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AddJoining: a novel additive manufacturing approach for layered metal-polymer hybrid structures

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Abstract

A novel assembling technique based on additive manufacturing and materials joining principles has been introduced for layered metal-polymer hybrid structures. The AddJoining technique produces layered hybrid structures, using polymer 3D printing methods. The feasibility of the technique was demonstrated using fused deposition modeling for single-lap joint configuration. Microstructure and mechanical strength of the joints were studied using two combinations of materials; aluminum 2024-T3 with acrylonitrile butadiene styrene and aluminum 2024-T3 with alternate layers of polyamide-6 and carbonfiber-reinforced polyamide-6. The latter reached an average ultimate lap-shear strength of 21.9 ± 1.1MPa, showing 19% superior performance to the adhesively bonded joints. This exploratory investigation showed the potential of AddJoining to produce metal-polymer layered structures.

Keywords: Additive manufacturing; Aluminum 2024-T3; ABS; Carbon-fiber-reinforced polyamide-6; Composite materials; Laminates.

1. Introduction

There has been a growing interest in clean technologies to decelerate CO_2 emissions. For this purpose, automotive and aerospace industries are seeking for innovative, efficient and cost-effective manufacturing technologies to reduce structural weight. Developing the appropriate manufacturing and joining technologies can help to enable high specific-strength lightweight structures.

The current manufacturing techniques for metal-polymer layered parts display usually long processing cycles to cure the thermoset-based resin, such as in epoxy-based fiber-metal laminates (FML) [1]. Thermoplastic-based FML (T-FML), such as carbon-fiber reinforced PEEK/Ti investigated by Cortés and Cantwell [2] are emerging materials. T-FML can be thermoformed in short cycles. However, automation and the ability to make complex parts are still the main challenges in the current FML manufacturing methods. A similar scenario is found for co-bonding and co-curing of metal-composite layered structures. Additive manufacturing (AM) is an alternative approach to overcome such challenges by automating the FML manufacture and increasing the freedom in complex part design [3]. Janssen, Peters and Brecher [4] reported an AM approach to join tape-placement of tailored carbon-fiber-reinforced polyamide-6 with 3D-printed polyamide-12 parts. Türk *et al.* [5] produced polyamide-12 honeycomb cores by AM and combine them with carbon-fiber-reinforced epoxy using conventional lamination method. Nevertheless, there is still no work published in the literature using polymer 3D printing to produce metal-polymer (composite) layered structures.

The AddJoining technique - Additive Manufacturing of Layered Metal-Polymer Hybrid Structures (German patent application DE 10 2016 121 267.9, 2016) is a novel approach, combining the principles of AM and materials joining. AddJoining enables the combination of different materials in a layered configuration. In this work, the feasibility of the AddJoining process was demonstrated using aluminum 2024-T3/acrylonitrile butadiene styrene (ABS) and aluminum 2024-T3/unreinforced polyamide 6 (PA6)/carbon-fiber-reinforced polyamide 6 (CF-PA6) materials combinations. The quasi-static mechanical performance of the single-lap joints was evaluated. Furthermore, the microstructure of the joints was studied using optical and laser scanning confocal microscopy (OM and LSCM).

1.1 AddJoining

In a preferred process variant using fused deposition modeling (FDM), the AddJoining manufacturing route is divided into three steps (Fig. 1). In the first step, the metallic substrate is fixed on a building platform into a slot (Fig. 1(a)). The polymer filament is melted by the extrusion head and deposited by a nozzle to form a full layer on top of the metal substrate (Fig. 1(b)). The next polymer layers are subsequently deposited until the desired thickness and stacking sequence of the polymeric part is achieved (Fig. 1(c)); variable layers of unreinforced and reinforced polymer can be intercalated. At the end of the deposition step, the metal-polymer layered joint is removed from the building platform (Fig. 1(d)). Although not adopted in this work, additional post-printing steps (e.g. thermo-mechanical treatment) may be applied to eliminate intrinsic voids in the layered component.

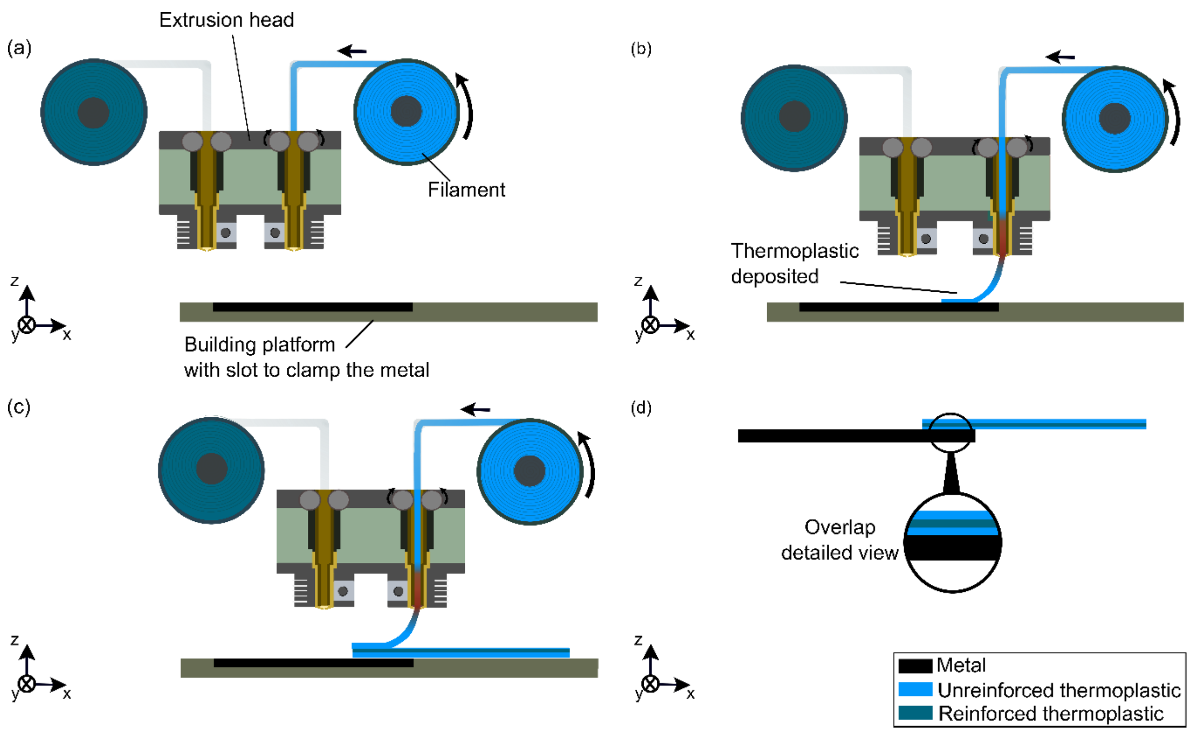

Fig. 1. Schematic representation of the AddJoining process for layered metal-polymer composite hybrid structures.

2. Materials and methods

The base materials used in this work were two-millimeter-thick aluminum alloy 2024-T3 rolled sheets (Costellium, France), 1.75-millimeter-diameter unreinforced ABS (VShaper, Poland), 1.75-millimeter-diameter unreinforced PA6 and 0.38-millimeter-diameter continuous-carbon-fiber towpreg polyamide 6 (CF-PA6) filaments (MarkForged, USA). The latter consists of carbon fiber bundles pre-impregnated with the PA6 resin to form the filament. The supplier withheld the information related to the fibers mechanical properties or chemical compositions. However, van der Klift [6] established the properties of the carbon fibers and determined that the fibers have comparable properties to TORAYCA T300 tow (TORAY, Japan).

Before AddJoining, the surface of the aluminum part was sandblasted with corundum (Al_2O_3) with particle size ranging from 100 μm to 150 μm (WIWOX Surface Systems, Germany). The surface of aluminum was treated with the pressure of 6 bar, the work distance of 200 mm, and the projection angle of 45°. The samples were cleaned afterwards in an ethanol ultrasonic bath for three minutes. Thereafter, a homogeneous coating layer using the respective unreinforced filament materials, was deposited on the aluminum part to promote better adhesion between the aluminum and subsequent printed polymer layers. In the case of aluminum 2024-T3/ABS joint a solution of 25 wt% ABS filament in pure acetone was manually spread on the aluminum surface using a custom tool design to ensure a homogeneous coating (nominal thickness of 100 µm). The sample was subsequently dried in the horizontal position for five minutes at room temperature. For the aluminum 2024-T3/PA6/CF-PA6 joints, the coating was applied by indirect heating as follows: (1) printing a stand-alone layer of PA6 (13 mm x 26 mm x 0.2 mm); (2) heating the aluminum part with the stand-alone PA6 printed layer using an external hot plate at 270°C for one minute (to remelt and homogenize the stand-alone printed layer); (3) allowing a two-minutes consolidation time to form the coating.

VShaper PRO (Poland) FDM 3D printer was used in this work to produce aluminum 2024-T3/ABS hybrid joints. A preliminary investigation was carried out to select the optimal controllable process parameters. The selected parameters were the printing temperature of 280°C, road thickness of 0.1 mm, deposition speed of 60 mm/s, and 12 contours. The number of contours represents the enclosed loops of road deposition in the filled-perimeter region. A Markforged MarkTwo (USA) FDM 3D printer was used to produce aluminum 2024-T3/PA6/CF-PA6 hybrid joints. In this case, alternate layers of PA6 and CF-PA6 were distributed across the thickness of the printed polymeric part; eight layers of each PA6 and CF-PA6 with fiber orientation of $[0°]_S$ were deposited with printing temperature of 270°C. The road thickness was 0.125 mm to form a two-millimeter composite part with 16 alternate layers of PA6 and CF-PA6. Note that the controllable process parameters are different for the selected printers.

101.6 mm x 25.5 mm x 2 mm aluminum parts were machined according to the ASTM D3163-01. The polymer and composite parts were printed with the same dimensions on top of the aluminum, forming single-lap joints with a nominal overlap area of 12.5 mm x 25.5 mm. The lap shear tensile testing under quasi-static loading was performed using a universal testing machine (Zwick/Roell 1478) with a traverse speed of 1.27 mm/min at room temperature. The joint microstructure was studied by OM (DM IR microscope, Leica, Germany) and LSCM (VK-9700 microscope, Keyence, Japan).

3. Results and discussion

The cross-sectional microstructure of the joints is shown in Fig. 2. For both case-study materials combinations, an intimate contact could be achieved between the coating layer and the surface of the aluminum, and between the deposited polymer and coating layer (Fig. 2(a-1) and Fig. 2(b-1)). This suggests a strong bond formation at the respective interfaces. Moreover, no bond line could be detected between deposited polymer and coating layers, suggesting the occurrence of intermolecular diffusion at the interface. Fig. 2(a-2) shows the presence of voids in the ABS coating probably due to the evaporation of residual acetone, from the coating solution, during the AddJoining printing stage. Such phenomenon was not present in the PA6 coating because no solvent was used to form the coating. However, the presence of voids exists between the CF-PA6 and PA6 layers (marked with arrows in Fig. 2(b-2)). Presence of voids in the printed composites was also observed by Van der Klift *et al.* [6]. Further investigation is required to explain the presence of voids in the AddJoined parts.

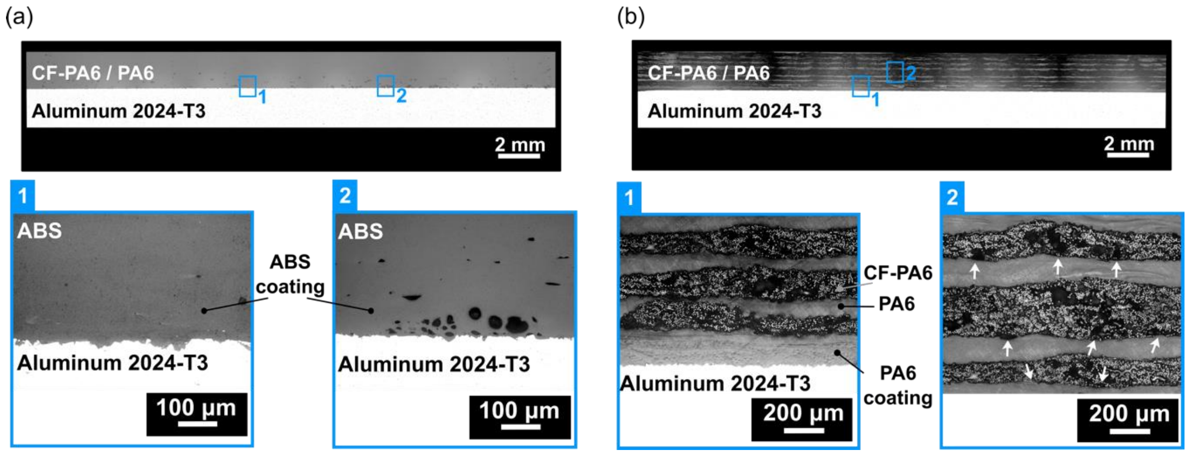

Fig. 2. Cross-sectional microstructure of hybrid joints: (a) aluminum 2024-T3/ABS; (a-1) the interface of aluminum 2024-T3/ABS coating/ABS and (a-2) the presence of voids in the ABS coating layer. (b) Aluminum 2024-T3/PA6/CF-PA6; (b-1) interface of aluminum 2024-T3/PA6 coating/PA6/CF-PA6 and (b-2) presence of voids between PA6 layer and CF-PA6 layer.

An example of force-displacement curves is shown in Fig. 3(a) for both AddJoining specimens. The joints with the CF-PA6 layers obviously lead to higher ultimate lap shear force and stiffness of the joint (reducing proneness of the joint to secondary bending). Fig. 3(b) illustrates the average ultimate lap shear strength (ULSS) and strain at break (SaB) for the aluminum 2024-T3/ABS (ULSS= 5.3 ± 0.3 MPa; SaB= 1.5 ± 0.1 %) and aluminum 2024-T3/PA6/CF-PA6 (ULSS= 21.9 ± 1.1 MPa; SaB= 1.6 ± 0.1 %) hybrid joints. For both joints, brittle fracture with relatively low SaB was observed, a similar behavior reported for adhesively bonded overlap joints [7,8].

Furthermore, the average ULSS of AddJoining structures was qualitatively superior to established adhesive bonding methods for metal-composite overlap joints, such as aluminum 5083/GFRP (ULSS: 8.3 MPa) [7] state-of-the-art adhesively bonded and AlMg3/CF-PA66 (ULSS= 11 MPa) [9] induction heating bonded joints. Moreover, adhesively bonded reference joints were prepared with the same materials used for AddJoining hybrid joints, to compare the mechanical performance of the joints. For this purpose, an epoxy-based adhesive, DP490 (3M, USA), was used following the supplier curing procedure at 80 °C for 1 hour. The average ULSS and SaB for the aluminum 2024-T3/ABS was respectively 52% and 40% higher than the adhesively bonded reference joints (ULSS = 2.8 ± 0.2 MPa; SaB = 0.6 ± 0.1%). Following a similar tendency, aluminum 2024-T3/PA6/CF-PA6 hybrid joints achieved a superior performance to the adhesively bonded joints (ULSS = 17.7 ± 0.9 MPa; SaB = 1.4 ± 0.1%), showing 19% and 15% higher in ULSS and SaB, respectively. Further investigation needs to be performed to understand the different mechanical performance between the AddJoining hybrid joints and reference adhesive bonded joints.

Fracture analysis showed a net-tension failure in the ABS part (Fig. 3(c)) for the aluminum 2024-T3/ABS joints. It suggests that the joint strength is higher than the strength of the printed ABS base material, resulting in failure initiation from the edge of the joint, where the non-uniform shear and peeling stresses are developed. Owing to higher stiffness of the CF-PA6 layers, the aluminum 2024-T3/PA6/CF-PA6 joint is less prone to secondary bending. Therefore, cohesive failure took place (Fig. 3(d)) within the printed fiber-reinforced layer by delamination in the vicinity of the voids between the CF-PA6 layers.

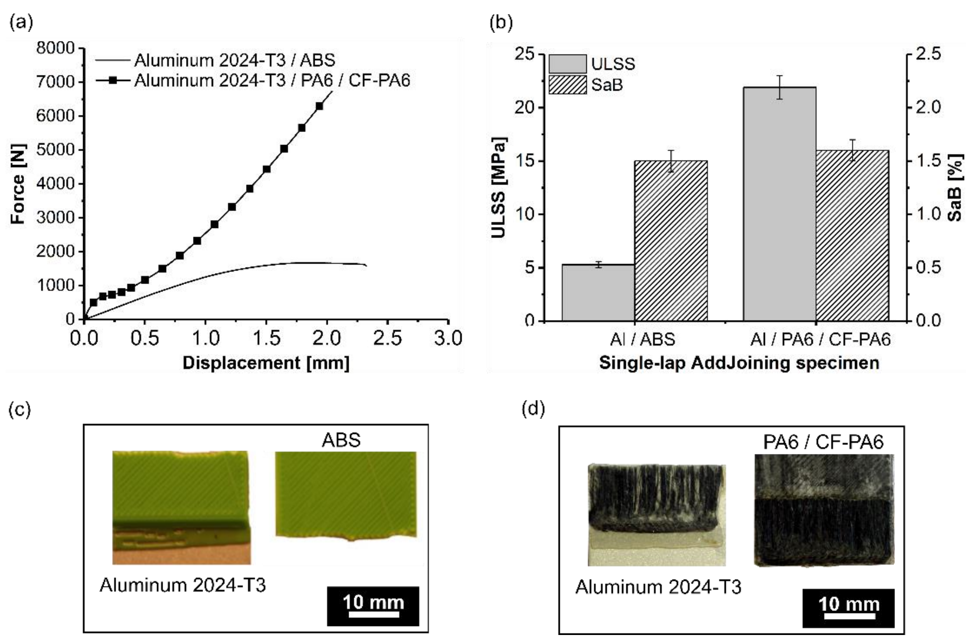

Fig. 3**.** Mechanical performance of the AddJoining specimens: (a) representative force-displacement curves and (b) average ULSS and SaB. Fracture surface of (c) aluminum 2024-T3/ABS and (d) aluminum 2024-T3/PA6/CF-PA6 hybrid joints.

4. Conclusions

AddJoining was introduced as a novel additive manufacturing approach to produce layered metal-polymer hybrid structures. The feasibility of the process was successfully demonstrated with fused deposition modeling to produce aluminum 2024-T3/ABS and aluminum 2024-T3/PA6/CF-PA6 single-lap joints. Case-study joints presented high average ultimate lap shear strength but with relatively small strain at break. The quasi-static mechanical behavior of the AddJoining parts was comparable to the joints produced with the state-of-the-art adhesive bonding. This shows the potential of the AddJoining process for manufacturing future layered metal-polymer structures.

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