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Ultrasonic joining: A novel direct-assembly technique for metal-composite hybrid structures

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ABSTRACT

Ultrasonic joining (U-Joining) is a new direct assembly technique developed by Helmholtz-Zentrum Geesthacht that uses ultrasonic energy to join fiber-reinforced thermoplastics to surface-structured metallic parts produced by metal injection molding. Ultrasonic vibration and pressure create frictional heat at the materials interface, which softens the composite matrix and allows the reinforcement (structured on the surface of the metallic part) to penetrate the composite. As a result, a metal-composite hybrid joint with improved out-of-plane strength is achieved. In this work, the features of U-Joining are briefly introduced, and the feasibility of the technique is demonstrated with Ti-6Al-4V/glass-fiber-reinforced polyetherimide joints. Optical microscopy reveals that a close contact between metal and composite was achieved after U-joining. Lap shear testing of six-pin joints showed an improvement in strength of up to 5.5 times (2011 ± 530 N) that of pin-less reference joints (368 ± 29 N).

1. Introduction

Due to stringent CO_2 emission regulations and requirements for the efficient use of natural resources, innovative lightweight manufacturing routes as well as design and joining technologies are becoming increasingly relevant for the success of the transportation industry. Therefore, designers and engineers are compelled to select lighter and more sustainable materials to reduce vehicle weight and to improve fuel consumption [1–3].

For this reason, the selection and development of fiber-reinforced polymer (FRP) – lightweight alloy hybrid structures has significantly increased over the last few decades. However, the application of consolidated joining technologies to join these materials is not a straightforward task and problems related to the physical or chemical dissimilarities of the two components arise [4,5].

Current direct-assembly joining methodologies seek to overcome these limitations by integrating through-the-thickness reinforcements that improve the load-transfer and out-of-plane mechanical performance of rivet-free overlap joints. The reinforcements are integrated onto the surface of the metallic part, usually with a pin-like geometry. Some state-of-the-art surface structuring processes that are currently available include: additive layer manufacturing (ALM) [6], Surfi-Sculpt™ [7,8] and Cold-Metal Transfer (CMT) [9]. After the structuring process, the composite is laminated onto the metal surface by co-curing or vacuum infusion. These technologies are still under development and limitations related to their fusion-based nature may result in reduced geometrical reproducibility and limited production rates. Moreover, composite assembly by co-curing and vacuum infusion is time-consuming.

In this context, a new direct-assembly method that utilizes ultrasonic energy to join metal injection molded parts with reinforced surfaces (MIMStruct) [10] to polymeric materials is proposed. The Ultrasonic Joining technique (U-Joining, patent application EU 15163163.7) introduced in this work, for the first time, is applied to Ti-6Al-4V/glass-fiber-reinforced polyetherimide (GF-PEI) overlap joints to assess its feasibility. Selected microstructural features, mechanical properties and failure mechanisms of the hybrid joints are presented.

1.1. Ultrasonic Joining (U-Joining)

The U-Joining process can be divided schematically into five steps (Fig. 1). In the first step, the parts are fixed between the

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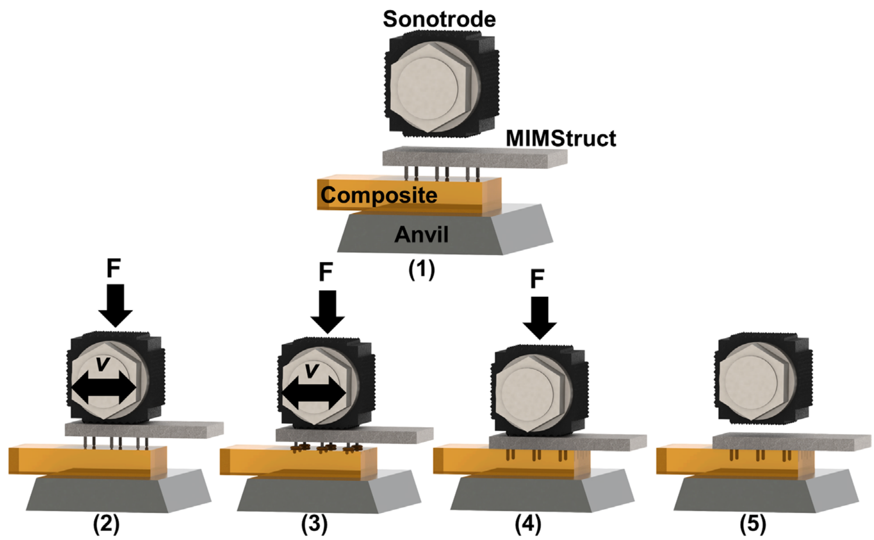

Fig. 1. Schematic representation of the U-Joining process. (1) Positioning of joining parts, (2) application of ultrasonic vibration and axial force, (3) softening of polymer by frictional heat at the interface and onset of pin insertion, (4) polymer consolidation and (5) end of the process and sonotrode retraction.

sonotrode and the anvil, with the MIM-structured elements (pins) touching the composite surface (Fig. 1). Next, the sonotrode moves down and applies a clamping pressure, while ultrasonic vibration (in this example by back-and-forth motion parallel to the contact surface) begins (Fig. 1(2)). This vibrational motion is transmitted to the interface, which combined with the joining pressure (applied pneumatically and perpendicular to the contact surface) produces frictional heat that locally softens the polymer matrix. Then, pins are inserted into the composite (Fig. 1(3)). After the pins are completely inserted, the metallic surface is wetted by the compressed molten polymer and the sonotrode vibration stops (Fig. 1 (4)). At this point a consolidation pressure can be applied to compensate for any shrinkage of the polymer matrix. Finally, the sonotrode is retracted from the now joined hybrid joint (Fig. 1(5)).

2. Materials and methods

$15.5 \times 35 \times 3$ mm metallic parts with 3 mm high round-tip conical pins were produced from a Ti-6Al-4V alloy by metal injection molding. Pre-alloyed and gas atomized spherical powder from TLS Technik, Germany was used to prepare the feedstock, which consisted of a mixture of Ti-6Al-4V powder and a binder system (60 wt% paraffin, 35 wt% polyethylene-vinyl-acetate copolymer and 5 wt% stearic acid) in a ratio of 1:9. The feedstock was injection molded in an ARBURG 320-S machine. The chemical debinding of the green parts was performed using a Lömi EBA-50 chemical debinding system with cycles of 900 min that reached a maximum temperature of 40 °C. Thermal debinding and sintering were performed in a cold-wall furnace (Xerion XVAC) at 600 °C in an argon atmosphere and at 1300 °C under high vacuum, respectively.

The polymeric part of the joints consists of a glass-fiber-reinforced polyetherimide laminates (GF-PEI) comprised of 50 vol% [0°, 90°] ply glass fibers from TENCATE, Netherlands. Laminate parts measuring $15.5 \times 35 \times 6.35$ mm were machined to produce the overlap hybrid joints.

Joining was performed using an Ultraweld L20 metal welder from Branson Ultrasonics. Based on an exploratory study, a joining energy of 2200 J, clamping and joining pressures of 1 bar and a two-step tool amplitude of 32 and 52 μm (amplitude threshold of 500 J) were used. The frequency of the sonotrode oscillation was fixed at 20 kHz. These joining parameters were applied to produce joints with metallic parts containing four- or six- pins.

The microstructures of the joints were evaluated by optical and confocal optical/laser microscopy. The Ti-6Al-4V microstructure was revealed using Kroll's etchant (96 mL H_2O, 6 mL HNO_3 and 2 mL HF). The global mechanical performance was assessed with a customized lap shear test performed at room temperature and a traverse speed of 2 mm/min. The fracture surfaces of the tested specimens were evaluated using scanning electron microscopy.

3. Results and discussion

The lengths of the joining cycles for the chosen joining parameters were 1.42 ± 0.03 and 1.21 ± 0.28 s for the four-pin and six-pin joints, respectively. A representative microstructure of the ultrasonically joined joints is presented in Fig. 2. After U-Joining, the conical pins were fully inserted into the composite, as shown in the metallographic cross-section of the four-pin joint (Fig. 2(a)) and the X-ray tomography image of the six-pin joint (Fig. 2(b)). The frictional heat and pin feeding create a thermo-mechanical affected zone (TMAZ) in the composite part. However, the thermo-mechanical processing does not change the microstructure of the Ti-6Al-4V component because it still exhibits a fully lamellar α-phase with the β-phase distributed at the grain boundaries (Fig. 2 (c-1)). Moreover, the as-produced MIM part presents residual porosity of $4.4 \pm 0.7\%$ and surface roughness average of 4.2 ± 1.1 μm.

During pin penetration, the molten polymer matrix and pieces of broken fiber flow upwards, filling the undercuts around the pins, Fig. 2(c-2). As a result, the woven glass-fibers are reoriented upwards (Fig. 2(c-3)). Apart from the thermal-induced defects (pores), a close contact was achieved at the metal-composite interface, Fig. 2(c-4).

Fig. 3 shows the specimen geometry (Fig. 3(a)) and assessment of global mechanical performance of the joints. Force-displacement curves (Fig. 3(b)) clearly demonstrate that the through-the-thickness reinforcement increases the quasi-static strength and ductility of the joints in comparison to the non-reinforced reference joints. Moreover, the increase in the number of reinforcement elements positively influenced the mechanical performance of the joint. The ultimate lap shear forces of the six-pin joints (2011 ± 530 N) and four-pin joints (831 ± 336 N) were 5.5 and 2.4 times greater than that of the pin-less reference joints