Assessments of staked hybrid joints made by studs 3D printed at different manufacturing conditions

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Abstract. The integration of polymers and metals in engineering applications has led to the development of hybrid joints that combine the distinct advantages of both materials. The staking process is a manufacturing technique, which involves the joining or the securing components through the controlled deformation of materials. It involves forming a permanent and strong connection by reshaping or displacing material, often using force or pressure without the need of additional fasteners, like screws or adhesives. This study presents a comprehensive experimental analysis of a specific hybrid joint performed by staking and by using a polymeric 3D printed partner and a steel plate. The influence of the printer machine and the related printing speed on the joint strength is discussed and the findings demonstrate a strong correlation between this variable and the mechanical properties of the hybrid joints.

Introduction

Designers and engineers are involved in the selection of lighter, recyclable, and sustainable materials due to increasingly stringent environmental policies. In fact, the lightweight design, and specifically in the transportation sector, responds to the need to reduce weight, aiming to limit emissions of harmful substances to the environment and climate.

The integration of polymers and metals in engineering applications has led to the development of hybrid joints that combine the distinct advantages of both materials and play a fundamental role in lightweighting, particularly in automotive and aerospace, as well as in the medical field for the development of implants and prosthetics, and in civil engineering for bridge construction. They promote sustainable production while simultaneously allowing the creation of robust structures.

To create hybrid joints, it is necessary to optimize both material selection and geometry simultaneously. Hybrid joints are created by combining different materials with diverse properties to achieve the desired performance. Therefore, despite the advantages of using lightweight materials, the union of metal alloys and composites poses a significant challenge due to their different chemical and physical properties. On one hand, metals possess key properties such as high strength, high toughness, high thermal conductivity, and good stability at high temperatures. On the other hand, plastics are characterized by lightness, high corrosion resistance, and excellent formability. However, due to the different properties, problems may arise during the joining process, as well as in terms of the structural integrity of the component [1].

Recent studies have concentrated on the assembly of multimaterial structures using joining technologies distinct from traditional methods, including mechanical, bonding, and adhesive techniques. The analysis encompassed examination of failure modes and mechanical characteristics of the resulting hybrid joints.

Abibe et al. [2] experimented the Injection Clinching Joining (ICJ) as an alternative joining method for connecting polyamide 6,6 reinforced with 30% short glass fibres with aluminium alloy, 2024-T351, used for automotive components and engineering structures, respectively. The microstructures and the failure modes of overlap joints were assessed and related to the process conditions, and the mechanical performance was considered satisfactory.

Liu et al. [3] designed a new technique, named friction lap welding (FLW) for direct joining AZ31B Mg alloy polyamide 6, aiming at analysing the effect of the welding parameters on the bubble formation and at improving the strength of the hybrid joints. Recently the authors demonstrated a robust bond at interface, by using aluminum alloy and polyamide 66 (PA66) surpassing mere mechanical interlocking, as evidenced by XPS measurements [4].

Abibe et al. [5] introduced for the first time, the innovative Friction-based Injection Clinching Joining technique (F-ICJ). The authors formed joints between polyetherimide (PEI) and aluminium alloy 6082-T6, provided details on the microstructure and alterations in local properties, and demonstrated that the process represent a promising joining technology for polymer–metal hybrid structures, also for some advantages related to the absence of gas o fume and to the general less environmental impact.

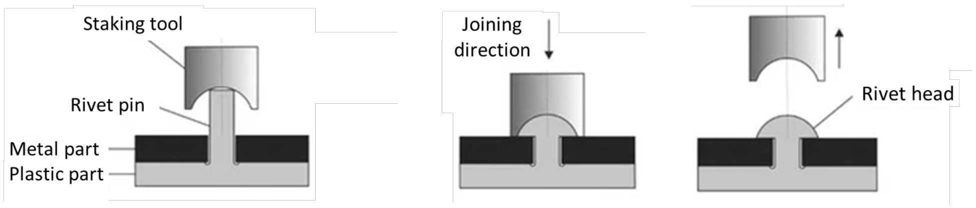
Huang et al. [6] investigated a novel technique named Friction Filling Staking Joining (FFSJ) for joining 6082-T6 aluminium alloy and poly propylene polymer sheets. The mechanical performance obtained, really close to the state-of-the-art welding, demonstrate the potential of this technique.

Liu et al. [7] presented a high-speed friction lap welding (FLW) technique for directly joining of aluminium to polymer. The influence of the welding temperature and speed was analysed thought X-ray observation and lap-shear tests. The results revealed that the bond strength was consistent irrespective of the cited investigated parameters.

Huang et al. [8] provided a review on the laser joining technology of polymers and metals, highlighting the impact of some factors, such as the bubbles morphology or the depth of molten pool, on the joining strengths.

Considering the growing interest in directly connecting metal to polymer material, this paper focused on the staking process, another interesting joining technique, which find application in several fields (e.g. aerospace and automotive) and allows the creation of a mechanical interlocking through the application of pressure and deformation, and without the use of additional fastening elements, such as screws [9]. Various forms of staking exist (e.g. cold staking, heated-tool staking, hot-air staking, ultrasonic staking and infrared/laser staking), and the selection of a particular method depends mainly on the materials to be processed, the distinct application, and the specific joint requirement.

A general scheme of the staking process has been described by Härtel et al. [10]. It consists, first, in the preparation and positioning of the components to be joined (Fig. 1 – a) and, then thought a staking tool, such as a punch, pressure in applied on the rivet pin (Fig. 1 – b), therefore this latter is deformed, becoming a rivet-like element, and a mechanical interlocking is created (Fig. 1 – c).



(a) (b) (c)

Fig. 1 - Staking process principle [10]

This study assesses the Hot-Air-Cold-Staking (HACS) variant, aiming at testing the joining feasibility between polymer and metal, evaluating the impact of the key process parameters on the rivet pin geometry and on the resulting joint strength assessed by lap-shear test.

Materials and method

The materials used to create the joint are the polylactic acid (PLA) and steel C40.

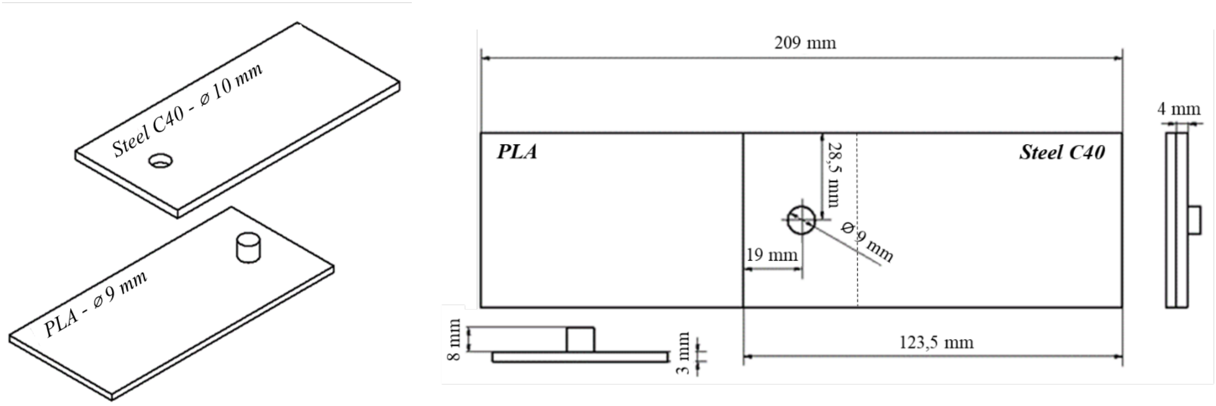
PLA is a biomaterial widely used for industrial applications, replacing conventional petroleum-based polymers, therefore it is considered environmentally friendly. Furthermore, it is a biodegradable aliphatic polyester that can be produced from renewable raw materials. It is a thermoplastic polymer, with high tensile strength and rigidity [11]. Additionally, it has a better thermal workability compared to other biopolymers and can be processed using additive manufacturing techniques. In fact, it is one of the most commonly used materials in the Fused Deposition Modeling (FDM) process [12] due to its ease of printing, low smell emissions and biodegradability. Steel C40, on the other hand, is classified as a non-alloy steel and is a high-quality carbon structural steel applied for various industrial applications owing to its strength, ductility, toughness and good machinability.

The physical and mechanical properties of both materials are displayed in Table 1.

Table 1 – Physical and mechanical properties of the investigated materials

	PLA	**Steel C40**
Density (ρ) [g/cm^3]	1,21-1,25	7,85
Tensile strength (σ) [MPa]	21-60	650-800
Young's modulus (E) [GPa]	0,35-3,5	210
Elongation (ε) [%]	2,5-6	20-25
Glass transition temperature (Tg) [°C]	45-60	-
Melting temperature (Tm) [°C]	150-162	-

Fig. 2 - a displays the geometries of the metal and polymeric partners, based on the ASTM: D5961 standard, which provides details on the execution of the lap shear test (Fig. 2 – b). The steel C40 sheet has been drilled according to the suggested hole size, while the PLA sheet has been produced by additive manufacturing and it was characterized by a rivet pin height of 8 mm.



(a) (b)

Fig. 2 - Staking process principle

As previously introduced, the FDM, a versatile and cost-effective 3D technique, allowed to create the thermoplastic component layer by layer. More in detail, printer heats the thermoplastic filament (⌀ = 1.75 mm) which is fed in the extrusion nozzle and deposited layer by layer on a build platform to create the desired solid objects based on a digital and sliced model [13]. To the aim of this study, two different printers were used in order to test their influence, working at the printing speed recommended by the Bambu Studio software, which was used for slicing, according to the selected printer. The printing speed is the velocity at which the nozzle moves in relation to the printing platform.

Sample 1 was produced by the Creality Ender-3 V2 (Fig. 3 – a), characterized by a recommended print speed of 50 mm/s, while *Sample 2* by the Bambu Lab P1P (Fig. 3 – b) characterized by a print speed of 270 mm/s.

(a) (b)

Fig. 3 – a) Creality Ender-3 V2 and b) Bambu Lab P1P

The overlapped polymeric and the metallic plates (Fig. 4 – a) were joined using the Hot-Air Cold Staking (HACS) technique. The pin rivet was heated by a hot air gun and the temperature was monitored by a thermocouple inserted in the middle of the pin using a drilled hole on the opposite face of the sample respect to the hot air jet. As soon as a temperature of 55°C was reached, the pin was shaped using a cold deformation tool, installed on a manual hydraulic press, whose movement was fixed and maintained constant for the all tests (Fig. 4 – b). Flat-headed rivets, characterised by the same height of the head, were obtained creating the joints between the polymeric and metallic plates.

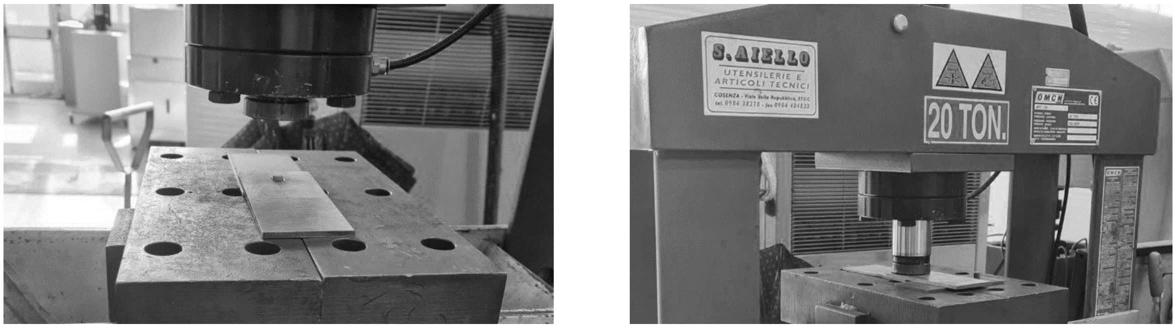

(a) (b)

Fig. 4 – Experimental test of Hot-Air Cold Staking: a) partners positioning, b) joint execution

The details of the process for printing the polymeric samples are schematised in the following Table 2.

Table 2 – Experimental details of the polymeric parts

Sample	Printer	Print speed [mm/s]	Total printing time [min]	Filament used [g]
1	Creality Ender-3 V2	50	128,70	26,54
2	Bambu Lab P1P	270	30,28	26,98

Metal and polymeric components were prepared and joined, as discussed above (Fig. 5 – a, b). Lap shear tests were performed using the MTS Criterion Series 40 testing machine (Fig. 5 – c). Considering the ASTM: D5961 standard procedure, a traverse speed of 2 mm/min was set. Three replicates for each processing condition were investigated at room temperature and curves for each test were obtained recording load and displacement.


(a) (b) (c)

Fig. 5 – a) Metallic and polymeric partners, b) hybrid joint (Test 1), c) lap shear test

Results and discussion

The load–displacement curves in Fig. 6 illustrate the effect of the type of the printing machine on the strength of the joints. Test 1, produced using Sample 1, which was printed by means of the slowest FDM machine (Fig. 3 - a), exhibits higher mechanical performance in the all replicates. This result is supported by a higher maximum load and the ability to withstand greater displacement before reaching the breaking point. On the other hand, lower strength is observable in case of Sample 2, where the increasing printing speed seems compromising the interface bond strengths between the deposited layers within the polymeric partners. The reason may be related to the plasticization time of the polymer. In fact, a higher printing speed does not allow the material to plasticize in a proper manner, increasing the residual stress produced and therefore weaker mechanical properties of the final hybrid joint are observed. The second replicate of Sample 2 shows a special behaviour, which would deserve an in-depth analysis.

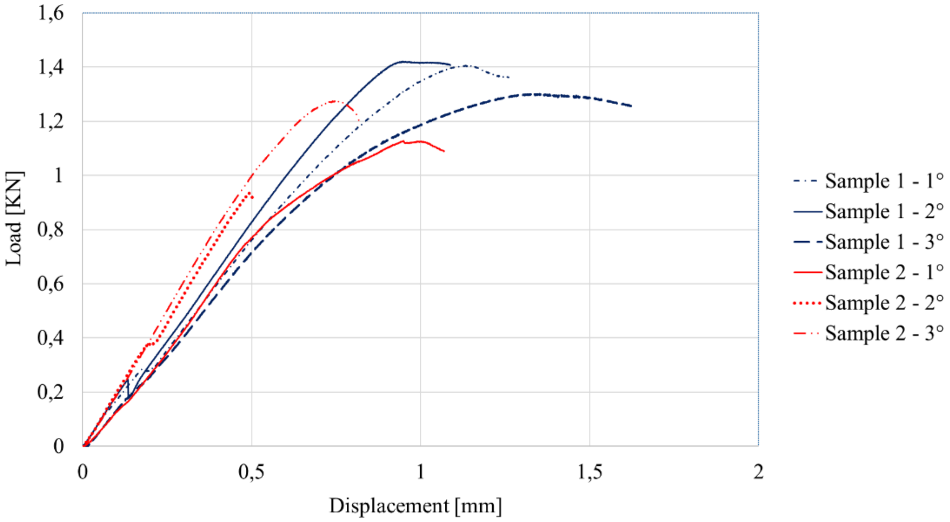


Fig. 6 - Load–displacement curves for all replicates of Sample 1 (print speed=50 mm/s) and Sample 2 (print speed=270 mm/s)

The aforementioned considerations were also supported by the experimental evidences. In fact, Fig. 7 displays the samples at the end of the lap shear tests. Fig. 7 – a refers to Sample 1 and the pin rivet experienced a slower detachment, while the fracture occurred subsequently at the base of the pinhead after detaching from the metal partner. In contrast, in Sample 2 (Fig. 7 – b), produced at higher speed, the poor material plasticization appears evident also here from the detachment of the layers from the base.

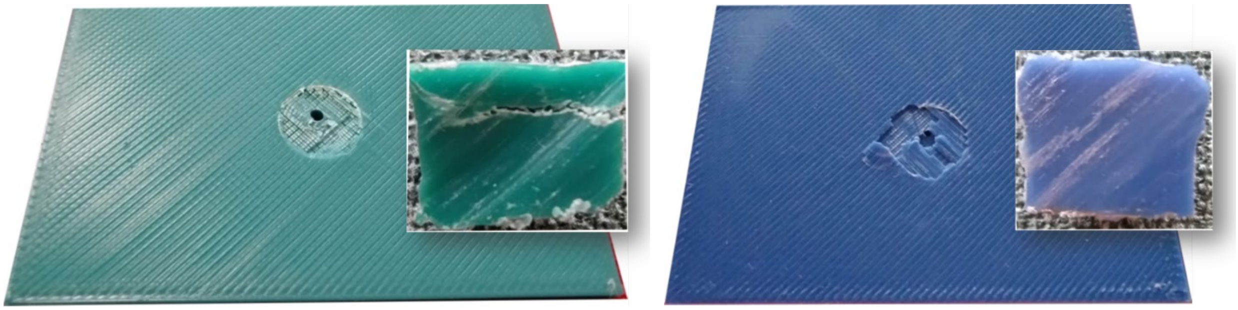

(a) (b)

Fig. 7 – Failure mode of a) Sample 1 and b) Sample 2

Conclusions

In this work, hybrid joints were experimentally investigated. The polymeric partners were produced by additive manufacturing, specifically by FDM, using PLA as base material and joined with a holed steel plate. The joint was performed by the Hot-Air Cold Staking (HACS) technique. The polymeric partners were produced by means of two different printers, which allowed the setting of two printing speeds. The influence of these latter on the final joint strength was evaluated by lap shear test which revealed that a slower printing speed (50 mm/s) yielded a stronger joint, attributed to enhanced material plasticization and the consequent formation of robust bonds. Conversely, the machine operating at a higher printing speed (270 mm/s) demonstrated increased process efficiency but compromised joint strength. A distinctive failure mode was also observed at the end of the lap shear test. The delamination of layers from the polymeric base emphasized the impact of reduced material plasticization at higher speeds. These preliminary results allowed to reflect on the joining process planning based on the characteristics that the produced pieces have to possess. This involves also the evaluation of the optimization of the process duration according to the structural requirements of the parts.

Future experimental tests will be performed in order to investigated further printing speeds on the same printers to take into account the machine stiffness and the related deposition load that could affect the intimate contact for better diffusion of polymer chains across the interface at subsequent layers resulting in the formation of strong bonds. In addition, experimental results will be verified by numerical investigations, aiming at proving a tool useful for optimizing the staking process for joining polymers and metals according to the specific context where thy hybrid joints could be used.

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