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Experimental investigation and performance enhancement of inserts in composite parts

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Abstract

New joining technologies are needed due to the increased use of carbon fibre reinforced plastics (CFRP) in the automotive industry. Traditional joining technologies cannot fulfill the requirements, especially for multimaterial assemblies of CFRP and metal. A suitable technology for the integration of mounting points in CFRP parts is the embedding of inserts. In this paper, two approaches to increase the tensile and bending strength of inserts are evaluated experimentally. Bead patterns are added in the metal sheet of the inserts to increase stiffness. Furthermore, surface treatments are used to enhance the co-cured bonding strength between insert and CFRP.

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Keywords: composite; joining; insert; RTM process

1. Introduction

The significant importance of lightweight design in the automotive industry is leading to an increased replacement of metal parts by parts made of carbon fibre reinforced plastic (CFRP). New joining technologies are needed to install these parts in multimaterial assemblies of CFRP and metal.

Nowadays, a frequently used way to mount components on the metallic bodywork of a car is to weld threaded M6 bolts on it. These bolts can be used for the detachable installation of other parts. Since this welding process is not suitable for CFRP, alternative ways for the integration of mounting points have to be found. One promising alternative is the integration of metal inserts into the CFRP material. These inserts can directly be embedded during the part manufacturing in the resin transfer molding (RTM) process. Thus, no additional drilling process is needed and the continuity of the carbon fibres is not interrupted.

Metal inserts for CFRP parts manufactured by injection molding or compression molding processes are already frequently used [1]. These inserts are not suitable for thin-walled continuous fibre reinforced plastic parts manufactured by the RTM process. Inserts for thin-walled continuous fibre reinforced parts usually consist of a thin metal sheet which is embedded between the plies of the laminate. A threaded bolt on the metal sheet is used to introduce the loads through the metal sheet in the laminate. However, this type of insert has only been investigated in a few studies yet. The mechanical characteristics of different types of bigHead® inserts were investigated in [2]. A parameter variation for inserts manufactured by the hand lay-up technique was performed in [3].

Within this paper, possibilities to enhance the performance of embedded inserts are demonstrated. Therefore, CFRP plates with metal inserts are manufactured by the RTM process. Quasi-static tests are performed to measure the tensile and bending strength of the embedded inserts.

Based on the results of investigations of standard inserts, two ways for possible improvements of the performance are derived: A bead pattern in the metal sheet of the insert is used to increase the bending stiffness and thus the bending strength of the embedded inserts. Surface treatments of the metal

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inserts are used to increase the co-cured bonding strength between the metal and the CFRP.

2. Experimental conditions

The tested standard inserts consist of a flat round metal sheet with a diameter of 30 mm and a height of 1 mm. The parameters are assessed based on previous tests [4], [5]. A bolt with an inner M6 thread is welded on the metal sheet by stud welding. This enables low-cost manufacturing of the inserts, which is an essential requirement for fasteners, especially in the automotive industry. Both, the metal sheet and the bolt are made of stainless steel (1.4301) to prevent corrosion. Figure 1 shows the dimensions of the tested standard insert.

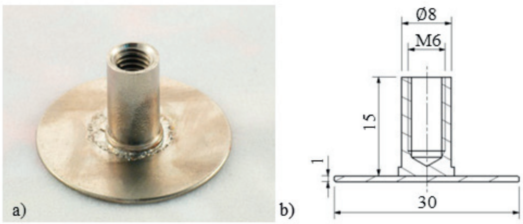


Fig. 1. a) Tested standard insert b) Dimensions of the tested inserts

The inserts are embedded in flat CFRP plates with dimensions of 150 x 150 x 2 mm³. The used resin is an epoxy system by Sika® (Biresin® CR170/Ch150-3). The reinforcement consists of eight plies of a multiaxial non-woven carbon fibre fabric (0°/90°, 200 g/m²), leading to a fibre volume fraction of .46.

For the manufacturing in the RTM process, the metal sheet of the inserts is placed between the single plies of the laminate during preforming. Thereby, the inserts are integrated in the middle of the laminate, with four plies above and four plies below the inserts. The threaded bolt of the insert is slid through the upper plies of the laminate with the help of a cone to maintain the fibre continuity. The infiltration of the parts is done in an especially adapted RTM mould with exchangeable cavities for different insert geometries described in [5].

The dimensions of the specimens and an exemplary picture of a manufactured specimen are given in figure 2.

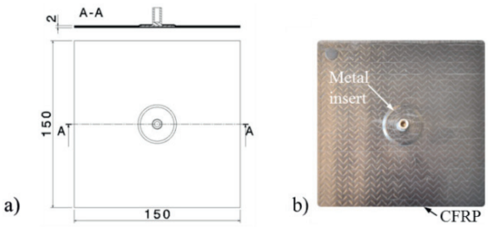


Fig. 2. a) Dimensions of the specimens b) exemplary picture of a specimen

Tests with the manufactured parts are carried out in a quasi-static material testing machine (Co. Zwick GmbH & Co. KG). Two different test devices are used to measure the tensile (pull-out) and bending strength of the embedded inserts. The used devices are shown in figure 3. At least five specimens with each type of insert are manufactured and tested.

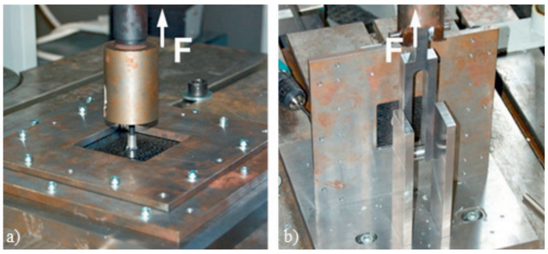


Fig. 3. Test devices for a) tensile tests and b) bending tests

3. Investigations of standard inserts

In the following, the results of the experimental investigations of the standard inserts described above are presented.

3.1. Results

Figure 4 shows exemplary runs of the test curves in the tensile and in the bending tests.

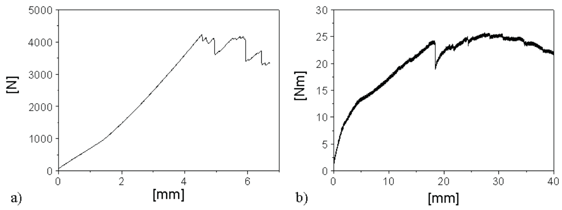


Fig. 4. Exemplary course of the test curves in tensile (left) and bending (right) tests

3.1.1. Failure behaviour

In the tensile tests, the course of the test curves reveals a linear behaviour up to high loads (with a small change of the slope resulting from the subsidence of the plates in the support). At high loads, the laminate above the inserts fails in a crosswise way, beginning from the bolt of the insert. The failure of the fibres is clearly visible on the failed specimens. Additionally, a plastic deformation of the insert's metal sheet and a failure of the co-cured bonding connection between the lower side of the insert and the lower plies of the laminate can be seen in the polished cut images of the failed specimen (cf. Fig. 5).

In the bending tests, all specimens fail because of a delamination between the upper and lower plies, which is revealed in the run of the test curves (cf. Fig. 4, at ~20 mm) and can also be observed by a sudden buckling of the laminate around the inserts during the bending tests. Furthermore the failed specimens reveal a failure of the co-cured bonding connection between the insert and the plies of the laminate and a strong plastic deformation of the metal sheet of the inserts as they did in the tensile tests (cf. Fig. 5).

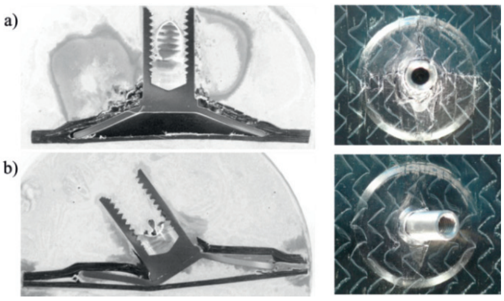


Fig. 5. Polished cut images and pictures of the failed specimens of the a) tensile tests and b) bending tests

3.1.2. Evaluation of the tensile and bending strength

The measured maximum tensile forces and bending moments of all tested specimens are evaluated to gain a reference value for the performance enhancement described later.

A mean tensile strength of 4367 N was achieved in the tensile tests. In the bending tests, a mean bending moment of 25.5 Nm was achieved.

4. Investigations of the effect of a bead pattern to enhance the performance of embedded inserts

The plastic deformation of the failed inserts revealed that one reason for the failure is the low bending stiffness of the thin metal sheets of the inserts, especially at the bending tests. A further increase of the thickness of the metal sheets could increase the bending stiffness and thus the performance, but an increased thickness could favour delamination between the upper and lower plies of the laminate. Furthermore, a thicker metal sheet is coupled with an increase of the weight of the inserts which is counterproductive to the idea of lightweight design. Another opportunity to increase the bending stiffness of metal sheets are bead patterns [6]. By adding a bead pattern to a metal sheet, the area moment of inertia is increased which leads to a higher bending stiffness. Nevertheless, the influence of bead patterns on embedded inserts in CFRP parts has not been investigated yet. To identify the potential of bead patterns for enhancing the performance of embedded inserts, specimens with inserts having a bead pattern are manufactured and compared to specimens with standard inserts having no bead pattern.

4.1. Design of the beads

For the investigations, a square bead pattern was chosen, which is generally suggested for round metal sheets. Also, with this shape the edges of the bead pattern can be aligned parallel to the fibres of the laminate, leading to a higher bending stiffness especially within the orientation of the fibres. The height of the bead pattern is set to 2 mm, which is the minimum recommended height for 1 mm thick metal sheets. The width is set to fit on inserts with a diameter of 30 mm and to allow enough clearance within the bead pattern for the welding of the used threaded bolts. Figure 6 shows a tested insert with a bead pattern and the dimensions of the used bead pattern.

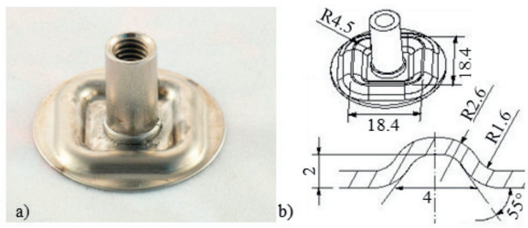


Fig. 6. a) Tested insert with a bead pattern b) Dimensions of the used bead pattern

Polished cut images of CFRP parts with these embedded inserts indicate that a complete infiltration of the inserts with the bead pattern is possible in the RTM process, also in the areas on top and underneath the inserts.

4.2. Design of experiments

Different variations of inserts are tested to evaluate the influence of the above described bead pattern on different inserts. Inserts with different diameters (30-50 mm) in combination with different thicknesses (.6-1 mm) in combination with 2-6 plies above the inserts are tested and compared to specimens with inserts having the same parameter settings but without a bead pattern.

The bead pattern mainly aims at improving the bending strength of the inserts. Anyway, additional tensile tests are performed to ensure that the bead pattern does not have a negative effect on the tensile strength.

4.3. Results

4.3.1. Failure behaviour

The failure behaviour in the tensile tests is adequate to the failure of the inserts without a bead pattern. However, the failure behaviour in the bending tests differs from the one in the tests without a bead pattern. In the previous tests the metal sheet of the inserts without a bead pattern showed a strong plastic deformation across the whole metal sheet. This deformation could be prevented by the bead pattern. When testing the inserts with a bead pattern, the deformation remains small and only occurs in-between the bead pattern (see Fig. 7).

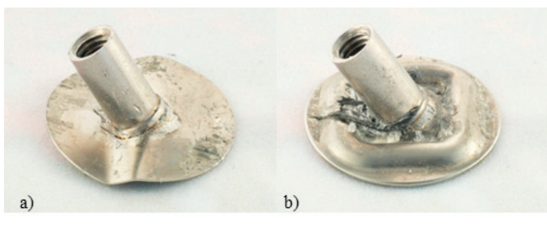


Fig. 7. Deformation of an insert without (a) and with a bead pattern (b)

The prevention of the plastic deformation also reduces the risk of delamination. Thus, some of the tested inserts with a bead pattern failed by a crack in the threaded bolt instead of delamination of the CFRP.

4.3.2. Evaluation of the tensile and bending strength

In the tensile tests, neither a positive nor a negative effect of the bead pattern on the tensile strength could be identified. The load-bearing capacity of the specimens remains the same for inserts with and without a bead pattern.

In the bending tests, the bending strength could be increased significantly. Thereby, the positive effect of the bead pattern on the bending strength became particularly apparent in tests with more plies above the insert due to the higher bending stiffness of the laminate above the inserts. Tests with different diameters revealed that a larger diameter of the metal plate outside the bead pattern does not result in a higher bending stiffness, since only the metal sheet in-between the bead pattern is deformed (cf. Fig. 7). The additional material outside the bead cannot increase the bending strength any further. The effect of the bead pattern is independent of the thickness of the metal sheet. The bead pattern highly improved the bending strength in both insert types, the one with a metal sheet thickness of 0.6 mm as well as the one with a metal sheet thickness of 1 mm .

On average over all tested variants, the bending strength could be enhanced by 38% in comparison to the same specimens with inserts without a bead pattern.

5. Investigations of the effect of surface treatments and coatings to enhance the performance of embedded inserts

The failed inserts showed a separation of the insert's metal sheet from the CF laminate (cf. Fig. 5). Thus, it is assumed that an increased strength of the co-cured bonding connection between the metal and the CFRP can lead to an enhanced performance of embedded inserts.

Several studies have already been performed to detect the influence of surface treatments and coatings on the performance of bonded joints between metal and CFRP [7]. Investigations of the influence of surface treatments or coatings for co-cured bonding joints between CFRP/metal parts manufactured by the RTM process are not known. In the following, the effect of different surface treatments and coatings of the metal parts of the specimens is tested in preliminary tests on single lap joint specimens before the most promising treatments are applied on embedded inserts.

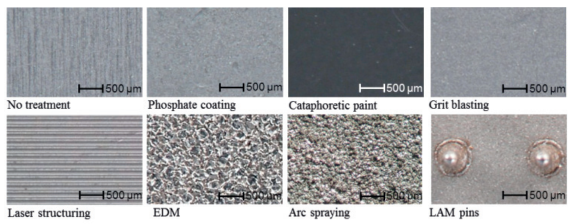
5.1. Selection of surface treatments and coatings

Many possible treatments to increase the strength of adhesively bonded joints are known. In this paper, mainly treatments to increase the mechanical adhesion between the metal and the resin of the CFRP by generating a high surface roughness are tested. In addition to commonly used treatments for increasing the surface roughness, a laser additive manufacturing process is used to add a pin pattern to the surface of the specimens in order to generate a high mechanical locking between the carbon fibres of the CFRP and the metal.

Furthermore, two types of coatings are tested, since they can increase the bond strength as well as prevent corrosion which is important for the combination of CFRP and metal. Additionally, reference specimens with untreated metal sheets are tested. All metal parts are cleaned and degreased before they are joined with the CFRP. Table 1 provides an overview and contains microscopic images of the applied coatings and treatments used for the metal parts of the specimens in this paper.

Table 1. Tested surface coatings and treatments

Coatings
Phosphate coating
Cataphoretic painting
Mechanical treatments
Grit blasting
Laser structuring (line pattern)
Electrical discharge machining (EDM)
Arc spraying
Laser additive manufacturing (LAM) pins
Microscopic images of the different surface treatments / coatings:



5.2. Preliminary tests (single lap joint specimens)

5.2.1. Manufacturing and testing of the specimens

Single lap joint specimens with dimensions according to DIN EN 1465 are manufactured to test the influence of the different surface treatments and coatings. The dimensions of the specimens and an exemplary picture of a manufactured specimen are shown in figure 8.

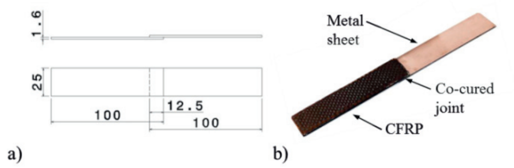


Fig. 8. a) Dimensions of the specimens b) exemplary picture of a specimen

The metal sheets and the CFRP are not adhesively bonded, but already joint in the RTM process by the curing of the resin (co-cured joint). Therefore, the dry fibre textiles (six layers of fabric with a weight of 200 g/m², fibre orientation 0/90°) and the metal sheets are placed in a purpose-made RTM mould (illustrated in figure 9) which is infiltrated with the epoxy resin.

The strength of the adhesive joint between the metal sheets and the CFRP is measured according to DIN EN 1465 on a quasi-static material testing machine (Co. Zwick GmbH & Co. KG, Fig. 9). At least five specimens with each type of surface treatment are manufactured and tested.

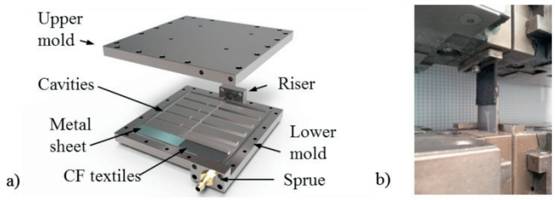


Fig. 9. a) RTM mould for the manufacturing of the specimens, b) used test device with a single lap joint specimen

5.2.2. Results

Figure 10 provides an overview of the mean tensile load-bearing capacity of the tested specimens. All tested surface treatments and coatings lead to an increased failure load of the specimens compared to the specimens with the untreated metal.

Even the treatments/coatings with the lowest increase in strength could strengthen the joints by 87% (phosphate coating), 45% (grit blasting) respectively 156% (electrical discharge machining).

The best results could be achieved by the cataphoretic painting (+ 295%), laser structuring (+294%), arc spraying (+409%) and the laser additive manufacturing pins (+455%).

Beneath the improvement of the load-bearing capacity, a decrease of the standard deviation is noticeable for most of the applied surface treatments and coatings.

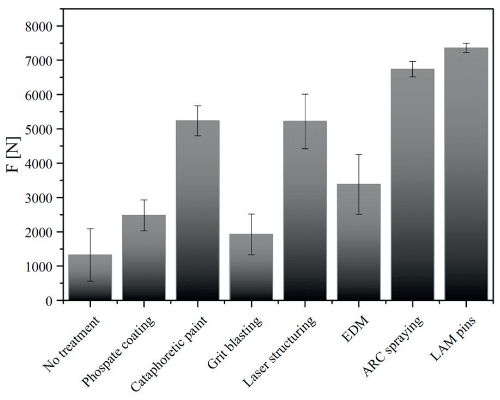


Fig. 10. Tensile load bearing capacity of the single lap joint specimens with different surface treatments/coatings of the metal sheets

The tested specimens thereby reveal different modes of destruction. The untreated specimens and the specimens that did not lead to a substantial increase in strength show a mainly adhesive failure, whereas the specimens with a significantly increase in strength show a cohesive-adhesive failure. The specimens with the cataphoretic paint also display a separation of the coating from the metal substrate. The fracture surfaces of the metal parts of the specimens after the tests are pictured in figure 11.

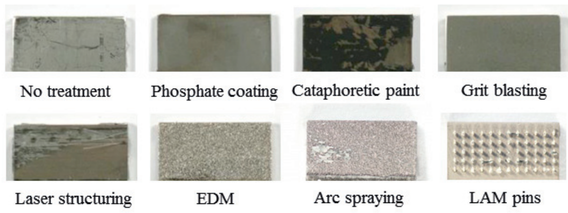


Fig. 11. Fracture surfaces of the metal parts of the specimens

5.3. Tests with embedded inserts

Based on the results of the preliminary tests, the surface treatments/coatings with the best results are chosen for tests with embedded inserts. Altogether, the following three surface treatments and one coating are tested (cf. Fig. 12):

- Laser additive manufacturing pins
- Arc spraying
- Laser structuring
- Cataphoretic painting

The surface treatments/coating are applied on the upper and lower side of the insert's metal sheets, with the exception of the laser additive manufacturing pins, which could only be added on the lower side of the inserts. The CFRP specimens are manufactured and tested according to the untreated specimens described in chapter 2. Five specimens of each variant are tested.

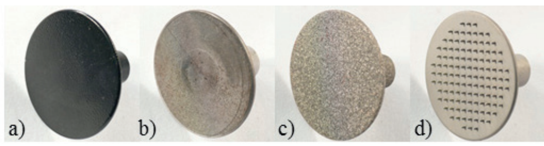


Fig. 12. Inserts with surface treatments: a) Cataphoretic paint, b) Laser structuring, c) ARC spraying, d) LAM pins

5.3.1. Results

As for the untreated inserts, the failure behaviour is analysed and the achievable tensile and bending strength is evaluated.

5.3.1.1. Failure behaviour

The observable failure behaviour of the specimens with surface treatments is very similar to the specimens without a surface treatment. However, the run of the test curves differs for some of the treatments.

The run of the tests curves of the inserts with cataphoretic paint is similar to the untreated samples, with a failure at only slightly higher loads. The significant increase in strength of the preliminary tests with the single lap joints could not be transferred to the tests with inserts, possibly because of the separation of the coating from the metal inserts (cp. Fig. 11) which also occurred in the tests with inserts.

The run of the test curves of the inserts with the laser structuring and the arc spray differs considerably. The curves already show small irregularities at low loads (2-3 kN). This can be explained by the damage of single carbon fibres due to the extremely rough surface in case of the arc-spray. In case of the laser structuring, excessive resin or trapped air in the laser structures of the inserts could explain the irregularities. Nevertheless, after some minor irregularities, the curves show a linear behaviour to loads considerably higher than the untreated samples.

The specimens with the laser additive manufacturing pins lead to the most substantial increase in tensile strength of all tested sampled and feature a linear run of the test curves up to high loads, followed by an abrupt failure of the specimens.

In the bending tests, the inserts with the laser structuring show similar failure behaviour as the untreated samples, with delamination between the upper and lower plies of the laminate visible in the test curves and the failed specimens.

The specimens with the other treatments and the cataphoretic painting reveal a different behaviour. A strong increase of stiffness can be recognized, apparent by a much steeper progression of the test curves. Additionally, the specimens can bear much higher loads. In case of the cataphoretic painting, delamination occurs at much higher loads compared to the specimens with untreated inserts. The delamination between the upper and lower plies can even be avoided completely due to the better adhesion between the insert and the laminate at the specimens with laser additive manufacturing pins and arc-spray.

5.3.1.2. Evaluation of the tensile and bending strength

Table 2 provides an overview of the achievable tensile and bending strength of the tested specimens (in percent, compared to the specimens with untreated inserts).

Table 2. Results of the tensile and bending tests with embedded inserts (100% ≙ results without surface treatment)

	Tensile tests	Bending tests
Untreated inserts	100%	100%
Cataphoretic painting	110%	131%
Laser structuring	119%	112%
Arc spraying	128%	141%
Laser additive manufacturing pins	142%	127%

Overall, all tested surface treatments lead to an improved performance of the embedded inserts. Since also other parameters effect the strength of the embedded inserts (e.g. stiffness of the CF laminate and insert), the effect of the surface treatments/coating is not as big as it is for the single lap joints, where the strength of the adhesion between metal and CFRP is the main determining parameter for the performance. Nevertheless, a clear enhancement of the performance of embedded inserts can be achieved by using surface treatments/coatings which confirms the assumption that the adhesion between the inserts and the CFRP constitutes a weak point of embedded inserts.

6. Conclusion

Performed tests with embedded standard inserts in CFRP parts manufactured by the RTM process revealed two main weaknesses of the used inserts: A small bending strength of the insert's metal sheets leads to a strong plastic deformation of the inserts. A weak adhesion between the insert's metal sheets and the laminate leads to a separation of the insert and the laminate in the tensile and bending tests. Two approaches to enhance the performance of embedded inserts were investigated experimentally:

An additional bead pattern was added to the inserts to improve the bending stiffness of the insert's metal sheets. A significant increase of the bending strength of the embedded inserts was proven with the chosen geometry of the bead pattern.

Different surface treatments and coatings were tested to raise the strength of the co-cured bonding between the inserts and the laminate. Suitable surface treatments and coatings were identified in preliminary tests with co-cured joined single lap joint specimens. The three most promising treatments and one surface coating were chosen for tests with embedded inserts. A considerable increase of the load-bearing capacity of the specimens in the tensile and bending tests could be achieved with the tested treatments and coating.

Acknowledgements

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