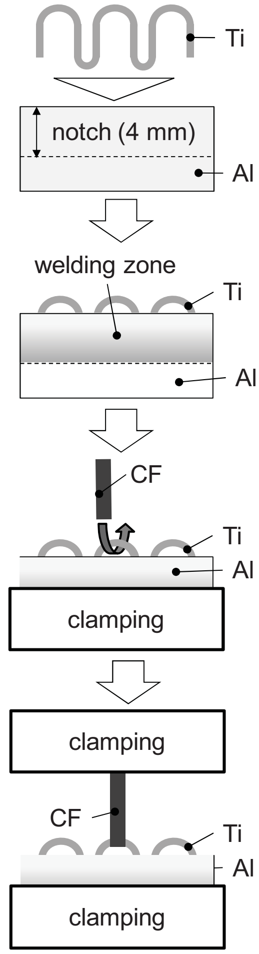


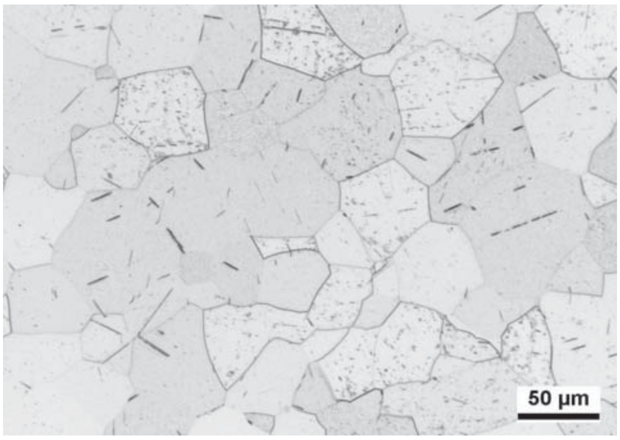
FIGURE 6. Procedure for testing the influence of welding on dry CF-Ti loops

Based on previous investigations 12 mm/min where chosen for the velocity of the tensile tests [13]. The deformation during tensile test was determined by the travel of cross beam. The position of failure was documented by photographs.

4. RESULTS

4.1. Microstructure

The microstructure (etchant: 5 % aqueous HF) of the used Ti wires in the initial state is documented in FIG 7 to FIG 9. Due to a final heat treatment above recrystallisation temperature globular grains are visible in the micrographs of “Ti-1”, which leads to the low hardness (FIG 7a).



a) Ti-1: Ti Grade 2 (~160 HV0.025), ∅ 0.8 mm

b) Ti-2: Ti Grade 2 (~255 HV0.025), ∅ 0.8 mm

FIGURE 7. Micrographs of the Ti wires: a) “Ti-1”, b)“Ti-2”

Without heat treatment the microstructure is characterized by elongated grains, which is typically for cold drawing processes (FIG 7b). Consequently the hardness is significantly higher in comparison to the heat treated wire.

Equally the micrograph of the Ti wire labeled “Ti-3” show elongated grains (FIG 8). However the lower deformation degree (∅ 1.0 mm) resulted in less elongation of the grains and a lower work hardening, which can be derived by the hardness. Primary a lamellar structure can be observed.

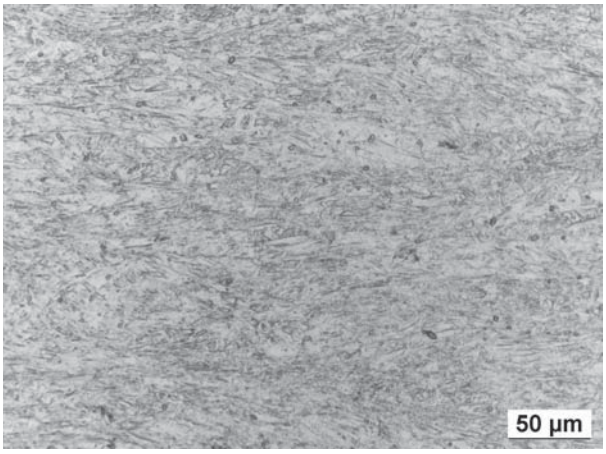


FIGURE 8. Micrograph of the Ti-wire “Ti-3”

4.2. Tensile strength

As expected from the metallographic analysis the tensile strength increases with increasing hardness (Fig 9). In minimum an elongation of ~10 % were measured. Due to the equiaxed grains the Ti wire “Ti-1” reached about five times higher elongation in comparison to”Ti-2”.

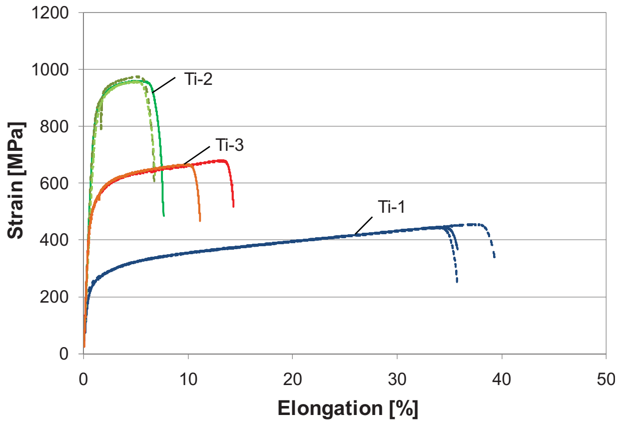


FIGURE 9. Results of tensile test on Ti-wires in the initial state

Within further analysis of the tensile strength a linear correlation between hardness and tensile strength were determined for the Ti2-wires (FIG 10). This allows an estimation of strength in the welding zone for simulations.

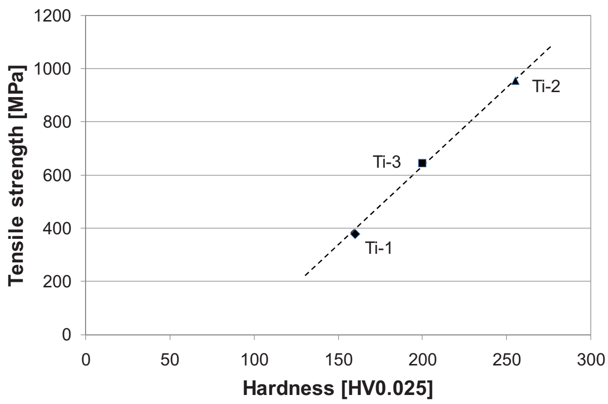


FIGURE 10. Correlation between hardness and tensile strength of the Ti wires in the initial state

In accordance with the measured tensile strength of the Ti wires, the highest fracture load of nearly 800 N was determined for the dry CF-Ti loops made with "Ti-2" (Fig 11). Their fracture load is twice as high as "Ti-1". In contrast the wires "Ti-1" show a significant higher deformation as expected. The Ti-wires with a diameter of 1 mm ("Ti-3") combines a high level of strength with very good deformation behaviour.

Referring the fracture load to the double cross section area of the corresponding Ti wire [15] nearly the same proportions will appear. However the failure strength of the CF-Ti loops is about 3 % to 6 % lower for "Ti-1" and "Ti-3" than the tensile strength of the corresponding Ti wires in the initial state. In contrast the strength of the Ti wires named "Ti-3" decreased about 20 % in comparison to the initial state.

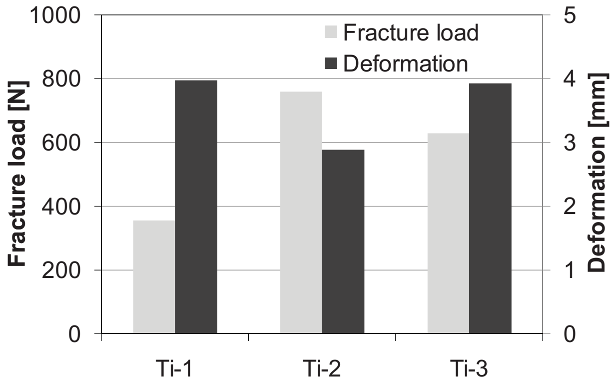


FIGURE 11. Fracture load and deformation of dry CF-Ti loops

Due to the deformation behaviour the Ti loops were elongated during the tensile test (FIG 10 and FIG 11). Comparing the deformation of the Ti wires in the initial state with those of the CF-Ti loops it is conspicuous that "Ti-1" and "Ti-3" differs in the initial state but have nearly the same deformation in combination with the carbon fibre.

Due to the low difference in tensile strength between initial state (Fig 10) and CF-Ti loop (FIG 11) and additionally better weldability the Ti wires "Ti-3" were chosen for further investigations on the influence of laser beam welding on the resulting strength for CF-Ti loops. Even after welding a value of 629 N for fracture load was reached, although the hardness and consequently the strength of the Ti wire itself decrease due to the welding process and the resulting recrystallisation of the microstructure in the heat affected zone [16]. The elongation was similar to these without welding.

4.3. Fracture behaviour

All Ti wires were elongated during tensile test, deformed in direction of the load and failed finally in the top of the loops mostly near edge of the carbon fibres. The contraction of fracture is negligible low for the Ti-wire itself but the elongation of the loops is significantly high (FIG 12).

FIGURE 12. Elongation and fracture of Ti loop without welding: before (left) and after tensile test (right)

The fracture behaviour after welding is similar to the CF-Ti loops without welding (FIG 13). The Ti loops were elongated and failed in the top. Hence the welding has a negligible effect on the failure of the CF-Ti loop, although an influence on the microstructure was occurred [16].

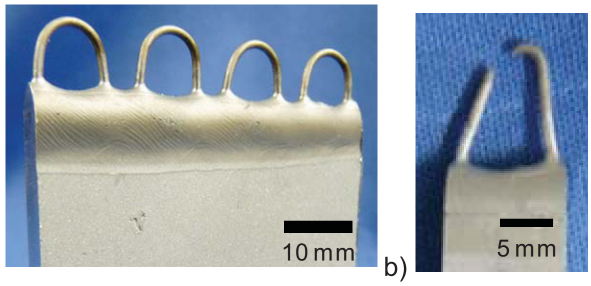
a)  b)

FIGURE 13. Ti loops after welding (a) and after tensile test (b)

5. DISCUSSION

The tensile strength of the Ti wires is reduced after bending and looping with carbon fibres. Further more the deformation behaviour differs in these two states of the Ti wires. To exclude the influence of bending of the Ti wires metallographic analysis were done after bending of Ti wires with lowest and highest hardness. Ten times lower bending radius were chosen for enhancement of the bending effect on microstructure as well as to satisfy the decreasing radius caused by elongation of the loops.

The micrograph of "Ti-1" shows a slight accumulation of twins in the inner and outer radius (FIG 14a). Hardness measurements documented negligibly increased values for the corresponding areas. It is to suggest that the influence is significant lower for higher bending diameters.

a)

b)

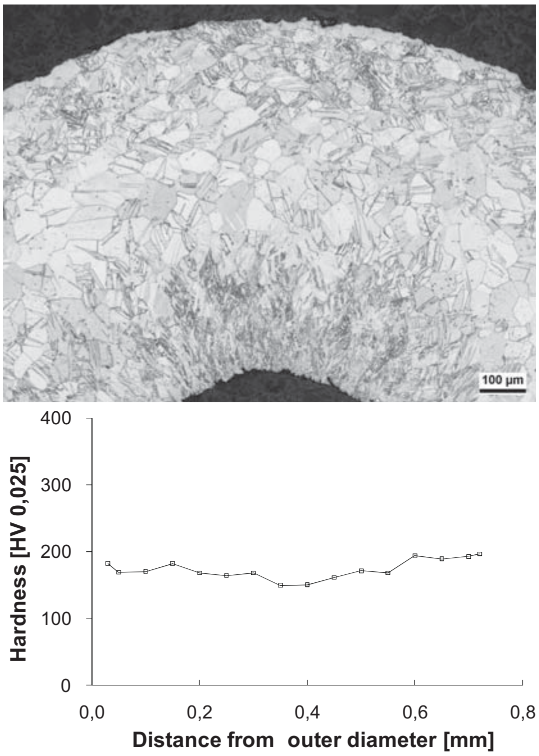


FIGURE 14. Microstructure (a) and hardness distribution (b) of “Ti-1” after bending about a diameter of 0.8 mm

The results of the metallographic investigations of “Ti-2” are displayed in FIG 15. In contrast to the microstructure of “Ti-1” neither modifications of the microstructure (FIG 15a) nor influences on the hardness were measured (FIG 15b).

a)

b)

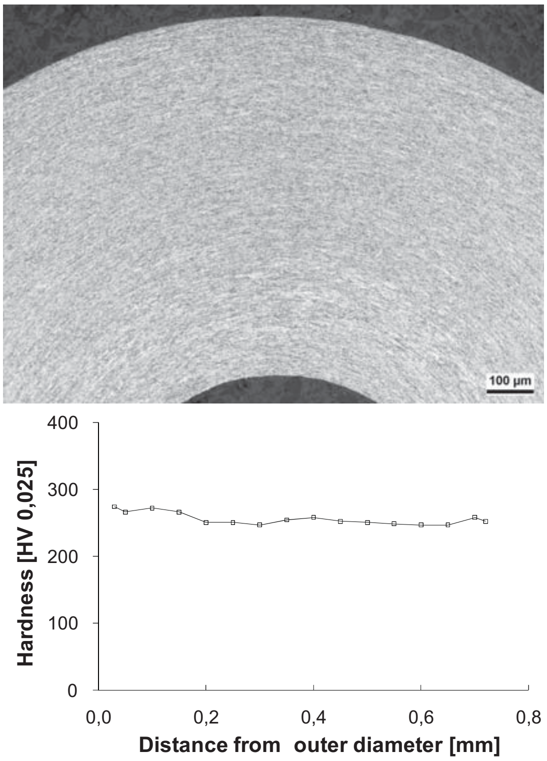


FIGURE 15. Microstructure (a) and hardness (b) of “Ti-2” after bending about a diameter of 0.8 mm

Based on the metallographic investigations the bending can almost exclude for the decreasing of the tensile strength of the Ti loops.

Besides the metallographic analysis the stress distribution (von-Mises) in the Ti loops during tensile were calculated by non-linear FEM. Therefore a travel controlled tensile test was simulated wherein the position of the carbon fibre roving was fixed in transverse direction to the loop. For the simulation an elasto-plastic behavior of the Ti-wires was assumed. For the first approach the Ti-wires were set without any residual plastic strain at the beginning of the simulated tensile test.

The FEM-results evidence a stress concentration on the inner side in the left end of the radius and near the top of the wire on the outer radius of the Ti loops (FIG 16). In comparison to these areas the stresses at the interface Al-Ti are about 25 % lower and can accordingly disregarded. The location of the calculated stress concentration correlates with the location of failure for most of the Ti wires (FIG 12 and Fig 13) but for some Ti loops the failure was also located in the middle. This is caused by the observed deformation of the Ti loops (FIG 12), which leads to a displacement of the carbon fibres in direction of the middle of Ti loop. In consequence a shift of the stresses in the same direction and therefore a modification of stress distribution are expected.

Due to the stress distribution in combination of the low deformation capability the mechanical performance of the Ti wires named “Ti-2” could not fully used. The stresses lead to an early failure of the Ti loops. In terms of loops, which are reinforced by resin, higher loads are expected due to the supporting effect of the resin [14, 16]. In that case the elongation of the Ti loops might be insignificant and the use of Ti wires with higher strength but lower deformation (like “Ti-2”) increases the assignable loads of the transition structures.

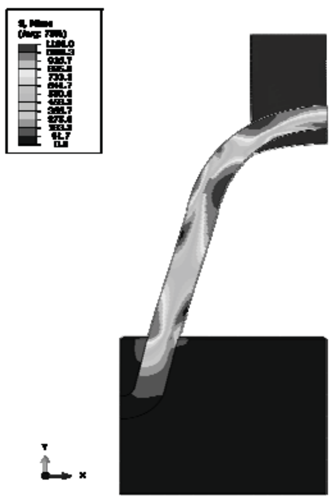


FIGURE 16. Calculated stress distribution in the Ti wire during tensile load

6. CONCLUSIONS

Based on the results on dry CF-Ti loops following principles for the investigated transition structures were derived:

- Low elongation of fracture leads to insufficient utilization of the strength of Ti wires. Because of the best relation between tensile strength in the initial state (FIG 10) and achieve fracture load (FIG 11) Ti wires with 1 mm in diameter were determined for further investigations.
- Neither the bending nor the welding process of the Ti wires significantly influence the assigned fracture loads of CF-Ti loops. Welding of Ti loops is suitable for integral FRP-Aluminum transition structures.
- Because of their low stiffness the Ti loops should be bent less than 180° for optimal bearing in view of the flux of force.
- It is expected that the use of resin prevents the displacement during tensile test of the dry CF-Ti loops and might leads to higher fracture loads.

7. SUMMARY

Novel concepts for transition structures were actually developed within the DFG researcher group “Schwarz-Silber”. Investigations on the wire concept show good correlation of the microstructure and tensile strength of the Ti-wires. The marginal decrease of tensile strength for the CF-Ti loops in comparison to the initial state could be derived to stress concentration at the edge of the threaded carbon fibre. Influences of the bending on the failure behaviour and fracture load could be excluded due to the metallographic analysis. Rather the inhomogeneous stress distribution in combination with the elongation of the Ti wires is mainly responsible for the failure of the CF-Ti loops. The strength of Ti wires is not significantly influenced by the welding process.

Further investigations are necessary to evaluate the influence of resin as well as of the interaction of several Ti-loops on the fracture load of a specimen. In this context the effect of Ti wires with higher strength will be analysed. In addition following aspects will be part of the investigation within the research group:

- Development of manufacturing strategies
- Investigations on corrosion resistance of the CFRP-Ti-Al structure
- Influence of different thermal expansion on stress distribution
- Photo elastic study of stresses during tensile load
- Enhancement of the transition structure in view of compression load and bending.
- FEM implementation of residual stress due to cold work and welding

8. ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Deutsche Forschungsgemeinschaft (DFG) within the researcher group “Schwarz-Silber” (FOR 1224) at the University of Bremen.

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