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INCREASING THE STRENGTH OF MECHANICALLY JOINED CONNECTIONS OF METAL AND FIBER-REINFORCED PLASTICS USING A STRUCTURED AUXILIARY JOINING ELEMENT

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ABSTRACT

The low plasticity in comparison to metals represents a limiting factor for fiber-reinforced plastics in mechanical joining systems. While previous approaches to solving this problem have provided for new joining processes or local metal sheet inserts in the fiber composite, the present study aims at a pin-structured auxiliary joining element as a new technology support for increasing the load-bearing capacity of mechanical joints between metal and fiber reinforced plastics. The increase in load-bearing capacity principle is based on the relieving of critical hole edge areas of the FRP by introducing loads across the pin structures of the auxiliary joining element. Therefore, the following paper shows different approaches in manufacturing of the new type of auxiliary joining element with integrated pin structures. Furthermore, the influences of the pin-geometry on the composite fracture behavior by insertion under various heating strategies have been investigated, whereas ultrasonic assisted insertion leads to favourable results. To define the most effective manufacturing process for a pin-structured auxiliary joining element with increasing in load-bearing capacity ability single-lap tests for detecting the shear tensile strength were examined. With an improvement of the load-bearing capacity of up to 47%, auxiliary joining elements with ten pins, produced by a combined punch-forming process, have achieved the highest shear tensile strengths.

1 INTRODUCTION

In the last decades, the use of fiber reinforced plastics (FRP) increased continuously due to their specific weight and advantageous mechanical properties [1]. In particular, the multi-material design of FRP and metal offer a great potential in lightweight structures. Although structural components made of FRP ideally consist of a single unit, the majority of present frame structures are built-up designs. Therefore, almost all main frame structures are connected by fastened joints like rivets, screws and bolts. As a result of the holes, stress concentration occurs at the edge of the holes when under load. Because of the low plasticity of FRP and the inability to sustain pressure loads even low stresses can lead to failure of FRP. The failure behavior of FRP under bearing load can be described as good-natured due to the fact of high stress peeks relocated in inter-fiber failure and delamination [2, 3]. However, in comparison to metallic materials the bearing strength of FRP is significantly lower. This reduces the load capacity of the joint system and leads into a higher thickness of FRP what subverts the idea of lightweight design.

Hence, numerous investigations in increasing the joint strength of mechanically joined connections of metal and FRP are carried out. Most approaches based on adding metal pins at the metal surface which penetrates the FRP [4, 5]. Whilst many researches face in alternative solutions for joining technology like the resistance spot welding for multi-material parts [6] or the hybridization of composites bolted joints by local metal sheets [7], the present study aims at using an integrated pin-structured auxiliary joining element to enhance the strength of current mechanical joining systems for connections of metal and FRP. For this the hole edge area of the FRP is relieved by transferring the loads over the pins into the FRP. The increase in load-bearing capacity is based on the large-area load application over almost the entire thickness of the FRP and the additional locking effect caused by the pin-structures on the fibers lying transverse to the load direction. The mechanism of load transfer by the pin-structured element is shown in Figure 1. In order to achieve a compromise between load transfer into the FRP laminate to low fiber and inter-fiber damage different manufacturing processes for the auxiliary joining element, have been investigated. Moreover, the different concepts were analysed with respect to their load-bearing capacity enhancing effect of the joint.

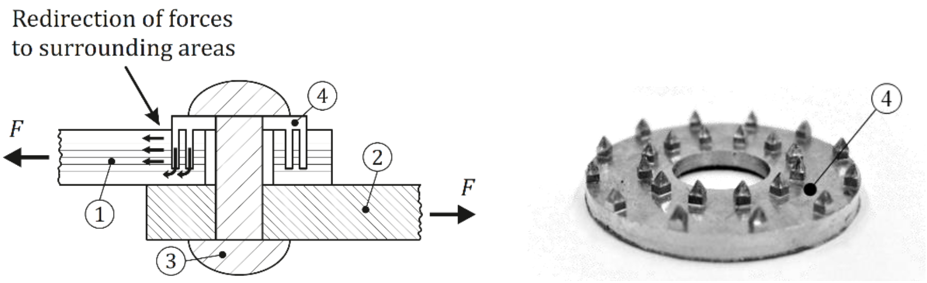

Figure 1: Mechanism of load transfer by the structured auxiliary joining element and prototypical approach the auxiliary joining element, (1) FRP, (2) Metal, (3) Rivet, (4) Auxiliary joining element.

2 MANUFACTURING OF AUXILIARY JOINING ELEMENTS

2.1 Selective Laser Melting approach

The approach by Selective Laser Melting (SLM) was used to produce pin-structured elements with variations in the amount of pins and geometric differences such as radii, height and width. For the SLM approach 1.4404 (316L) metal powder with 50 µm in particle diameter was utilized in a SLM 250 machine. In Table 1 a list of used parameters for manufacturing pin-structured elements by the SLM method is given. In order to detect limits of the manufacturing approach three different parameter sets were defined.

Sample	Number of pins	Length of pins	Base diameter of pins	Tip radius of the pins
A	24	0.8	0.3	0.15
B	24	1.0	0.5	0.25
C	12	1.25	0.8	0.45

Table 1: Parameters for the demonstration of the auxiliary joining elements produced by the SLM method.

The selected stainless steel is mainly used for medical implants, maritime and automobile industries and is characterized by high corrosion resistance, high hardness (89 HRB) and toughness. After heat treatment the tensile strength is between 485 - 595 MPa with an elongation at break of 25 - 55%. [8] In Figure 2 the produced result is shown using variant C as an example.

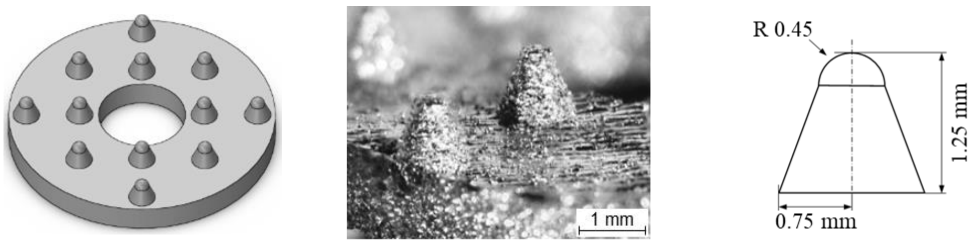

Figure 2: Presentation of a pin-structured auxiliary joining element produced by SLM.

2.2 Chip forming approach

Given the fact, additive manufacturing still cannot be used in large series production, a chip forming approach has been examined. Therefore, a thin gauge sheet metal made of 1.5528 (1.5 mm of thickness) with mechanically set interlocking elements was used [9]. The auxiliary joining elements were cut-out by waterjet using a OMAX 5555. Due to the curved shape and their inverted movement the interlocking elements provide a through-thickness reinforcement and offer a great potential in mechanical interlocking with fibers. The height of the pin-structure is approximately 1 mm and varies according to the curved shape. For the auxiliary joining elements produced, the average number of pins is around 16. For the use of the auxiliary joining element in a quasi-isotropic multi-layer composite of FRP, it is assumed that the use of a radial-symmetric structuring is suitable, since the load-bearing fibers would be stressed transversely to any orientation present. In addition to the experimental implementation of the manufacturing concept, a possible tool concept for the production of radially symmetrical structures was developed. The tool concept uses a slide kinematics which is triggered by a press stroke orthogonal to the part being machined. Figure 3 shows the radial-symmetric structuring concept, a schematic sketch of the tool concept and the linearly structured prototype produced with an outside diameter of 15.0 mm and a drilling diameter of 4.9 mm.

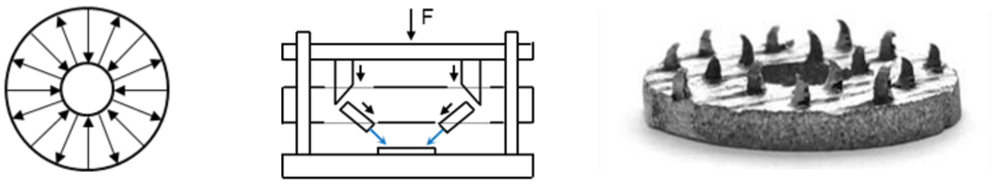

Figure 3: Concept of a radial symmetric structure (left), schematic sketch of the corresponding tool concept (middle) and the auxiliary joining element manufactured by a chip forming approach (right).

2.3 Punch-forming approach

In addition, a punch-forming manufacturing process for the pin-structured auxiliary elements was developed using experimental and numerical investigations. Before forming the pin-structured elements by using a particular designed tool, two-dimensional pin-structured blanks (1.5 mm of thickness) with various pin numbers (3, 5, 7 and 10) were prototypical cut-out by waterjet. To define the forming tool a parameter-study has been carried out. Furthermore, a numerical investigation of the forming process has shown a good agreement between solidified areas and stress concentrations by comparison to hardness tests performed according the Ultrasonic Contact Impedance (UCI) method. The tool now is able to form a 10-pin-structured auxiliary element by a one stroke-process at 5 kN and is shown together with the two-dimensional pin-structured blanks and the manufactured 10-Pin auxiliary joining element in Figure 4.

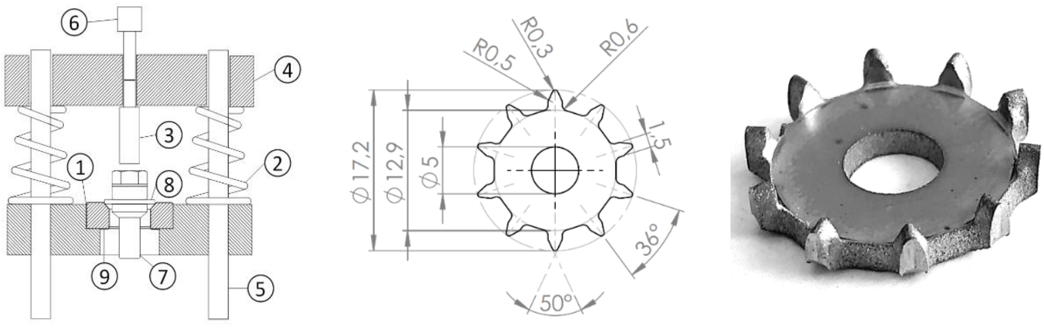

Figure 4: Forming tool with (1) down tool plate, (2) compression springs, (3) punch, (4) upper tool plate, (5) guide columns, (6) tool stamp, (7) disc holder, (8) disk blank, (9) forming bushing, dimensions of the two-dimensional pin-structured blanks and the 10-pin auxiliary joining element.

3 INSERTION BEHAVIOR

While for FRP with a thermosetting matrix only a non-heat introduction of the auxiliary joining elements is possible, fiber-reinforced thermoplastics offer the possibility of local plasticization under the influence of heat. Therefore, glass-fiber-reinforced thermoplastics (woven fabrics with fiber volume ratio of 47%) with polypropylene (GF-PP) and polyamide 6 (GF-PA6) were used in these studies. In order to find a suitable method for the insertion of the pin-structured auxiliary joining elements into the FRP, three different heat-assisted insertion methods were investigated. Thereby on the one hand a heat input into the FRP by means of a heating cartridge on the underside, a heat input by an infrared (IR) radiator on the upper side as well as an ultrasonic-assisted system were investigated. After heating with an IR radiator, the auxiliary joining elements were inserted using a Zwick Z1484 tensile-compression testing machine. For ultrasonic-assisted insertion of the elements, a WEBER Ultrasonics Weld & Cut SAPHIR-D2040 ultrasonic system was used. The aim was to insert the pin-structured auxiliary joining elements reliably and within a short process time into the various FRP materials. The tested heating strategies are obtained in Figure 5.

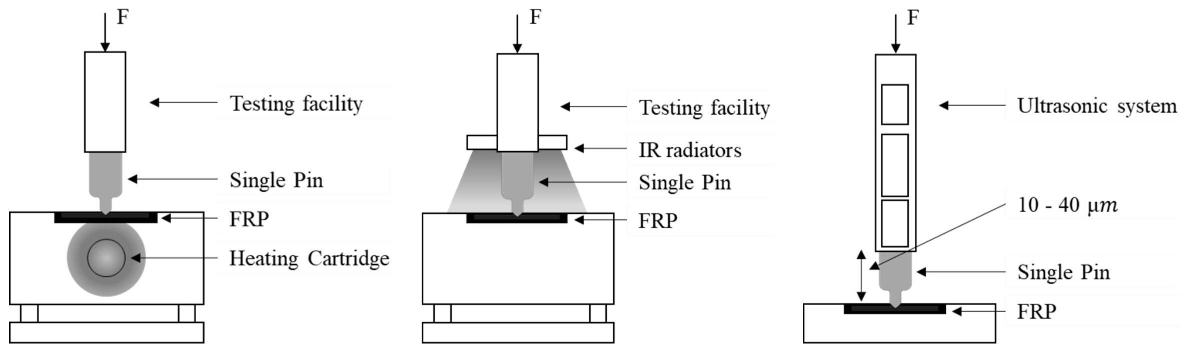

Figure 5: Heating cartridge (left), IR radiator (middle) and ultrasonic-assisted system (right).

The experiments using a heating cartridge were supported by preliminary tests with single pins varied in pin-tip angles (30°, 60°, 90° and 120°) and geometries (gable and shed roof types) to determine the necessary penetration forces as a function of the penetration depth. While using a heating cartridge a selected temperature of 150 °C above the glass transition temperature of GF-PA6 (60 °C) or close to the melting temperature of GF-PP (165 °C). For the other two heating strategies, the auxiliary joining elements described above were investigated. The use of a heating cartridge below the FRP during pin insertion causes thermoplastic migration on the FRP bottom side and cross-sectional reduction of the FRP below the pin. The reason for this is the low thermal transmittance of the FRP which provides a temperature gradient between the top and bottom of the FRP. In Figure 6, the required penetration forces are shown as a function of the penetration depth (0.4 to 0.8 mm) and the pin-tip angle using the example of the gable roof.

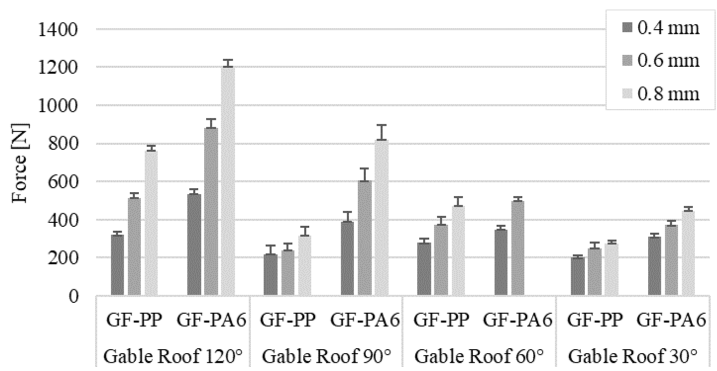

Figure 6: Comparison of the required penetration forces as a function of penetration depth and pin-tip angle at 150 °C for different fiber reinforced thermoplastics.

As the penetration depth grows, a significant increase in force can be detected. Furthermore, higher forces can be determined with increasing strength of the FRP. The smaller the inner angle of the tip, the less force is required for penetration. Due to the chosen temperatures, relaxation in the composite laminate is caused, which favors the penetration of the single pin. However, an accumulation of displaced thermoplastic forms around the pin and fiber breaks as well as delamination occur.

For the second heating strategy using an IR radiator with a power of 150 W and a distance of focus point of 40 mm the enlargement of the molten thermoplastic area was firstly analyzed over time. The influence of heating time and heat source distance is shown in Figure 7. The comparison shows that the melting process of polypropylene takes place earlier due to the lower melting point.

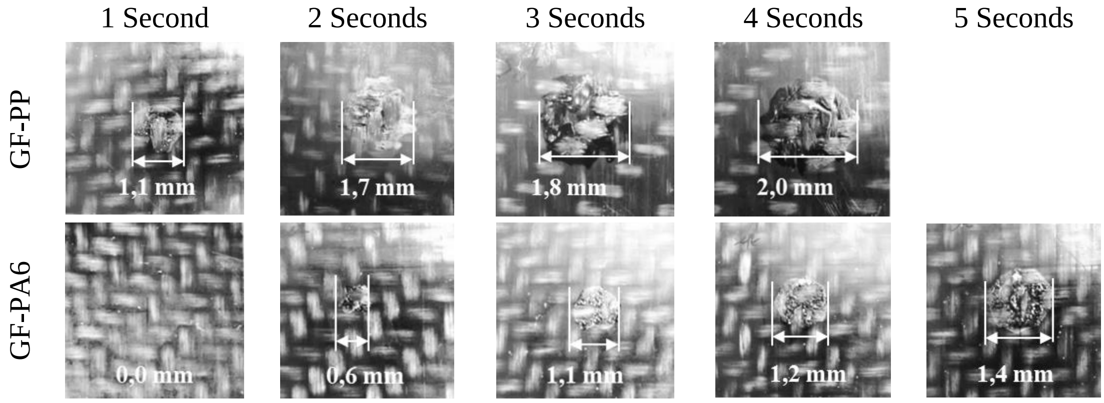

Figure 7: Influence of heating time on the molted area.

The insertion of the pin-structured auxiliary joining elements by the ultrasonic system was carried out with an energy of 250 Ws. The insertion tests have shown that a gap between the auxiliary joining element and the FRP is not avoidable. It turned out that the auxiliary joining elements manufactured by SLM could not be used without damage due to the low compressive strength of the pin structures. Both, the chip forming and punch-forming approaches have shown good results in insertion behavior for the case of using a IR radiator and an ultrasonic-assisted system. However, while using the ultrasonic-assisted system cracks at the pin-structure tips were detected at the elements manufactured by chip-forming. In addition to the heat-assisted insertion, the punch-formed auxiliary joining elements were inserted without heat input. The different results are compared in Figure 8.

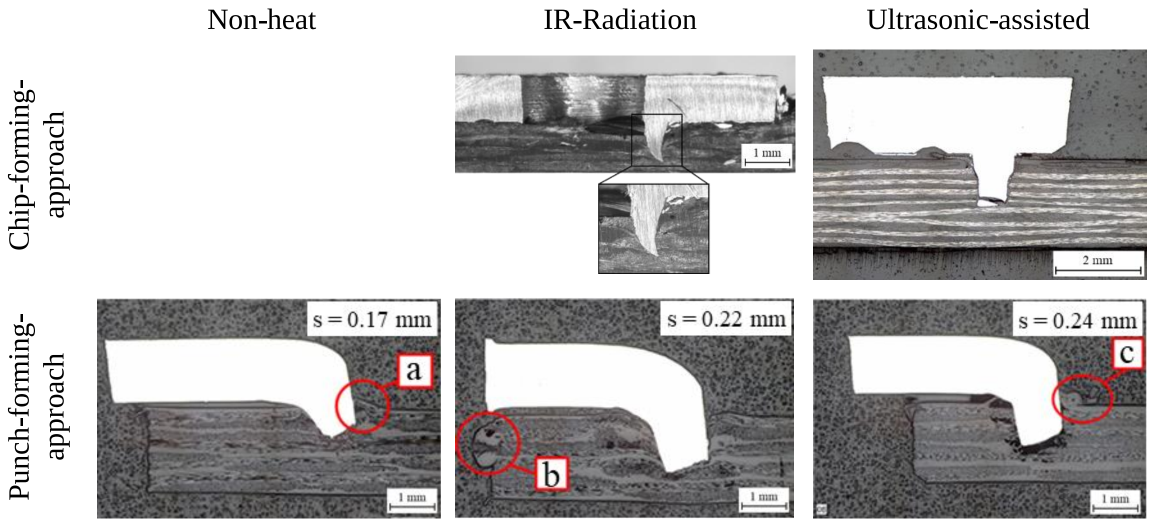

Figure 8: Results for different heating strategies.

For non-heat insertion, a crater-like formation of the displaced thermoplastic material around the pin-structures can be seen (see marking [a] in Figure 8). In contrast, using the IR radiator, molten material is displaced into the hole area of the FRP (see marking [b] in Figure 8). For the ultrasound-supported process, a local material displacement around the pin structures occurs analogous to the insertion without heating (see marking [c] in Figure 8). The insertion force depends strongly on the heat strategy. For ultrasonic-assisted insertion, these are less than 1 kN, for IR emitters about 3 kN and for heat-free insertion about 20 kN. Although the ultrasonic-assisted procedure is advantageous with a process time of less than two seconds and the low insertion forces, the strong material ejection of the FRP and very local thermal damage to the FRP in the pin penetration area has to be mentioned.

4 EXPERIMENTAL INVESTIGATION OF THE JOINT STRENGTH

In order to verify the mechanism in enhanced load transfer by the different pin-structured elements, shear tensile tests with single lap samples have been carried out. For the experiments, fiber-reinforced plastics made of GF-PP and GF-PA6 (woven fabrics) with a thickness of 2 mm (110 x 45 mm) and HC340LA with a thickness of 1.5 mm (105 x 45 mm) were used as joining partners. In the FRP, an edge distance of 16 mm and in the steel material 8 mm is defined. An enlarged bore diameter of 7 mm is set for the FRP to relieve critical hole edge areas. For joining metric screws of strength class 12.9 with a tightening torque of 2 Nm and rivets type Gesipa G-Bulb 4.8 x 15 mm have been used.

Figure 9 shows the results of the quasi-static shear tensile test using a pin-structured auxiliary joining element manufactured with the chip-forming approach. It can be seen that the pin-structures already fail at a force of about 2 kN and that an increase in the load-bearing capacity is not possible with the assistance of these auxiliary joining elements. The failure of the pin structures at an early stage is presumed to be due to a high degree of solidification due to the chip placement and the small cross-sections of the pins. In addition, ultrasonic-assisted insertion already caused cracks to appear in the pin-structures.

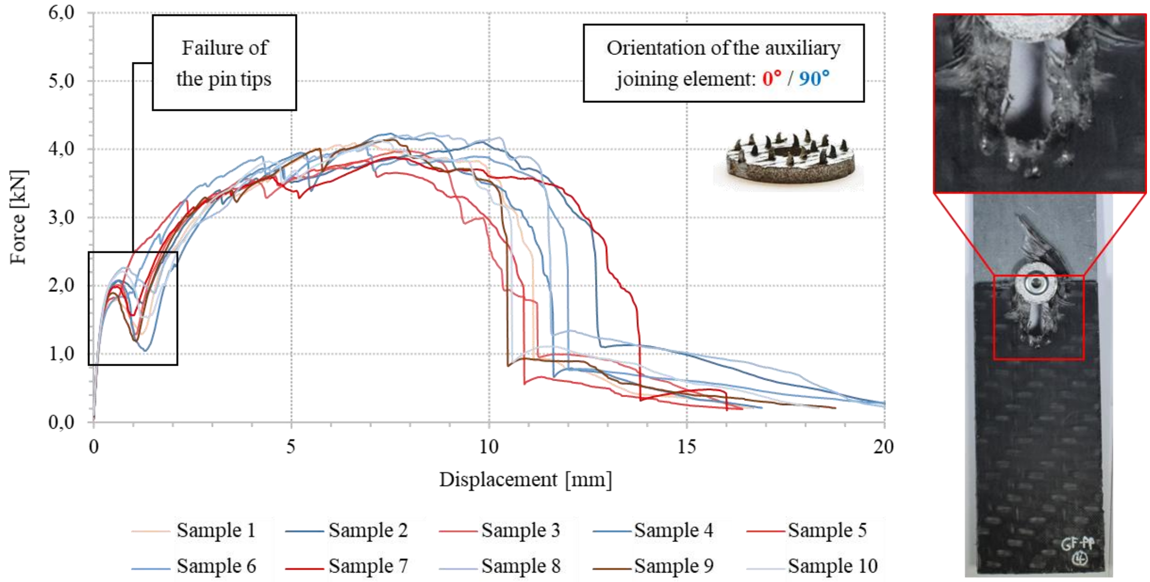

Figure 9: Results of the shear tensile tests of pin-structured auxiliary joining elements for GF-PP.

In order to find the necessary number of pins as well as a suitable material for the auxiliary joining elements, auxiliary joining elements of different types were manufactured. A pin number of 3, 5, 7 and 10 pins for the materials 1.4301, 1.4471 and 1.5528 was investigated. The results of the shear tensile tests can be seen in Figure 10. Thereby it becomes clear that a significant increase of the load capacity is achieved with increasing pin number. In comparison to a conventional washer an increase in load capacity can be achieved even with a pin number of 3. While using the 10-pin-structured auxiliary joining element, a load capacity increase of almost 50% can be achieved. Whereas the failure of the FRP of 3 pin elements is mainly caused by a shear failure, from 7 pins upwards a combined gap and tensile fracture occurs. As well as increasing the load-bearing capacity, the use of pin-structured auxiliary joining elements manufactured by a punch-forming approach results in a visible fail-safe behaviour as a result of the pin-structure being clawed into the fibers.

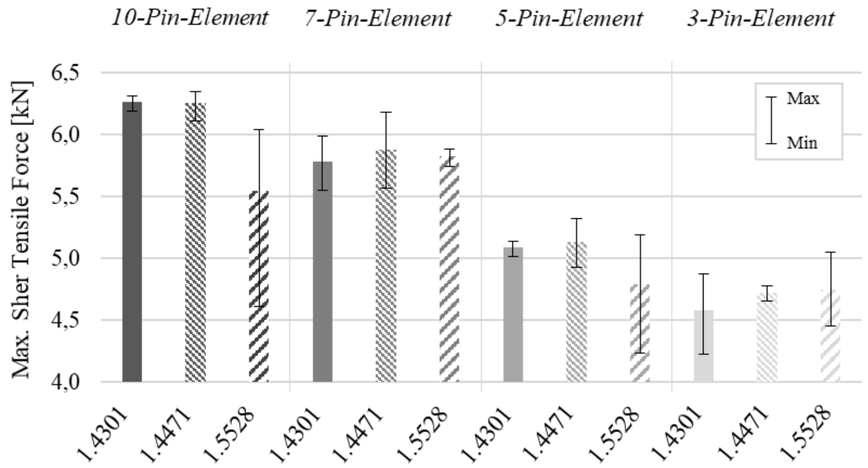

Figure 10: Results of the shear tensile tests of pin-structured auxiliary joining elements for GF-PA6.

5 CONCLUSION

It has been shown that the use of a punch-forming manufactured auxiliary joining element enables a significant increase in the joint strength of mechanically joined FRP/metal composites. Due to the enhanced load transfer into the FRP the high strength potential of the FRP can be effectively used. As a result of using the developed auxiliary joining element a load relieving of the critical FRP hole area can be achieved. Although there is induced damage to the fiber composite as a result of the pin-structures, a load capacity increase of up to 47 % is possible in comparison with classic metal and FRP bolt connections. Furthermore, with the ultrasonic-assisted insertion method a reliable and fast insertion of the auxiliary joining elements by less than 2 seconds and process forces of 1kN or less could be found.

ACKNOWLEDGEMENTS

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