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Procedia Structural Integrity 24 (2019) 204–212

Structural Integrity Procedia

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AIAS 2019 International Conference on Stress Analysis

The use of low pressure plasma surface modification for bonded joints to assembly a robotic gripper designed to be additive manufactured

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Abstract

The paper explores how different surface preparations modify the mechanical performance of bonded joints on components made in acrylonitrile butadiene styrene (ABS) processed by fused filament fabrication (FFF) additive manufacturing. Two alternative treatments are considered: surface abrasion compliant to the standard ASTM D2093-03 (17) and using low pressure plasma, an innovative solution. The assessment is performed on standard lap shear test specimens and structural epoxy adhesive. The bonding layer with abraded surfaces shows adhesive failure while after the low-pressure plasma treatment shows adherends failure. As case of study the bonding solution to perform the assembly is considered a jaw finger of a robotic gripper for the picking of garments from a table. The redesign of the finger availing of the performance of bonding with the new plasma treatment is proposed and discussed. Experimental testing assessed the feasibility of this innovative technical solution.

Keywords: Acrylonitrile butadiene styrene ABS, Fused filament fabrication FFF, bonded joint, low pressure plasma LPP, robotic, gripper

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1. Introduction

The fused filament fabrication (FFF) is already used to manufacture a variety of functional components, as discussed for ex. by Goudswaard et al. (2017), it was proven that it can be done also for robotic applications in a short time and in cost-effective way, for example in the work by Jilich et al. (2019). Considering the specificities of the realization with this technology, such as anisotropy as in Casavola et al. (2016) and Croccolo et al. (2013), or the need to include supports that have to be removed after the manufacturing as reported by Mirzendehdel (2016), Kumar and Regalla (2011), and Mirzendehdel and Suresh (2016), it is often convenient to split the component in more pieces to be manufactured separately and then assembled as in Araújo et al. (2019), Zhouet al. (2019), and Urbanic and Hedrick (2016). Many authors, for example Spaggiari and Denti (2019) or Dugbenooet al. (2018) have proven that bonding can be a suitable technology to assemble additive manufactured polymeric components.
In order to verify the feasibility of bonding for FFF components the assembly of a robotic gripper is chosen as case of study. In

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10.1016/j.prostr.2020.02.017

particular the study focuses on the assembly of the finger to the main body. It is interesting due to the design dedicated for additive. It consists of a thin acrylonitrile butadiene styrene sheet that takes advantage of the elasticity of the co-polymer that contains rubber and of the curved shape of the main frame that allows to carry the payloads given as input in the design process. The bonding surface is the curved overlap between the frame and the finger. A comparison was assessed by a configuration that used a pattern of screws along the surface, see Jilich et al. (2019). The screwed connections, as well known and shown by Budynas (2011), are affected by a relevant stress concentration at the screw holes and introduce zones of higher stiffness due to the different materials. These can cause premature failure of the component under cyclic loading as it is the loading mode for this application. The explored technical solution for assembly by bonding could improve the life span of the component with a better stress distribution, see Erdogan and Ratwani (1971), and Her & Chuan (1999).
The bonding of polymers may have issues like wettability, especially if the used polymer is non-polar, and limited cure temperature due to the relatively low melt point. Therefore, the choice of the adhesive, together with the corresponding surface treatment and cure cycle is crucial. Several works, as in Spaggiari and Dragoni (2013), and Liston (1989), suggest abrasion and plasma surface modifications as the most effective. Again, a work by Spaggiari and Denti (2019) explored the opportunity to take advantage of FFF readiness in adding geometrical features to improve the joint performance by surface tailoring. It was concluded that the solution is ineffective to improve or decrease the mechanical performance, then in this work features to obtain better repeatability of the bonded joint, as spacers and alignment pin, are used.

2. Robotic gripper finger design

In this section, the design of the components is presented providing details of the two assembly solutions, with screws and with bonding.
The robotic gripper considered is based on the gripper technology developed in the EU research FP7 project Clopema, see Leet al. (2015). The gripper has been adapted for fabrication using polymeric additive by sizing the structural elements based on the material modelling described and validated in the works by Casavola et al. (2016) and Croccolo et al. (2013). The gripper application is to manipulate clothes and fabrics in general with the ability of textile recognition and of picking from flat surfaces (such as a table). Consider (Fig. 1). The picking from a table function is performed by the lower finger mounted fixed to the frame of the gripper. Thanks to its shape and architecture, the finger bends up when contacting the table surface and then can slide beneath an edge of the garment to pick. In the subsequent phase of the lift up of the garment, the finger is loaded downward by the weight of the garment edge and keeps straight and rigid holding the load and making the pinching.

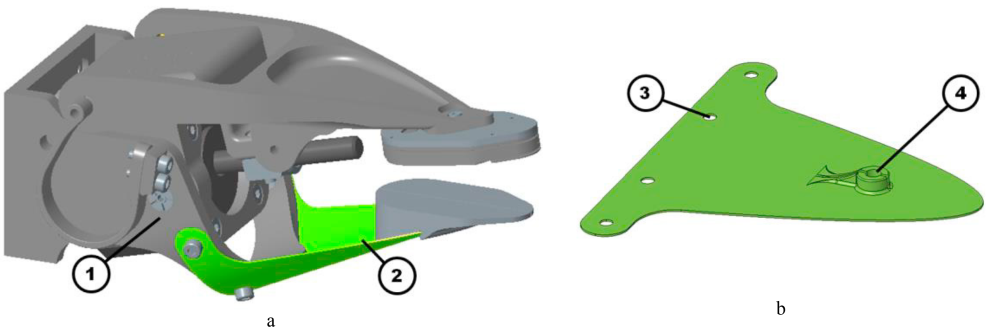

Fig. 1. (a) The CAD model of the gripper: (1) main frame; (2) lower finger; (b) In flat shape manufactured lower finger: (3) fixing holes, (4) expandable pin to fix the fingertip

The asymmetrical displacement of the finger when loaded is obtained taking advantage of the curved shape of the finger obtained designing a curved mounting. The shape is to be maintained as near as possible to the nominal one in service. This is easier to be obtained with a bonded joint (Fig. 2) compared to a threaded connection (Fig. 1). One of the drawbacks of the bonded joint is the limited possibility of disassembly the components. To keep the possibility of disassembling the finger from the gripper, for instance for maintenance or replacement with design for other applications, the thin sheet is glued to a curved interfacing frame (part 3 in Fig. 2). The assembly sheet-frame is assembled on the gripper through a snap joint pin (part 10 in Fig. 2) and secured by lateral screws (part 11 in Fig. 2). The disassembly for replacement is now enabled replacing the assembly finger-sub frame.
The bonding of the finger with the sub frame is performed adding features for repeatability and geometrical control. On the frame are placed alignment pin (part 9 in Fig. 2), the finger is built with spacers (part 5 in Fig. 2) for constant and controlled thickness of the adhesive on the bonded surface. The spacers prevent the layer of adhesive from becoming locally thinner than 0.25 mm while applying pressure to bond the two items together. The alignment pins have a dual function: to ensure the correct relative position of the components for bonding and to prevent creep of the adhesive that can cause service failure.

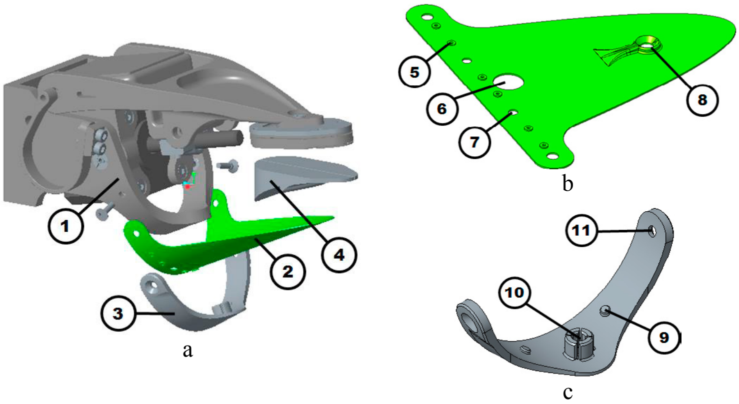

Fig. 2. (a) Redesigned gripper: (1) unchanged main frame, (2) redesigned lower finger, (3) additional arc element; (4) lower fingertip; (b) New finger shape before wrapping: (5) spacer to guarantee constant thickness of the adhesive, (6) hole for the central alignment pin, (7) hole for the lateral alignment pin, (8) reinforcement for the screw connection to the fingertip; (c) Additional arc element (9) lateral alignment pin, (10) central alignment pin, (11) hole for the screw connection between the arc element and main frame

3. Materials and methods

3.1. Materials

The components are printed with the delta 3D printer Wasp 4070 industrial. It has a closed chamber with printing volume enclosed in a cylinder of diameter 400 mm and height 700 mm. The bed is heated; the maximum build plate temperature is 120 °C. The 3D printer is equipped with a nozzle of 0.4 mm diameter, compatible with 1.75 mm diameter filament. The material chosen according to the specifications of the application and on previous experience by Frascio et al. (2018) is the ABS filament by Sienoc. ABS is a co-polymer that is characterized by durability, flexibility and mechanical strength compliant the design input of the lower finger.

The adhesive used is the 3M Scotch Weld DP 490, an epoxy adhesive for structural applications. This adhesive is selected because it can be heat-hardened in one hour at the temperature of 80 °C that is the highest possible with ABS (Table 1); this short time of hardening is required for an acceptable overall time of manufacturing of the gripper.

Table 1. Temperature depending length of cure cycle.

Adhesive	3M Scotch Weld DP 490
Cure cycle	24 h at 23 °C 1 h at 80 °C

The bonding is performed after surface treatments. The surface is cleaned with the Loctite SF 7063 solvent. Two alternative treatments are tested and assessed: abrasion with Scotch Brite tape and low pressure plasma. The low pressure plasma treatment is performed with Gambetti Tucano radio frequency RF generator operating at 13.56 MHz and maximum power of 200 W.

3.2. Material characterization

The mechanical characterization is performed on tensile testing specimens using a Zwick universal material testing machine Z010 TN ProLine. The machine is equipped with wedge clamps and a 10 kN load cell. The tensile testing specimens are built according to the ISO 527-2:2012 standard geometry, type 1BA (Fig. 3).

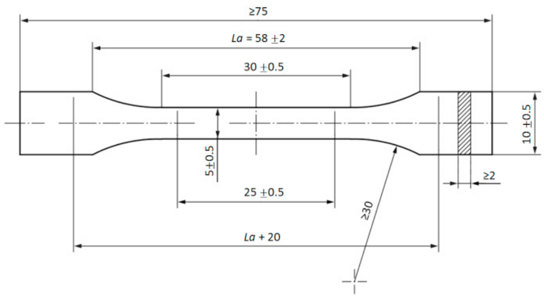

Fig. 3. Specimen dimensions.

The printing is performed with specimen positioned with the main direction along the *x* axis of the machine, raster pattern in directions ±45° about the *x* axis, and the *z* direction corresponding to the one of stacking, orthogonal to the bed plate (Fig. 4).

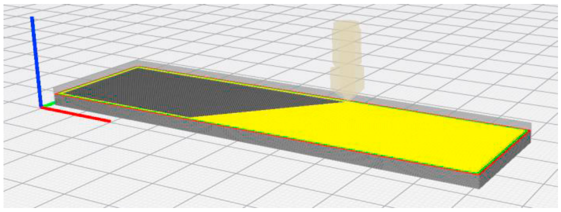

Fig. 4. Specimen positioning in the 3D printer.

The printing parameters used have been previously selected as reported in Frascio et al. (2019) to enhance the mechanical strength of the component and minimize the building time (Table 2).

Table 2. Printing parameters for the fabrication of the samples.

Printing parameters	
Layer height mm	0.25
Nozzle temperature °Ce	250
Print speed mm/s	120

The tensile test samples are prepared performing the same curing process of the adherends (e.g. sheet and frame in the gripper) to obtain relevant results to set a reference.

3.3. Surface treatments

As is well known, surface conditioning does affect the performance of the joint, as shown by Adams (2005). For ABS adherends obtained with a traditional process, like injection moulding, the standard ASTM D2093-03(17) prescribes mechanical abrasion of the surfaces. In the literature several works suggest using low pressure plasma (LPP) to improve the mechanical performance of bonded joints between polymers. However, LPP has not been investigated for polymers blended for additive manufacturing processes. In the first instance the parameters (Table 3) for surface abrasion and low pressure plasma are selected from literature review and previous experiences by Mandolfino et al. (2017).

Table 3. Surface treatment used for the experiments.

Treatment	Procedure and parameters
Abrasion (AB)	Cleaned with the Loctite SF 7063 solvent, abraded along width direction, cleaned
Low pressure plasma (LPP)	Cleaned with the Loctite SF 7063 solvent, Air, Power 150 W, Time 180 s, 0.65 mbar

3.4. Realization of the joint

The adherend specimens have dimensions 100 mm×25 mm×4 mm in the directions, respectively, *x*, *y*, and *z* (Fig. 5), according to the ASTM D3163-01(14). The lap shear joints are realized with 12.5 mm overlap and 0.25 adhesive thickness. This overlap configuration is selected because representative of the overlap configuration adopted in the gripper bonded joint between parts 2

– finger – and part 3 – arc element – shown in Fig. 2.

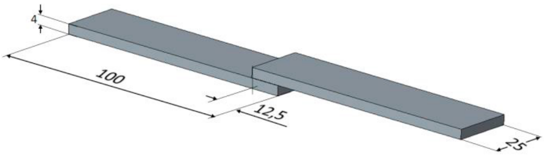

Fig. 5. Specimens dimensions.

First, the adherends are solvent sprayed and wiped along the main direction. Then, three groups of five specimens are prepared as reported in table 3. The adhesive is applied on both adherends. The specimens are then aligned and assembled as the specified overlap position with the help of a rig. Finally the bonded assemblies are cured in oven.
The fingers are 3D printed using the settings reported in (Table 2).

3.5. Construction of the finger

The finger is positioned flat resulting in a symmetric two layers laminate (Fig. 6). With this solution the bonding surface is on the top layer. It allows building it without supports despite the feature of the spacer used to obtain constant adhesive layer thickness; moreover, this surface has a characterized morphology as shown by Frascio et al. (2019) that is beneficial for the bonded joint mechanical performance. The additional mounting arc element is positioned with the plane of the main surface orthogonal to the bed (Fig. 6) in order to minimize the usage of supports and to obtain an optimal deposition of the filament for the geometrical tolerances of the curvature.

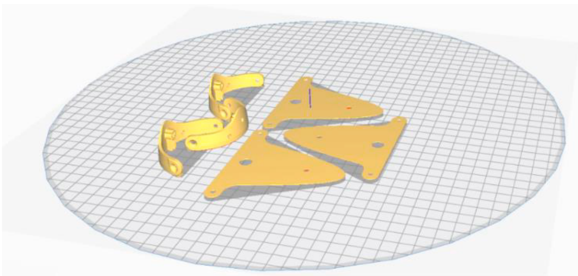

Fig. 6. Orientation of the component on the building plate.

3.6. Assembly of the finger

The first step of the assembly process is solvent cleaning to prevent the low pressure chamber of the Gambetti low pressure plasma machine (Fig. 7) to be contaminated.
Then the components are placed in the low pressure plasma chamber with the overlap surfaces upward to expose the bonding surface to the ionized gas flow.

Fig. 7. Gambetti low pressure plasma chamber.

The adhesive is applied on the surfaces to be bonded immediately after the components are taken out of the plasma chamber to maximize the effect of the treatment. Then the parts are assembled applying a pressure to obtain a constant adhesive thickness of 0.25 mm taking advantage of the spacers.
Once the adhesive fixing time is elapsed, the curing cycle is performed in the oven with controlled atmosphere, at the same time as the specimens, using the parameters reported in (Table 1).

3.7. Finger testing set up

A specific fixture in two parts, Fig. 8 (a), has been designed and 3D printed with the same Wasp 4070 Industrial 3D printer. This custom-made mounting tool is used to test the finger with the universal testing machine Zwick Z010 TN ProLine.

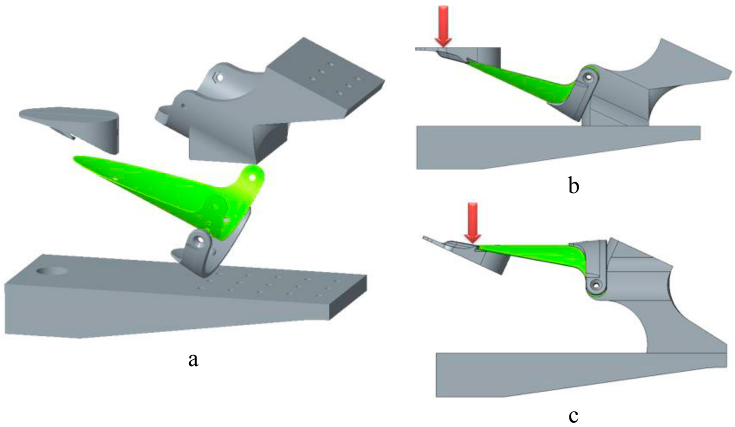

Fig. 8. (a) exploded view to the test set-up components; (b) set-up mounted to test with downward force; (c) set-up mounted to test with upward force.

The aim is to perform experimental design validation of the bonded component under realistic service conditions.
In Fig. 8(b) the set up for the assembly characterization is reported while performing garment transportation or recognition. As input for the textile sensor recognition the maximum displacement have to be less than 2.5 mm against a machine testing set force of magnitude about 20 N, esteemed from a mean of cloth weight. The set up shown in Fig. 8(c) is realized to test the picking condition where the force oriented downward must be minimized in order to protect the robotic arm. The test is performed imposing a finger displacement of 10 mm and recording the force applied to the support.

4. Results

4.1. Tensile test

The mechanical properties of additive components are strongly affected by the filament and by the build parameters.
A reference was set in the previous work by Frascio et al. (2019), then in Table 4 a comparison between the mean values obtained by tensile testing specimens after the curing, necessary for the bonding, is reported. This is done to assess the feasibility of the process. The stress strain values are obtained with a test speed of 1.3 mm/min.

Table 4. Experimental assessed mechanical properties of ABS FFF specimens.

	Reference	After curing
Tensile modulus (MPa)	2110	2280
Yield strength (MPa)	33	35.9

The analysis of the values confirms the feasibility of the process.

4.2. Lap shear tensile test

In this section, the experimental values of the single lap shear tests are reported (Fig. 9): the values are obtained with a test speed set at 1.3 mm/min.

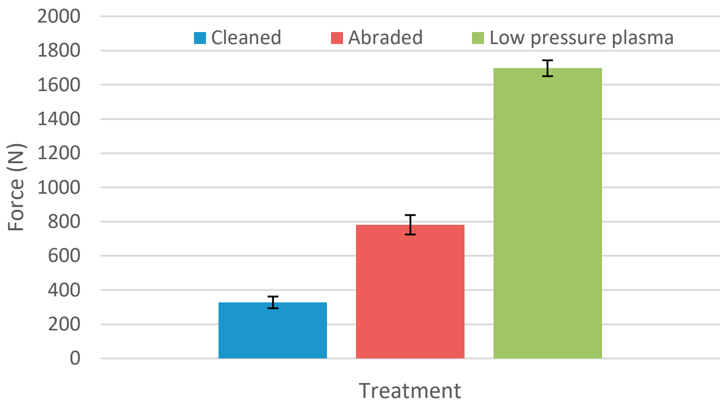

Fig. 9. Lap shear tensile test output.

The comparison between the average maximum shear stresses registered during the tests points out the low pressure plasma treatment as the best surface modifications between the explored ones. The failure surfaces are reported in Table 5 for the three cases considered: of solvent cleaned only; solvent cleaned, abraded, solvent cleaned again; solvent cleaned and low pressure plasma treated.

Table 5. The test results on the specimens treated according to the different treatments.

Treatment	**Failure type**	**Failure detail**
Cleaned	Adhesive	
Abraded	Mix adhesive and Cohesive	
Low pressure plasma	Adherend	

Adhesive failure occurs in the case of cleaning only. Abrasion treatments improve the performance of the joint (failure type is adhesive) and suggest the possibility of further performance improvement. The low pressure plasma treated joints showed adherends failure: the strength of the bonded joint is higher than the strength of the adherends. This does not permit to analyse the performance due to the surface modification but qualifies this bonded joint process as the best for the application.

4.3. Lower finger

The lower finger assembled with the adhesive bonding is tested to verify the compliance to the technical input requested for the application. The responses to downward force, Fig. 6 (b), and upward displacement, Fig. 6(a), are reported in Fig. 10.
The downward force-displacement curve has values compatible with the design input ones; a certain degree of hysteresis occurs: the instability of the finger, while the curvature is being modified by the tip displacement, can be addressed as cause. The curve of the upward force obtained for the imposed displacement shows a good match to the wanted behaviour for accidental collision protection with a limited recorded force for high displacement.

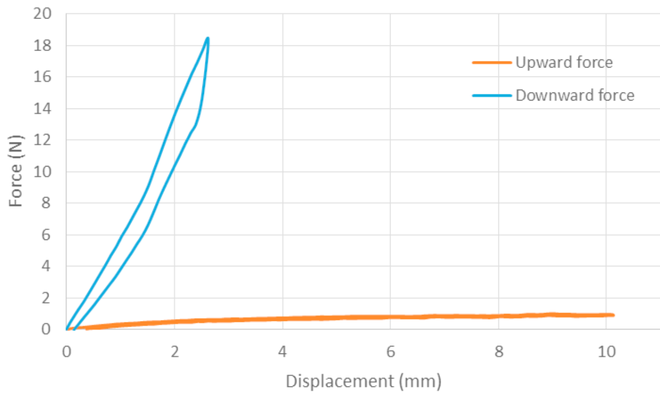

Fig. 10. Test results on gripper finger for cloth picking and transportation.

5. Discussion and conclusions

Splitting the polymer components designed for AM process into more parts manufactured separately increases the chances to find optimal design solutions related to the desired components mechanical properties and the building time, but it is necessary to find a suitable method for the subsequent assembly. The use of adhesives can be a consistent method to join these parts together, but surface treatments are needed. In this work polymeric AM components were bonded with a structural epoxy adhesive. It allowed quantifying how different surface treatment changed the mechanical properties of bonded joint. In particular, the best results were achieved by single lap joint prepared with low pressure plasma. Furthermore, examples of design considerations for FFF bonded joint as anti-creep elements, spacers for adhesives thickness control and the alignment pins are shown. Therefore, via experimental testing of a robotic component under realistic service conditions, the feasibility of bonded joint process for polymeric additive manufacturing was assessed.

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