PRODUCTION AND TENSILE TESTING OF ROTATIONALLY MOLDED HYBRID COMPOSITE TIE RODS

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ABSTRACT

An innovative production processes for manufacturing rotationally symmetric FRP-metal components, such as drive shafts or tie rods, is the rotational molding process. In the course of this process, a dry fiber preform and metallic load-introduction elements are inserted into a two-piece mold and subsequently clamped into a spindle. The matrix is injected directly into the rotating mold. Due to the arising centrifugal forces, the preform is impregnated and the component cures under rotation. In comparison to conventional joining processes, such as adhesive bonding or bolt connections, the metallic components as well as the FRP part are intrinsically joined during the forming process. A downstream joining process is not required. The joint is based either on the adhesive property of the matrix system or on a form-fit geometry with undercuts. The paper addresses the production and tensile testing of tie rods. Different rod geometries and different surface treatments, including sandblasting, knurling, and arc spraying, are compared and evaluated.

1. INTRODUCTION

1.1 Motivation

The world today is much more aware of the finite nature of energy resources, and in response, environmental regulations are becoming ever more stringent. Nevertheless, mobility is more and more increasing. One possibility to face this challenge is to rely on lightweight constructions to reduce the energy consumption and contribute to sustainable development. For components that need to meet high mechanical requirements at a low mass, the use of fiber reinforced plastics (FRP) is appropriative because of their excellent mechanical properties. Lightweight constructions with FRP reduce the energy consumption of moving systems during their operating phase or increase the payload of different applications.

Due to its force flow, the tension rod constitutes a highly suitable component for the use of these anisotropic FRP. Tie rods could be used for aircraft and spacecraft applications, such as actuators for landing flaps, lightweight hydraulic actuators or construction elements for solar panels [7, 8, 20, 21]. The loads are usually introduced into the composite tie rod with metallic load introduction elements, which are attached to the rest of the system. These metallic load introduction elements are joined to the FRP structure by using either friction locking, a form-fit, or substance bond. Although the component consists of FRP and metal, this fact should not be confused with multifunctionality. The joining technologies required to obtain these hybrid components can generally be divided into two groups: intrinsic and extrinsic hybridization methods. An intrinsic hybrid component is an integral component for which the connection of the different materials is carried out by primary shaping or forming the metallic or fibre-reinforced component. Hence, no extrinsic joining process, such as riveting, screwing or adhesive bonding is needed [3]. There are many different production technologies for producing hybrid composite tie rods. Selecting a process depends on the target cost, number and requirements of the product. This paper presents a new manufacturing process for the production of composite tie rods by rotational moulding, which is based on the principle of centrifugal force. In order to evaluate the mechanical strength, a large test row of composite tie rods with different geometries and surface treatments is manufactured and tested.

1.2 State of the Art

According to the current state of the art, hollow structures made of FRP for drive shafts or tie rods are produced by winding [16], pultrusion [11] or blow molding [1]. One variant of the winding process is wet filament winding where a roving is drawn through a thermoplastic matrix bath and wound onto a heated core. Another possibility is prepreg winding, in which both thermoset and thermoplastic prepregs are used. The pultrusion process also uses either thermoset or thermoplastic materials. In addition, pull braiding pultrusion provides the option of implementing reinforcements transverse to the production direction [12]. In general, the pultrusion process shows the highest productivity compared to other production technologies. A less common method to manufacture hollow FRP structures is the blow molding process, where a blow hose is pressurized so that the dry fiber preform is pressed against the tool form. The matrix is then injected into the cavity between blow hose and tool form. If the mold is heated, blow molding can also be applied for thermoplastic materials [1]. Impregnation processes such as resin transfer molding (RTM) or vacuum assisted transfer molding (VARTM) can likewise be used. Similar to blow molding with thermosets, a dry fiber preform is needed. This preform is either manufactured through braiding or winding of fabrics. Additionally, a core must be used in order to avoid accumulation of excess matrix in the cavity. The core must then be removed in a downstream process step. In order to attach the hollow FRP structures to the remaining system or install bearings and gearwheels, metallic elements are necessary. Established technologies for joining metallic load introduction elements with hollow FRP structures are interference fit [18], adhesive bonding [9], bolt connections, pin connections [19], form fit [1, 17, 21] or joints created by friction locking [6].

An innovative process for the intrinsic production of hollow structures made of FRP and metal is the rotational molding process [2, 4]. A dry and hollow fiber preform is inserted into a mold, together with the metallic load introduction elements. The mold is sealed and then clamped in a spindle. Afterwards, the thermoset matrix system is injected under rotation. The dry fiber preform is infiltrated due to the generated centrifugal forces and hardens under rotation. Hence, the metallic load introduction elements can be intrinsically joined by co-cured bonding [15], a form fit or a combination of the two. Compared to established technologies, no additional process step is necessary. Furthermore, expenses for rotational molding are rather low, as only a simple mold along with a spindle are required.

1.3 Objective and Approach

First studies of the rotational molding process have already been conducted and a rough feasibility of the process could be demonstrated as both fiber volume content and geometric fidelity are satisfactory [4, 14]. Therefore, the objective of this paper is to evaluate the mechanical strength and the energy absorption during failure of the intrinsically manufactured FRP-metal joint. As a test component, a rotationally molded hybrid composite tie rod is selected. This hybrid composite tie rod is manufactured in varying ways. The first variant is a tie rod with a cylindrical co-cured bonded lap joint (see Figure 1a). The second variant has a form-fit geometry (see Figure 1b). Due to the adhesive properties of the epoxy matrix used, the second variant has a joint which is a combination of a form fit and a co-cured bonding. In the present state of research, various approaches exist to increase the mechanical strength of hybrid FRP-metal joints [1, 5, 6, 13, 22]. Therefore, different surface treatments for the metallic load introduction elements are chosen, such as grit blasting, knurling, and arc spraying. Some treatments clearly increase the manufacturing costs. Nevertheless, all treatments must be compared to one another in order to allow a final assessment. A large series of samples is manufactured and quasistatic tension tests are conducted to evaluate the strength and the energy absorption of the components. The failure of the specimens is analyzed with microsection.

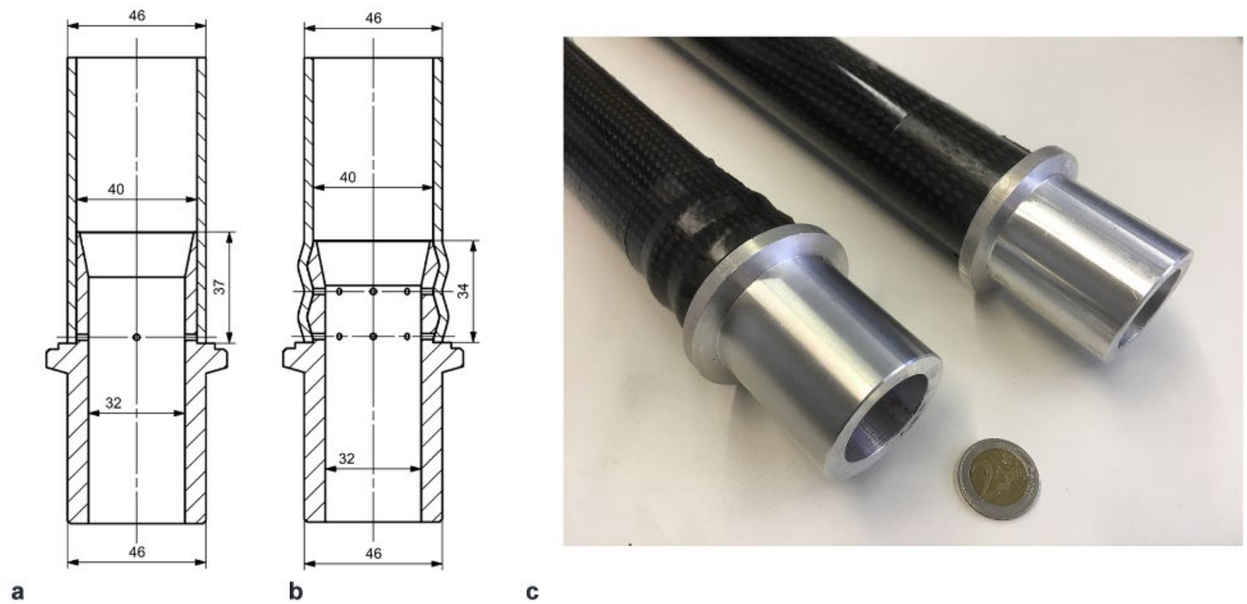

Figure 1. Overview of the different variants: (**a)** tie rod with a cylindrical co-cured bonded lap joint, (**b)** tie rod with a combination of a form fit and a co-cured bonding, (**c)** manufactured components.

1.4 Overview of Contents

Section 2 describes the manufacturing of the rotationally molded hybrid composite tie rods and the different treatments in detail. Furthermore, the test setup for the tensile tests is explained. In Section 3, the results of the tensile tests and the microsections are presented. The different treatments are compared to one another, and the achieved joint strength is discussed. Conclusions are drawn in Section 4 and finally, a short outlook is provided.

2. EXPERIMENTATION

2.1 Manufacturing of Test Specimens

First, the load introduction elements are turned out of steel. As described in Figure 1, there are two different component variants. In addition, different coatings and treatments are carried out (see

Table 1). In order to have an appropriate reference, the first treatment is an eight minutes cleaning carried out in an ultrasonic bath with acetone. The load introduction element is later joined to the FRP hollow structure by co-cured bonding using rotational molding. The second reference is a downstream adhesive bonded variant 1 with the structural adhesive Permabond ET5428. The cylindrical carbon fiber reinforced plastic (CFRP) structure is rotationally molded and later adhesively bonded to the metallic load introduction element. The aim of producing this reference is to compare the intrinsic approach with the common extrinsic production.

Table 1. Coatings and surface treatments of the metallic load introduction elements

Coatings and treatments	**Variant 1: (co-cured bonded lap joint)**	**Variant 2: (combination of form fit and co-cured bonding)**	**Example image of variant 2**
Reference 1: No treatment, only cleaning	x	x	
Reference 2: Adhesive bonding after production	x		
Grit blasting	x	x	
Arc spraying	x		
Knurling	x	x	
Coating with structural adhesive	x	x	

All other test specimens are mechanically treated or coated and produced by rotational molding. Mechanical adhesion is improved by increasing the surface roughness of the load inducing elements. A simple and cost-effective process to increase roughness is grit blasting. The test specimens are therefore grit blasted with corundum and 8 bar so that a roughness of Ra 2.7 µm is achieved. Another option to increase the surface roughness is the arc spraying process, in which wolfram carbide is melted and sprayed onto the workpiece surface at a very high speed. The gained surface roughness for the given load introduction elements is Ra 9.8 µm. Knurling deforms the load introduction element on the mesoscale. For variant 1, a RGE 30° knurling profile is chosen with two different profile depths of 0.4 mm and 0.7 mm. Variant 2 is structured with a similar profile and a depth of 0.7 mm by milling. The last treatment is a coating performed before rotational molding with the structural adhesive Permabond ET5428.

The processing of the load introduction elements is followed by the production of the dry fiber preform. Three layers of carbon fiber braided sleeves from Siltex are used for this (see Table 2). Components with a knurled surface get a braided sleeve with similar fiber orientation as first layer but a lower amount of filaments is used because this sleeve fits better into the knurled structures. The braided sleeve is then drawn layer by layer onto a core and applied together with the binder powder EPIKOTE™ 05311. After that, the binder powder is activated layer-wise by heat to obtain a dimensionally stable preform, which can be placed into the two-piece mold together with the load introduction elements. Subsequently, the mold is sealed and preheated for half an hour at 60 °C in a heating oven. By preheating the mold, the viscosity of the matrix system can be influenced, and thus improve infiltration and accelerate the curing cycle.

Table 2. Manufacturing parameters

Parameter	**Value**
Ply stack	$\pm 32°_1 / \pm 22°_1 / \pm 32°_1$ (Siltex 6430, 6K/ Siltex 4803, 6K/ Siltex 6430, 6K)
Ply stack for components with knurled surface	$\pm 30°_2 / \pm 22°_1 / \pm 32°_1$ (Siltex 3770, 3K/ Siltex 4803, 6K/ Siltex 6430, 6K)
Preheating	30 minutes at 60 °C
Resin	NEUKADUR EP 986
Hardener	NEUKADUR Hardener 269
Binder powder	EPIKOTE™ 05311
Centrifugal speed	3600 rpm
Rotation time	2.5 hours
Tempering	18 hours according to instructions

The tool is then clamped in a turning machine and set in rotation with 3600 rpm. A unit injects the epoxy matrix NEUKADUR EP 986 directly into the mold [10]. Due to centrifugal forces, the dry fibers are impregnated (see Figure 2). The radial impregnation takes place before the axial overlap area is impregnated [14]. To obtain a pore-free FRP structure, ventilation holes are drilled into the metallic load introduction elements as shown in Figure 1 and Table 1. After 2.5 hours, the rotation is stopped, and the mold is put into a heating oven for tempering according to the manufacturer's instructions. Subsequently, the hybrid composite tie rods are demolded.

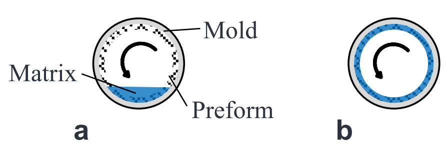

Figure 2. Process sequence: (**a**) injection of matrix system during rotation, (**b**) completely infiltrated component.

2.2 Tension Tests of Test Specimens

With the objective to increase the number of test specimen, the tie rod is cut in the middle, to obtain two test specimen, each consisting of one hollow CFRP structure with the corresponding load introduction element. One test specimen comes from the right and the other from the left mold half. Hence, four test specimen are available per variant. Using appropriative collets and a pressure of 140 bar, the test specimen are attached to the testing machine (see Figure 3). The specimens are then quasistatically tested at a speed of 2 mm per minute.

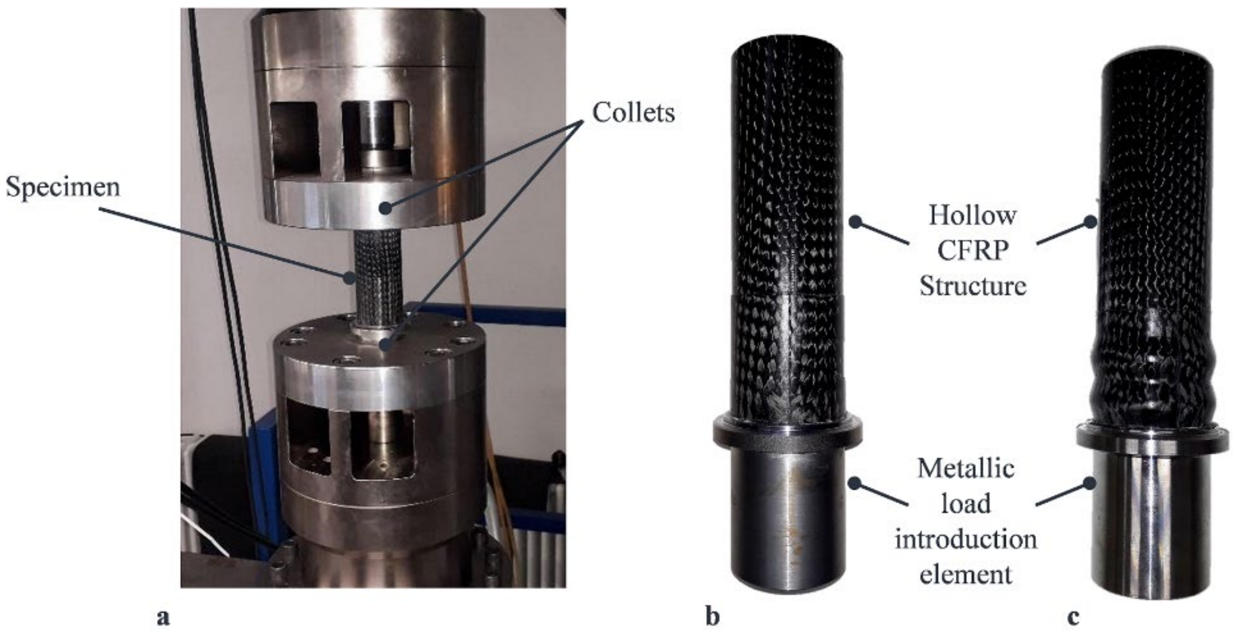

Figure 3. Overview tensile tests: (**a**) test setup, (**b**) variant 1, test specimen with co-cured bonding c variant 2, test specimen with combination of form fit and co-cured bonding.

3. RESULTS

3.1 Mechanical Joint-Strength and Force-Displacement Analysis

The results indicate that the test specimens with untreated load introduction elements feature significantly lower strengths compared to mechanically treated or coated specimens (see Figure 4.) Simply cleaning the specimens with acetone (untreated reference) does thus not seem to be sufficient in order to transfer high forces between the CRFP-metal joint. Furthermore, it can be seen that all test specimens from the left half of the mold achieve very poorer results compared to the right half (see Figure 5). It can be concluded, that the left half of the mold produced by milling is not sufficiently accurate, resulting in a parallel and angular offset between the load introduction element and the CFRP structure, which negatively effects the strength. Therefore, the components from the left half of the mold are not considered in Figure 6. Some of the specimens slip out of the collets and could not be tested to failure (see Figure 5, grit-blasted specimen 2 on the right side of the mold). Particularly high joint strengths for variant 1 are achieved by coating with structural adhesive, grit blasting and arc spraying. The strength can be increased both by coating and by mechanical treatment. Comparing the results of the arc spray treatment with Ra 9.8 µm to those of the grit blasting treatment with Ra 2.7 µm indicates, that a higher surface roughness positively influences the joint strength. Compared to reference 2, which is adhesively bonded after production with Permabond ET5428, the intrinsically rotation molded specimens demonstrate increased strength. Due to the centrifugal force, the load introduction element is concentrically integrated into the CRFP structure. The reference 2 specimens may have been less accurately bonded, which could explain the difference in joint strength.

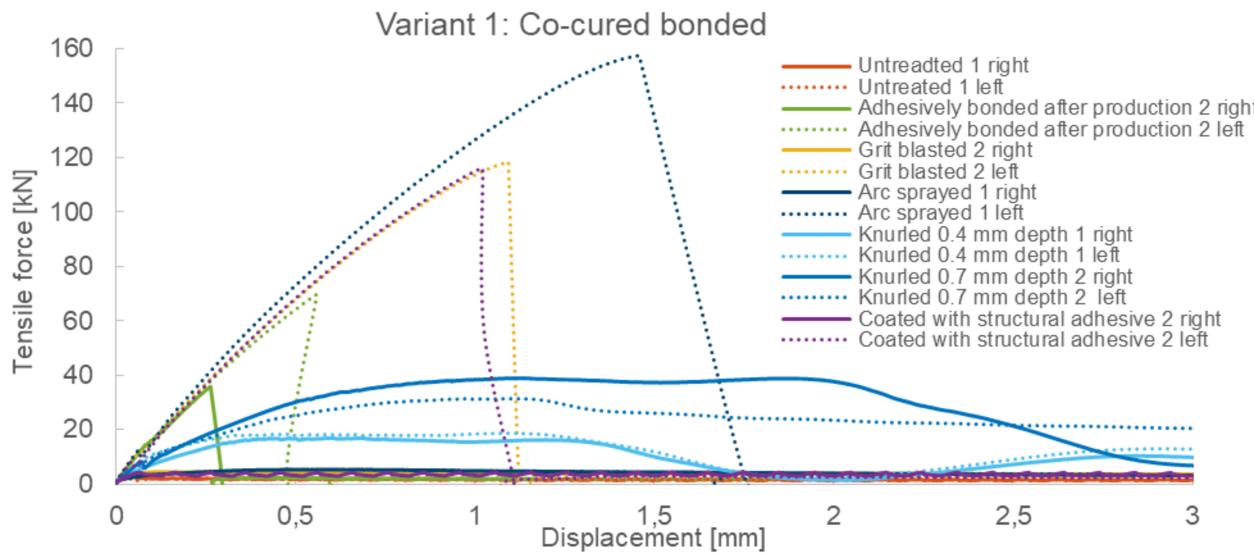

Figure 4. Force-displacement diagram of variant 1 with co-cured bonding specimens. The data displays a selection of the specimens and is classified into first and second specimen as well as left and right mold side.

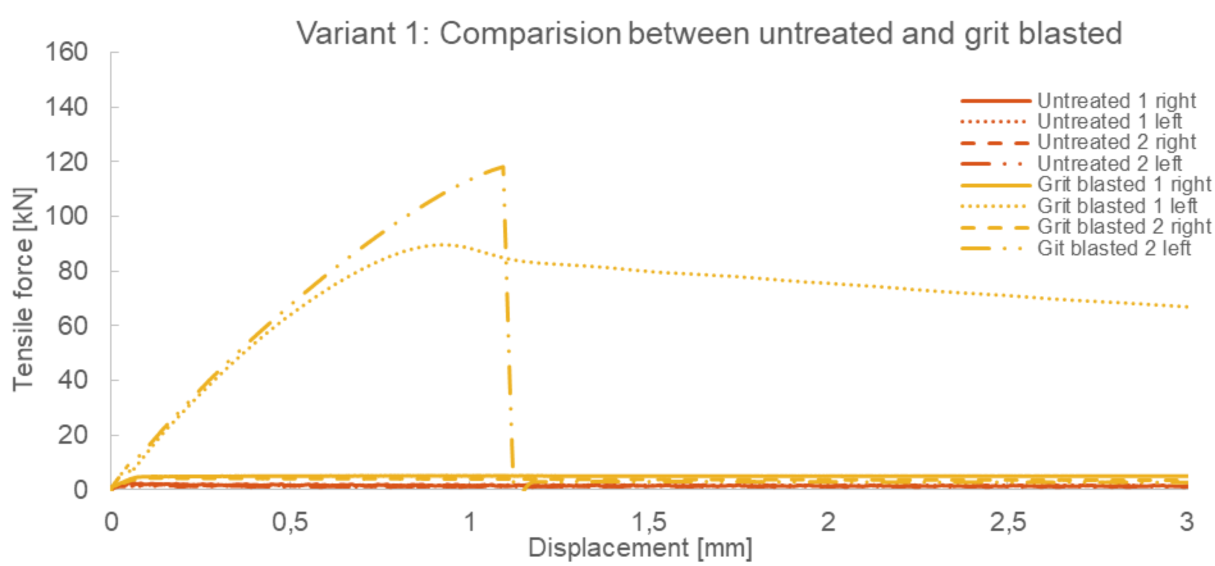

Figure 5. Force-displacement comparison between untreated and grit-blasted specimens for all tested parts

The knurled specimens are of moderate strength, whereby a positive influence can be observed with increasing knurling depth. As opposed to the other components, no abrupt failure occurs but a successive failure with a high energy absorption. By means of knurling, a meso-form fit is created, which is responsible for the energy absorption. Hence, the knurled components are suitable for use in crash-relevant structures. Figure 6 summarizes the maximum tensile forces with the corresponding joint strength and the standard deviation. The joint strength is the shear stress which is related to the surface area of the metallic load introduction elements, taking into account the ventilation holes. The best specimen with an arc spray treatment fails at a force of 157 kN, resulting in a maximum joint strength of approximately 34 MPa.

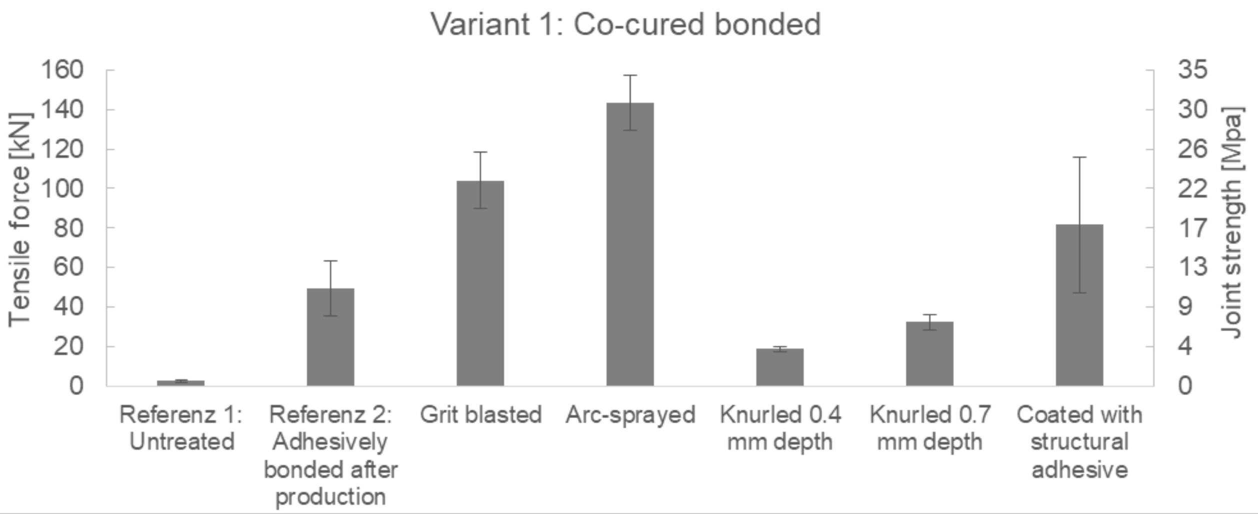

Figure 6. Bar chart with maximum tensile force and joint strength of variant 1 specimens with co-cured bonding

In contrast to variant 1 with a co-cured bonded joint, the variant 2 specimens show a combination of a form fit and co-cured bonding. Figure 7 displays the quasistatic tensile test results of this variant. In general, the strength values are lower than the ones of variant 1.

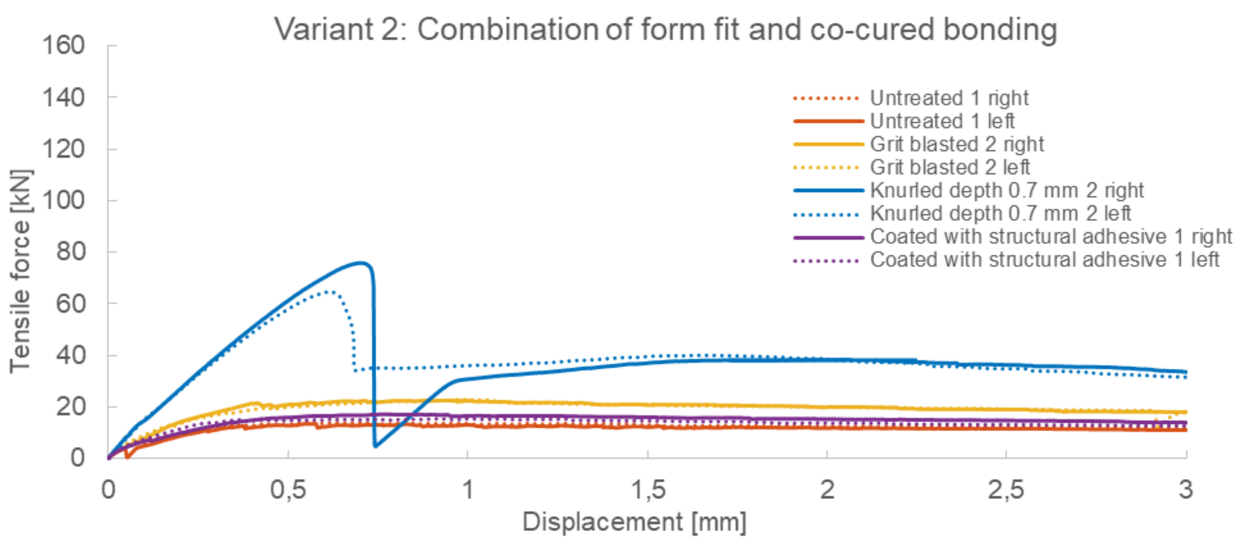

Figure 7. Force-displacement diagram of variant 2 with combination of form fit and co-cured bonding

Even mechanical treatments such as grit blasting or coating with structural adhesive do not generate any significant added value. A clear advantage is only achieved with knurling on the mesoscale. Similar to the knurled specimens of variant 1, all specimens of variant 2 contain energy absorption in the failure process, which is much higher than the energy absorption of variant 1. This energy absorption can be attributed to the form fit. The comparison of variants 1 and 2 reveals that high joint strengths can be achieved by co-cured bonding with appropriate treatment, whereas the use of form-fit geometries can lead to great energy absorption in the event of failure, which can be relevant for crash applications.

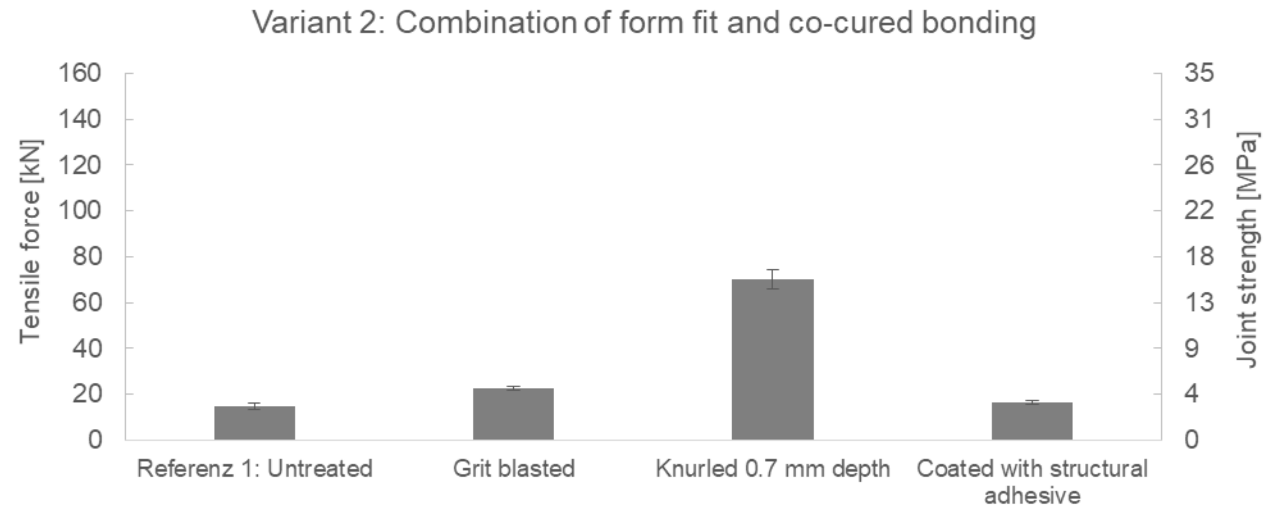

Figure 8. Bar chart with maximum tensile force and joint strength of variant 2 specimens

3.2 Microsections of the Interface

Microscopic analyses are carried out in order to analyze the knurled interface between the CFRP and the metal more precisely (see Figure 9). It can be concluded that the individual fiber bundles do not completely fit into the knurled structure. Furthermore, a pure matrix area between the laminate and the metal is visible. In addition, a wrinkle of the carbon fiber preform is formed in the mold parting line, as shown in the picture on the left. In future experiments, a preform with smaller fiber bundles should be used to allow them to be fully embedded in the knurled structure. In addition, more attention must be paid to the preform's production to avoid wrinkles when closing the two halves of the mold.

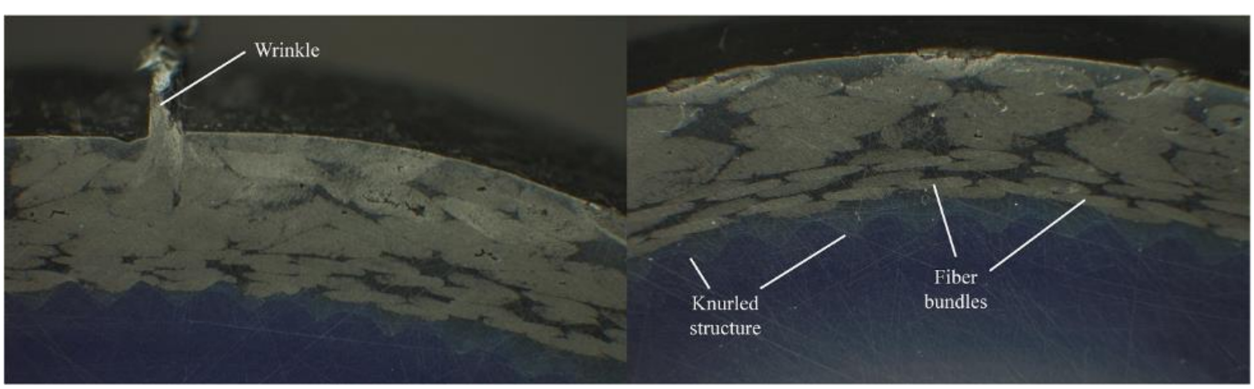

Figure 9. Microsections of the knurled interface between CFRP and metal

4. CONCLUSIONS AND OUTLOOK

In this paper, the intrinsic manufacturing of a hybrid composite tie rod with rotational molding has been presented. Different mechanical surface treatments and coatings have been compared with one other on the basis of different specimen geometries. In general, the results have shown that higher joint strengths can be achieved by appropriate treatments. For components with co-cured bonding, mechanical treatments that increase the surface roughness, such as arc spraying, turn out to be suitable. The failure of these specimens occurs abruptly without any energy absorption after the first failure. In order to avoid parallel and angular offsets, the mold for this intrinsic technology must be produced highly accurately. In contrast to co-cured bonded test specimens, samples with a combination of a form fit and co-cured bonding show a moderate joint strength but good energy absorption. A surface treatment with a structure similar to a knurled interface is particularly well suited for these types of components. The energy absorption behavior during failure qualifies these components for crash applications. However, microsections reveal a pure matrix area between the CRFP and the metal.

The achieved results show a reasonable joint strength for the chosen treatments. In future works, numerical simulations have to be conducted to optimize the joint geometry. In addition, the precision of the mold shape must be increased, and the filament bundles should integrate more into the knurled surface to further increase joint strength. Finally, fast curing matrix systems with heat supply should be used in order to significantly reduce production times.

5. ACKNOWLEDGEMENTS

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