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Adhesion of continuously manufactured fusion bonded multi-material structures consisting of steel and carbon fibre reinforced Polyamide 6

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ABSTRACT

In regard to e-mobility and the correlating additional battery storage weight as well as the demand for the reduction of exhaust emissions in the automotive industry the development of lightweight solutions is required. Load-adapted tailored hybrid structures manufactured within a continuous production process offer a high potential for the automotive industry. With focus on high production rates and a high degree of automation, roll forming of multi-material structures is a promising approach. In order to improve strength and stiffness in relation to density, roll formed parts consisting of steel sheets reinforced by carbon fibre reinforced thermoplastic tapes (CFR-TP) are investigated. The evaluation of the adhesion between both materials joined in a continuous manufacturing process still is an important challenge, because the adhesion between both adherends is mandatory to transfer loads between both materials, and thus considered within the present work.

To minimize the amount of process steps for a large-scale production of hybrid structures, the steel sheets and the thermoplastic tape are joined by fusion bonding while the surface of the thermoplastic matrix is melted and thus joined to the steel surface. Therefore a defined heating of both materials is required and consequently the effects of various temperatures on the adhesion have to be considered. With focus on achieving sufficiently high joint strength of multi-materials structures, various pre-treatments of steel as well as of CFR-TP were investigated.

Hence, the present work focuses on the one hand on the evaluation of the adhesion between steel and CFR-TP dependent on various steel as well as CFR-TP temperatures within continuous manufacturing processes. On the other hand, effects of different surface conditions of both materials, due to surface pre-treatments of steel and CFR-TP, on the adhesion are examined. The continuously manufactured specimens are destructively tested by roller peel testing. In addition, evaluation of fracture patterns was carried out for the destructively tested hybrid joints. The examinations show the improvement of adhesion with increasing steel as well as CFR-TP temperature. Furthermore, additional pre-treatment results in an improved adhesion.

1. Introduction and state of the art

Along with the research on manufacturing technologies as injection moulding, pressing or thermoplastic resin transfer moulding (RTM), roll forming of multi-material structures offers high development potential, due to possibility to join steel and CFR-TP continuously. However, major challenges are joining and subsequent forming of both materials in a continuous process.

Fusion bonding can be used for joining of thermoplastics or hybrid structures, i.e. metals and fibre reinforced thermoplastics, in a continuous roll forming process. The surface of thermoplastic matrix is melted with the consequence that the metal surface is wetted by the thermoplastic matrix and thus a multi-material joint is created.

The implementation of fusion bonding processes into automotive large-scale production is still a relevant challenge and has to be investigated. On the one hand, multi-material mix leads to interactions between both materials, especially considering corrosion as well as hygrothermal stresses and strains. On the other hand, implementation in large-scale production, especially relating to cathodic dip painting prior or subsequent to the joining process, affects the joining technology of multi-material structures. The integration of fusion bonding processes in a continuous roll forming line is considered to be beneficial because of the non-required application of an additional adhesive.

The state of the art focuses on fusion bonded CFR-TP-metal joints and is divided into commonly applied testing methods, the influence of temperature and surface pre-treatments.

Fusion bonded CFR-TP-metal structures were mainly tested by lap shear tests [1,2]. With regard to continuous fusion bonded structures,

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roller peel tests of DC 01 steel and carbon fibre reinforced Polyamide 6 tape were performed [3,4]. In addition, mandrel peel tests with rigid adherend of titanium with a thickness of 1 mm and flexible adherend of carbon fibre reinforced Polyetherketoneketone with thickness of 0.15 mm were carried out [5]. The effective peel resistance was around 0.61 N/mm. During peel test, the flexible adherend is bent with a defined curvature [6] which can lead to tape breakage [7,8].

Research relating to the influence of temperature focuses on the sequential fusion bonding process, especially on hybrid joints of aluminium or steel and glass or carbon fibre reinforced thermoplastics [1,3,4,9,10]. Continuous fusion bonding processes with induction heating were investigated for lap shear specimens of Polypropylene and aluminium [11]. Highest lap shear strength of 10 MPa was achieved at processing speed of 2 mm/s and pressure of 0.12 N/mm^2. Continuous fusion bonding process of separately heated DC 01 steel and carbon fibre reinforced Polyamide 6 tape has been considered and evaluated by roller peel specimens [3]. Processing speed of 11.7 mm/s and applied pressure of 5.76 N/mm^2 were kept constant. Highest peel resistance of 0.13 N/mm was achieved with a steel temperature of 240 °C and a carbon fibre reinforced Polyamide 6 temperature of 230 °C. The formation of iron oxides within the continuous fusion bonding process was observed as a result of heat accumulations at the ends of the specimens due to induction heating. The influences of these iron oxides on resulting peel resistance were also examined by the authors [4] and showed increase of peel resistance of more than 200%.

Concerning the surface pre-treatment in continuous fusion bonding processes, induction heated DC 01 steel with untreated as well as high pressure blasted surface conditions was joined with unheated carbon fibre reinforced Polyamide 6 tape. The parameters processing speed of 11.7 N/mm, steel temperature of 240 °C and applied pressure of 5.76 N/mm^2 were kept constant. Due to very low adhesion between untreated steel and the carbon fibre reinforced Polyamide 6, peel resistance of 0.02 N/mm was much lower compared to high pressure blasted steel specimens with peel resistance of 0.10 N/mm [3]. All specimens show clear interfacial failure. However, surface pre-treatment was only investigated to a limited extent in continuous fusion bonding processes. Therefore, the basic influence of various surface pre-treatments is shown for the sequential process by using procedures as sand blasting [12], laser structuring [10], high pressure blasting [1], pickling [13], plasma cleaning [1] or the application of primers [14]. The plasma pre-treatment of Polyamide 6 composites was also considered [15].

In conclusion, most of investigations relating to fusion bonding technology only focus on non-continuous joining of hybrid materials or continuous joining of mutual heated hybrid materials. The evaluation of influence of different temperatures and surface conditions of steel as well as CFR-TP on continuously manufactured fusion bonded joints was not investigated. Therefore, the aim of the paper is the examination of continuous fusion bonding process of steel substrates and CFR-TP and the evaluation of influence of various temperatures and surface conditions on the adhesion between both materials.

2. Materials and methods

Within this paper hybrid structures consisting of steel and CFR-TP, which were joined by fusion bonding, were examined. The objective of this work was to investigate continuously manufactured CFR-TP-steel structures and to characterize the fusion bond in dependency of temperature and surface condition. Therefore, both materials were pre-treated by various processes. The roller peel test was adapted for the evaluation of the adhesion between steel and CFR-TP.

2.1. Materials applied

The material properties of investigated steel and CFR-TP are shown in Table 1.

Table 1
Material properties of DC 01 and CFR-TP.

Metal adherend	DC 01
Yield strength [MPa]	Max. 280
Tensile strength [MPa]	270–410
Thickness [mm]	1.00
Coating	None
Thermal coefficient [10^{-6}/K]	11.5
Specific heat capacity [kJ/kg K]	0.46
CFR-TP adherend	Carbon fibre reinforced thermoplastic tape
Matrix material	Polyamide 6
Melting temperature [°C]	220
Glass transition temperature [°C]	47
Tensile strength [MPa]	1800
Tensile modulus [GPa]	107.7
Elongation at break [%]	1.53
Thickness [mm]	0.19
Density [g/cm^3]	1.46
Fibre volume ratio [%]	48
Thermal coefficient (0°) [10^{-6}/K]	0.5
Thermal coefficient (90°) [10^{-6}/K]	46.1
Specific heat capacity [kJ/kg K]	1.11

The glass transition temperature depend of the moisture content of the Polyamide 6 matrix and was determined by material stored at a temperature of 23 °C and relative humidity of 50%. The moisture content of Polyamide 6 matrix dried at a temperature of 80 °C for 7 days and afterwards stored at climatic conditions (23 °C, 50%) for 7 days was determined with 2.68%. Lower moisture content of the Polyamide 6 matrix would lead to increased glass transition temperature [16].

The CFR-TP was neither dried nor conditioned prior to the joining process, due to realistic and cost-efficient simulation of large-scale production of fusion bonded multi-material structures. In addition, all investigations (manufacturing and testing) were carried out at constant temperature of 23 °C and relative humidity of 50% to prevent influence of changing moisture content. The CFR-TP was cleaned by wiping the surfaces with Isopropanol to remove any present contamination, preventing influence on the adhesion between both materials, and afterwards dried for at least 10 min. The steel was cleaned with n-Heptane using same procedure. The steel samples were pre-treated according to Section 2.4 and in case of a mechanical pre-treatment repeatedly cleaned with n-Heptane. Remaining particles caused by steel specimens pre-treated by SACO® [17] (sandblast coating) were removed by oil- and water free compressed air.

2.2. Continuous manufacturing of fusion bonded multi-material structures

The continuous manufacturing focuses on the heating of the individual materials and the subsequent fusion bonding which are important process steps in a continuous roll forming process. The schematically test setup is shown in Fig. 1.

Relating to the continuous process, steel as well as CFR-TP has to be heated to a defined temperature for the subsequent joining process.

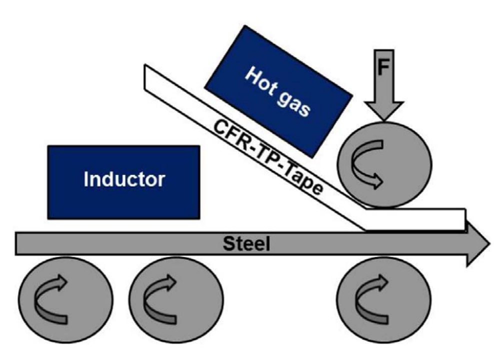

Fig. 1. Schematically test setup.