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High-tensile joints of continuously fusion bonded hybrid structures

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A B S T R A C T

Tailored hybrid structures manufactured within a continuous production process, for instance in a continuous roll forming line, offer a high potential for the automotive industry, due to its weight reduction compared to pure metal parts. Therefore, the hybrid roll formed parts consist of steel sheets reinforced by carbon fibre reinforced thermoplastic tapes (CFR-TP).

Both materials are joined by fusion bonding whereby the surface of the thermoplastic matrix is melted on the steel surface. The pre-treatment of the steel with a primer, customized for joining of steel and CFR-TP, is a promising approach, due to its easy implementation into continuous coil-coating processes. Major challenges consist in achieving sufficient joint strength as well as developing of a testing method for the evaluation of the adhesion between both materials.

Relating to joint strength, various process parameters (i.e. temperature of steel and CFR-TP) are examined. The fracture pattern are analysed optically by microscopy to detect possible primer damage. Furthermore, the evaluation is carried out by mechanical testing of peel specimens within climbing drum peel test to determine the production-related influence in a continuous process. The examinations show the usability of climbing drum peel test and the increase of joint strength with higher energy input.

1. Introduction and state of the art

Automotive serial production requires lightweight solutions manufactured within low cycle times and production costs. In consideration of multi-materials structures, innovative manufacturing and joining technologies have to be developed. Roll forming of steel sheets reinforced by carbon fibre reinforced thermoplastic tapes combines the approach of lightweight and high-volume production. Along with recyclability and decoupling of shaping and forming process, the application of a thermoplastic matrix enables reduction of process steps, due to no application of additional adhesive. Joining of steel and fibre reinforced thermoplastics can be carried out by fusion bonding. After melting of the surface-near area of a thermoplastic matrix, the metal surface is wetted and a hybrid joint is created by solidification of the matrix. However, integration of fusion bonding processes in automotive high-volume production is still and especially challenging because of interactions between both materials, especially corrosion as well as hygrothermal stresses and strains.

The state of the art focuses on commonly applied testing methods for CFR-metal joints as well as on the influence of process parameters and surface pre-treatments on fusion bonded CFR-TP-metal joints.

Lap shear tests were mainly used for testing of fusion bonded CFR-TP-metal structures [1–3]. Peel tests for multi-material structures mostly focus on investigations of adhesives [4] or fibre metal laminates [5,6] and vary with regard to fixture configuration. Exemplary used peel tests for multi-material structures are roller peel test [4,7–10], 90° degree peel test [11,12], T-Peel test [13] fixed arm peel test [14,15], mandrel peel test [5,16–18] or climbing drum peel test [19].

In consideration of fusion bonded structures, roller peel tests of DC01 steel and carbon fibre reinforced Polyamide 6 (CFR-PA6) tape were carried out [3,9,10]. In addition, relating to mandrel peel tests, rigid adherend of titanium and flexible adherend of carbon fibre reinforced Polyetherketoneketone (PEKK) were tested [18]. Peel tests with a flexible carbon fibre reinforced plastic (CFRP)-adherend could be critical. The material is bent with a defined curvature during peel test [20] which can result in fibre breakage [17,21,22]. Previous investigations showed breakage of CFR-PA6 tape during roller peel test by using SACO® (sandblast coating) pre-treatment for the steel adherend [10].

Most of the investigations in literature focus on the influence of various process parameters and were carried out by sequential fusion bonding processes. Various studies consider hybrid joints of metals consisting of aluminium or steel and glass fibre or carbon fibre reinforced thermoplastics [1,3,9,23,24]. The Influence of steel and CFR-PA6 temperatures on peel resistance of continuously manufactured joints was investigated with regard to separately heated DC01 steel and

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CFR-PA6 [10].The influence of surface iron oxides on the adhesion between CFR-PA6 and DC01 steel was also examined [3].

In consideration of the influence of various pre-treatments on the adhesion between continuously joined DC01 steel and CFR-PA6, mechanical pre-treatments of steel, i.e. low or high pressure blasting, or pre-treatment of CFR-PA6 by plasma were investigated [9,10]. The most promising approach was the pre-treatment of the steel surface by SACO®, which combines mechanical pre-treatment by high pressure blasting with application of a primer. However, surface pre-treatment for high tensile joints was only examined to a limited extent within continuously manufactured fusion bonded structures. In contrast to that, investigations with sequential processes already considered high pressure blasting [1], sand blasting [25], plasma cleaning [1], pickling [26,27], laser structuring [24] or application of primers [28,29]. Furthermore, pre-treatment of PA6 composites by plasma was investigated [30].

In summary, most of the examinations with regard to fusion bonding technology only focus on roller peel or mandrel peel tests. The investigations relating to continuous fusion bonding processes mainly consider joining of mutual heated hybrid materials or focus on basic research of the process without achieving sufficient joint strength for application in automotive components. Especially, the integration of surface pre-treatments in continuous fusion bonding process without lowering processing speeds and evaluation of these high tensile hybrid joints were not investigated. Hence, the aim of the paper was to close this gap by manufacturing fusion bonded hybrid joints with sufficient joint strength and modifying existing test methods to examine these multi-material structures.

2. Materials and methods

This paper examined fusion bonded multi-material structures consisting of steel with an applied primer and CFR-TP. The objective of this work was the continuous manufacturing of CFR-TP-steel structures and to characterize the fusion bond with an adequate testing method in dependency of process parameters, especially steel and CFR-TP temperature, as well as surface condition. Therefore, steel surface was pretreated by selected primer. Furthermore, climbing drum peel test was adapted for the evaluation of the adhesion between steel and CFR-TP.

2.1. Materials applied

The material properties of the investigated steel and CFR-TP as well as applied primer are shown in Table 1.

The CFR-PA6 as well as the primer Vestamelt® Hylink (VM) from Evonik Industries AG (Marl, Germany) were not dried or conditioned prior to joining process. On the one hand, manufacturing and testing were carried out at relative humidity of 50% and constant temperature of 23 °C to prevent influence of changing temperature and moisture content. On the other hand, objective of the developed process was the realistic and cost-efficient simulation of production of hybrid structures. Moisture content of Polyamide 6 matrix of 3.11% was measured after drying at a temperature of 80 °C for 7 days and afterwards storing at climatic conditions (23 °C, 50%) for 7 days.

The steel was cleaned by wiping the surface with n-Heptane to remove any present contamination and afterwards dried for at least 10 min. The pre-treatment was carried out according to Chapter 2.2 and in case of a mechanical pre-treatment again cleaned with n-Heptane. In addition, remaining particles on mechanically pre-treated samples were removed by oil- and water free compressed air.

2.2. Surface pre-treatment

The reference steel surface without primer application has been pretreated mechanically by high pressure blasting with white corundum with a grain size in the range of 210 µm to 300 µm. The pre-treatment

Table 1
Material properties of DC01, CFR-TP and primer.

Metal adherend	DC01	HX340 LAD Z100 MB
Yield strength [MPa]	Max. 280	340–420
Tensile strength [MPa]	270 – 410	410–510
Thickness [mm]	1.00	1.00
Coating	None	Galvanized
Coating thickness [g/m^2]	–	100
CFR-TP adherend	**Carbon fibre reinforced thermoplastic tape**	
Matrix material	Polyamide 6	
Tensile strength [MPa]	1909	
Tensile modulus [GPa]	100	
Tensile strain to fail [%]	1.76	
Melting temperature [°C]	220	
Glass transition temperature [°C]	47	
Density [g/cm^3]	1.45	
Thickness [mm]	0.13	
Fibre volume ratio [%]	48	
Primer	**Vestamelt® Hylink**	
Base	Copolyamide and curing agent	
Melting temperature [°C]	135	
Beginning curing temperature [°C]	160	
Density [g/cm^3]	1.0–1.3	

by SACO® with DELO-SACO® Plus [31] from DELO Industrie Klebstoffe GmbH & Co. KGaA (Windach, Germany) was used for reference with primer application and was also carried out manually comparing to the high pressure blasting process. No additional primer was applied after coating by SACO® process.

Due to the aim of an integration of the pre-treatment in continuous fusion bonding processes, the applied primer had to be adaptable into small or large scale production. The selected primer Vestamelt® Hylink offers this possibility and can be integrated into the manufacturing of steel by using a coil coating process. Within this investigation, the primer was available in powdered form. As a consequence, the powder was applied on cleaned DC01 and HX340 steel surface and was joined in a press at a temperature of 150 °C for 2 min [32]. Curing of primer begins at a temperature of 160 °C with the result that the primer is still able to cure within the following continuous fusion bonding process. The primer thickness on the steel surface was approximately 0.08 mm and was kept constant within this investigation.

2.3. Continuously manufactured fusion bonded multi-material structures

The continuous production focuses on heating of both materials as well as subsequent fusion bonding which are important process steps in a continuous manufacturing process of multi-material structures. Both materials had to be heated to a defined temperature for subsequent fusion bonding process. Therefore, steel with applied primer was heated by induction and CFR-PA6 by infrared heating. The CFR-PA6 could be heated from the upper side because of its low thickness of 0.13 mm. Furthermore, the upper aluminium roll was coated with a polytetrafluorethylene tape to prevent an adhesion between upper roll and heated CFR-PA6.

2.4. Test methods applied

The determination and evaluation of mechanical properties of multi-material joints produced within continuous fusion bonding process requires adequate testing methods. The approach presented within this paper was the application and modification of commonly used and standardized test methods for adhesive bonds. Therefore, testing of the interface of the CFR-TP-steel specimens was carried out by climbing drum peel test which is derived from the DIN EN ISO 2243-3 for sandwich testing and was modified for testing of CFR-TP-steel samples.