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Investigation of hybrid fusion bonds under varying manufacturing and operating procedures

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ABSTRACT

The desire to apply fiber reinforced plastics (FRP) in large batch production processes due to the ongoing challenge to build more efficient lightweight structures poses new demands for process technologies. One of many challenges is the request for short cycle times during production of FRP parts. One possibility to meet this demand is to use thermoplastic FRP which enables the decoupling of part production and material consolidation. In addition and based on the application of metallic components to so called hybrid parts, the parts costs can be significantly reduced. Furthermore, due to their fusibility thermoplastic materials enable the integration of process steps into the part production for example the joining process with the metallic component. To realize sufficient part strengths, a pre-treatment of the metal surface becomes necessary. In this investigation a laser pre-treatment is used which showed comparable results to a structural adhesive bond.

The presented investigations focus on the manufacturing process and the operating limits of fusion bonds built with a laboratory setup (lap-shear specimens). The tests will conduct the sensitivity of this fusion bonding process to different temperatures, dwelling times and applied pressures. Another focus is the durability of the fusion bonds under varying operating temperatures.

1. Introduction and state of the art

The aim to apply fiber reinforced plastics in large batch production processes due to the ongoing challenge to build more efficient lightweight structures poses new demands for process technologies. One of many challenges is the request for short cycle times during production of fiber reinforced plastic parts. One possibility to fulfill this demand could be the application of fiber reinforced materials with a thermoplastic matrix. The usage of these materials becomes more and more common in several areas of the mobility sector as [1–4] show. In combination with the application of a metallic components to so called hybrid parts [4,5], the overall costs in the usage of fiber reinforced materials can be reduced. In this hybrid approach the fiber reinforced material is only applied in areas where it is needed. To build such a hybrid part it is essential to find a joining technique that does not compromise the fiber reinforcement and provides sufficient strength for the resulting part. Due to their fusibility thermoplastic fiber reinforced materials enable a joining technique called fusion bonding. This technique as introduced by [6] was used to join two thermoplastic adherends by melting and consolidation of the resulting boundary layer. But it can also be applied to join two different materials as long as one adherend is providing a thermoplastic matrix to achieve the wetting of the other adherend as among others [7–9] showed.

Fusion bonding of thermoplastic fiber reinforced materials to metal parts provides several advantages over adhesive bonding. For example a fusion bonding process needs nearly no curing times (except from cooling times) and due to the missing adhesive it enables an easier recycling and repair of the produced hybrid part. Furthermore, the bonding process can be combined with the shaping of the thermoplastic material which leads to an integrated production of a hybrid part in a one-shot process [6,9,10].

In recent years different approaches for the application of fusion bonding for joining of hybrid parts have been investigated [5,11,12]. Among other things, the investigations can be structured by the applied heating technologies and the investigated pre-treatment methods. Heating technologies show a variety of possibilities but three main heat sources are normally applied: hot-plate resp. hot-tool [13], laser (transmission as well as conduction) [14–17] and inductive heating [18,19]. All heating techniques have in common that the metal part is heated above the melting temperature of the thermoplastic material which results in melting of the boundary layer when the metal part is pressed against the thermoplastic part. The heating techniques therefore result in comparable joint strengths due to the same mechanism of melting the thermoplastic material in the joining area via heat

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conduction.

The bigger influence on the achievable joint strength compared with the heating technique has the surface condition of the metal part as was shown by a multitude of publications [7,8,13,20–22]. In order to increase the joint strength of a fusion bond, the application of a complementary pre-treatment is generally necessary. Among other approaches, adhesion promoters [8,23,24] and different surface modification methods (physical [14,15,20,21], chemical [8,22] and mechanical [24–26]) have been investigated over the past. All investigated approaches for increasing the joining strength show promising results concerning their particular backgrounds.

Due to the objective of this paper, the examination of the state of the art is going to focus on a laser surface pre-treatment which was originally chosen because the laser pre-treatment is able to clean oil contaminations (from deep drawing or corrosion protection oils) from metal surfaces [27–29]. The laser pre-treatment has already been used in different investigations for a surface structuring but without a contamination focus [14–17,20,21,30]. The pre-treatment is necessary as mentioned to achieve sufficient strength of the hybrid joint for example [17] achieved a lap-shear strength of roughly 24 MPa between a PA6 GF15 and an Aluminum adherend. Furthermore the laser pre-treatment can achieve different surface structures depending on the pre-treatment settings. This is interesting for the investigation of surface influences on fusion bonding processes because the high reproducibility and the variability of the pre-treatment settings makes it possible to correlate manufacturing influences on different surfaces with the achievable joint strength.

The introduced investigation will use an inductive heating setup to further understand the influence of a complete laser surface pre-treatment on the joining process itself and on the operating temperatures the joint can be applied in.

2. Materials and methods

In this chapter the used materials for the investigations, the applied surface pre-treatment, the sample manufacturing and the testing methods are introduced.

2.1. Materials applied

The metal adherend for the investigations is a DC01 steel. The material properties are shown in Table 1. The other adherend is a thermoplastic glass fiber reinforced polyamide 6 from two different manufacturers. Both materials have a twill fabric (50:50) fiber reinforcement with a fiber content of around 60 wt%. All sample materials were stored at room conditions of roughly 23 °C/50% r. h. Under these storage conditions the average moisture content of the polyamide 6 material was measured to be around 2.6 wt%.

Table 1
Material properties.

Metal adherend		DC01
Yield strength [Mpa]		max. 280
Tensile strength [Mpa]		270–410
Thickness t_{St} [mm]		1.5
Coating		None
Coating thickness [g/m^2]		–
FRTP adherend	**GF-TP1**	**GF-TP2**
Matrix material	Polyamide 6	Polyamide 6
Melting temperature [°C]	~220	~220
Thickness t_{Pa} [mm]	2	2
Glass transition temperature [°C]*	52.9*	51.8*
Fabric	Twill (50:50)	Twill (50:50)
Fiber content [wt.%]	~60	~60

*Measured with Dynamic Scanning Calorimetry according to DIN EN ISO 11357-2.

2.2. Surface pre-treatment

The metal and thermoplastic adherends were cleaned using Isopropanol before further processing. After that, the metal adherend was in some cases laser pre-treated to achieve a rougher surface structure to improve adhesion.

The applied laser for the pre-treatment was a redEnergy G4 H Type from SPI Lasers UK Limited (Southampton, United Kingdom) with an average power output of 70 W. This fiber laser has a wavelength of 1062 ± 2 nm. Two different pre-treatment intensities were chosen for the pre-treatment of the cleaned surface. The definitions of the spot overlap along X and Y axes as well as the advancing direction of the laser along the X axis are shown in Fig. 1 on the left. During laser pre-treatment a surface of 16 × 27 mm was pre-treated in order to assure a complete pre-treatment of the joining area (12.5 × 25 mm) and to reduce edge effects. The applied laser settings for the two different pre-treatment intensities are shown in Fig. 1 on the right side. L1 represents the lowest pre-treatment intensity and L3 the highest.

2.3. Manufacturing of lap-shear samples

The fusion bonding setup for the sample production is based on inductive heating of the metal adherend which heats the thermoplastic material above its melting temperature via heat conduction. During the sample production a constant pressure is applied in two different ways. One setup uses a pressure cylinder (setup 1) and the other setup uses a universal testing machine (setup 2). Both setups use inducers connected to a EW5F induction generator with a power output of 5 kW from IFF GmbH (Munich, Germany). The control of the induction generator for setup 1 was achieved by a LabView from National Instruments Corporation (Austin, USA) program which recorded the temperature during the joining process via a thermocouple (type K) as an input parameter and regulated the power input accordingly. Due to the high heating rates of the induction process the thermocouple had to be placed in the joining area to achieve a sufficient control of the temperatures during the controlled joining process.

To eliminate the influence of the thermocouple in the joining area during the testing of varying operating temperatures another setup was used which used a fixed parameter setting for the induction generator. This parameter was conducted by temperature measurements in the joining area equally to setup 1. During these tests a setting for the induction generator to achieve a joining temperature spread of 230–250 °C was determined. The joining pressure for the investigation of the varying operating conditions was kept constant at 150 N during the whole joining process.

At the end of the joining process both setups used an air pressured cooling system to cool the samples. The cooling was applied for at least 10 s to cool the samples well below the melting temperature of the thermoplastic materials. Fig. 2 shows a schematic layout of the used joining setups.

2.4. Applied test method

The non-destructive surface characterization is done by using a scanning electron microscope and a stylus instrument. The destructive testing was done with a single lap-shear specimen according to DIN EN 1465. All applied methods will be explained in the following subchapters.

2.4.1. Scanning electron microscopy

The scanning electron microscopy (SEM) recordings have been acquired with a FEM Quanta FEG 650 from Thermo Fisher Scientific Inc. (Waltham, USA). The sample size for the SEM investigations was 25 mm × 15 mm. The DC01 steel was cleaned with Isopropanol before