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Mechanical strength of adhesively bonded joints using polymeric additive manufacturing

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Abstract

This paper investigates the combined use of one of the most widespread additive manufacturing techniques, fused deposition molding, with polymeric materials and structural adhesive. The aim is twofold: first, to enhance the adhesive performance exploiting the capability of the additive manufacturing to tailor the bonding surface of the adherend, and second to overcome one of the main limitations of 3D printing, i.e. the quite small printing volume, by means of adhesive bonding. Bonding multiple parts together without loss of performance could open new possibilities for this technology. The present research analyzes, by using a Design of Experiment technique, a wide set of single lap joints with two adhesives and seven different surface morphologies. The results highlight that the adhesive bonding does not undermine the load carrying capacity of the joints as well as their stiffness, and, in some cases, it causes a slight improvement of the peak force. The morphology of the surface plays only a small role in the performance of the system, since it cannot provide a strong mechanical interlocking of the parts due to peel stresses and because of the predominant effect of stress concentrations at the corners, which cause substrate failure.

Keywords

Adhesives, 3D printing, joints, epoxy resin, design of experiments

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Introduction

Adhesive bonding technology nowadays represents a reliable method to join different parts in a mechanical assembly, mainly driven by the application of composites in aerospace and automotive industries. Several advantages can be envisioned with adhesive bonding compared to other traditional mechanical techniques such as welding, riveting or threaded connections. First, the possibility of joining different materials, second, the load distribution along the entire bondline, and third, the good thermal and electrical insulation properties of the adhesive layer.[1,2] Unfortunately, there are also several drawbacks, such as the need of proper surface preparation[3–6] and the presence of an elastic mismatch which causes stress peaks at the bondline corners. Many adhesively bonded joints in fact present stress singularities at the edges of the bond-line, due to the strong difference in the elastic properties of the materials, both in peel and shear directions, regardless of the type of joint.[7–9] Several approaches were proposed in literature to mitigate and decrease the degree of singularity of these peaks. One of the most efficient way to lower the stress concentration in adhesive bonding is to modify the shape of the adherends,[10–12] which helps in reducing the elastic mismatch between the adherend and the adhesive. Several solutions were analyzed in the literature, such as spew fillet[13,14] or relief grooves,[15–17] but the effect is only partially due to the limited possibility given by traditional mechanical machining. Several authors considered the possibility of lowering stress concentration by reducing the adherends stiffness, or by increasing the adhesive stiffness with functionally graded materials.[18–20] These interesting works are mostly analytical or numerical, since the technology at that time was not able to provide an effective way of manufacture these kinds of joints. The strong development introduced by additive manufacturing (AM) techniques can be exploited to solve these issues. Several solutions are nowadays possible for AM of metals, such as selective laser sintering

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(SLS), selective laser melting (SLM) or electron beam (EB), while for polymeric parts the filament deposition molding (FDM) is the most widespread technique. The free shape of AM parts is ideal to design an adhesive bonded joint with outstanding performance in terms of strength compared to the traditional solutions. By means of careful design, the stiffness of the metal AM part can be lowered through several techniques, such as lattice structures or hollow components,[21,22] to be more similar to the adhesive stiffness and also introducing a positive side effect in terms of lightness of the structure. Moreover, the smart combination of AM and bonding could overcome one of the strongest limitations of the AM technology which is the small working volume of the AM machines. Many 3D printers can produce small components, but the scalability to higher dimensions (up to meters) is not straightforward. Stability, distortions, tolerances and especially cost are strongly dependent on the maximum dimension of the printed component. Therefore, by mixing the adhesive bonding and the AM manufacturing, it will be possible to obtain a combined advantage: to fully exploit the AM technique, enhancing its range of application and increase the mechanical resistance of the adhesively bonded joints. To date, the mechanical characterization of the AM components or adhesive joints can be traced in the literature, but the interactions of AM parts bonded with structural adhesives has not been deeply investigated yet, with only partial studies about the bonding of AM plastic components being available.[23,24] On the design side, it is possible not only to reduce the stiffness of the adherends to lower the stresses at the bondline edges,[21] but also to tailor the surface roughness or add a surface pattern to promote mechanical interlocking of the adherends. This additional feature will also improve the adhesion with the typical substrates used in AM, either metallic or polymeric, as studied in Dugbenoo et al.[25] for composite parts. This work aims at the experimental verification of the mechanical properties of bonded AM parts with several morphologies of the bonded area and a comparison with traditional bonding on flat surfaces or with the joint printed as a whole, directly with a 3D printer. The effect of the triangular pattern in the bondline was investigated by changing the orientation and the shape of the pattern. The results highlight that the performance of the bonded parts is comparable and in some case superior to the performance of the "monolithic joints" and the effect of the pattern depends on the flexibility of the adhesive. A discussion of the applicability of the adhesive bonding to AM polymeric parts is provided, adding a solid experimental base to promote the combination of the two technologies.

Materials and method

We decided to test the performance of the bonded AM polymeric material by means of the most widespread joint type, the single lap. We used a Stratsys Fortus 250 MC printer[26] which grants a reliable repeatability of the specimens, a minimum layer precision of 0.254 mm and a quasi-full dense filling of the ABS specimens. The specimen dimensions were decided after a set of preliminary tests (not reported here for the sake of brevity) since no ASTM standard could be used with AM technology. The specimen dimensions are reported in Figure 1(a).

Design plan

We also decided to investigate how the extreme freedom of shape granted by the AM technology is able to

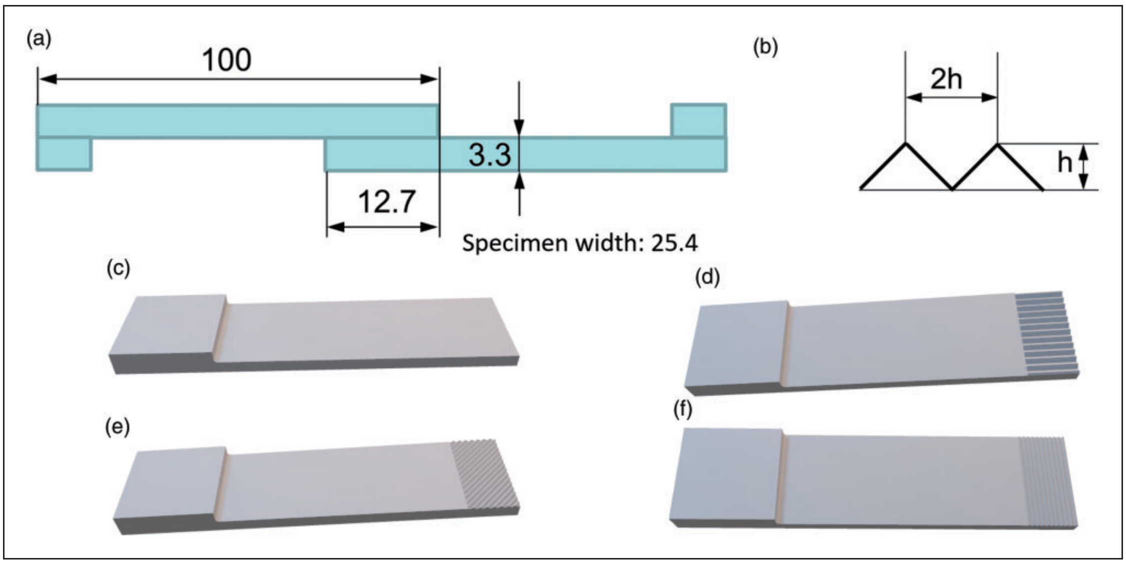

Figure 1. Schematic of the joint, not to scale, dimensions in mm, (a) zig-zag pattern, (b) h = 0.3 mm/0.6 mm, (c) flat specimen, (d) 0° specimen, (e) 45° specimen, (f) 90° specimen.

improve the joining performance. In order to increase the contact area and to promote a mechanical interlocking we decided to investigate a zig-zag pattern of the bonded surface. Three zig-zag patterns were taken into account: first a triangular sawtooth profile was oriented along the joint axis, second, the profile was rotated by 45° and third the profile was placed perpendicular to the joint axis. Moreover, two different dimensions were chosen for the sawtooth depth: 0.3 mm and 0.6 mm. The joint configurations are depicted in Figure 1. We tested these configurations with two different adhesives: a 2 K epoxy resin, the Henkel Loctite Hysol 3422[27] and an Hybrid structural adhesive, less rigid than the previous epoxy, the Henkel Loctite Hybrid 4090.[28] The Hysol 3422, having a Young's modulus of 1298 MPa, a tensile strength of 28.6 MPa and an elongation at break of 3.3% is a very stiff, high performance adhesive often used in combination with CFRP or GFRP and should provide a fair adhesion with ABS, nearly 1 MPa shear strength (ASTM D1002) according to the TDS.[27] The Hybrid 4090, having a Young's modulus of 565 MPa, a tensile strength of 7.1 MPa and an elongation at break of 3.6% is a quite flexible materials, which a higher ability of following the substrate deformation but will ensure a very good adhesion with ABS, above 5 MPa shear strength (ASTM D1002) according to the TDS.[28]

We arranged the experimental variables according to a design of experiment (DoE)[29] multilevel factorial design plan.[30] This methodology has several advantages, in particular it provides an easy statistical interpretation of the results and an increased reliability of the findings. The levels and variables considered are summarized in Table 1, while the system responses considered are: the maximum load, the effective stress and the stiffness. We printed five specimens per configuration (replicates) for a total of 70 bonded joints. While the stiffness definition (expressed in N/mm) and the maximum load (N) are quite trivial, the so called effective stress needs additional comments. We defined the effective stress as the ratio between the experimental measured peak force and the effective bonded area, which takes into account the real geometry of the zig-zag profile. This parameter is needed since we would like to determine if the surface morphology is enough to improve the joint performance or if it depends on the higher amount of adhesive used with non-flat surfaces. Moreover, we tested the tensile strength of a component printed as a whole component directly with the 3D printer, called "monolithic joint" (MJ), in order to estimate the performance of the base material.

Table 1. Experimental plan.

Design variable Adhesive type	Hysol 3422		Hybrid 4090
Profile depth (mm)	Flat	0.3	0.6
Profile orientation	0°	45°	90°

Experimental setup

The specimens were printed with the Fortus 250mc and bonded with the two adhesives by following the standard recommendations to grant a proper polymerizations and alignment. All the specimens were printed at full density, which grants the best mechanical properties of the ABS substrate, which is 33 MPa according to the producer.[31] A test rig was used to maintain the position of the specimens, and the Loctite 7030 Cleaner was used to remove any detrimental particles on the bonding area. No mechanical or chemical surface treatment was applied, even though these procedures increase the adhesive strength,[32–34] since the surface was already tailored with the 3D printer. The first batch of bonded specimens is reported in Figure 2, all specimens were made in ABS resin, regardless of the color. All the selected specimens were bonded and the adhesive thickness of 0.1 mm was ensured by the geometry of the specimen itself in the case of the zig-zag profile and by an external test rig in the case of the flat specimen. All the joints were cured at 45°C for 48 h, which ensures complete polymerization for both adhesives. The experimental setup is shown in Figure 3: we applied a quasi-static displacement to the specimens by means of a universal tensile machine (Galdabini SUN 500), equipped with a 5000 N load cell. The crosshead displacement is 1 mm/s, in order to avoid viscoelastic effects typical of the polymeric material. The joint was designed with built-in spacers tabs to ensure the correct alignment of the specimens with the machine grippers.

Results

Experimental results

The comparison of the several geometries tested is carried out on the basis of the force displacement curves recorded following the procedure described in paragraph 2.2. Figure 4 shows the curves for the two adhesives (Hysol 3422 in blue and Hybrid 4090 in red) in the three configurations analyzed for the profile depth of 0.6 mm and for the flat specimens. Figure 5 shows the curves for the two adhesives (Hysol 3422 in blue and Hybrid 4090 in red) in the three configurations analyzed for the profile depth of 0.3 mm and for the flat specimens. The geometry and the results of the tensile test on the "monolithic joints" (MJ) are reported in Figure 6, only three replicates were tested since there is less experimental noise compared to the bonded specimens. The joints depicted a variable situation in term of failure mode, most of the Hysol 3422 failed in the adhesive, while most of the

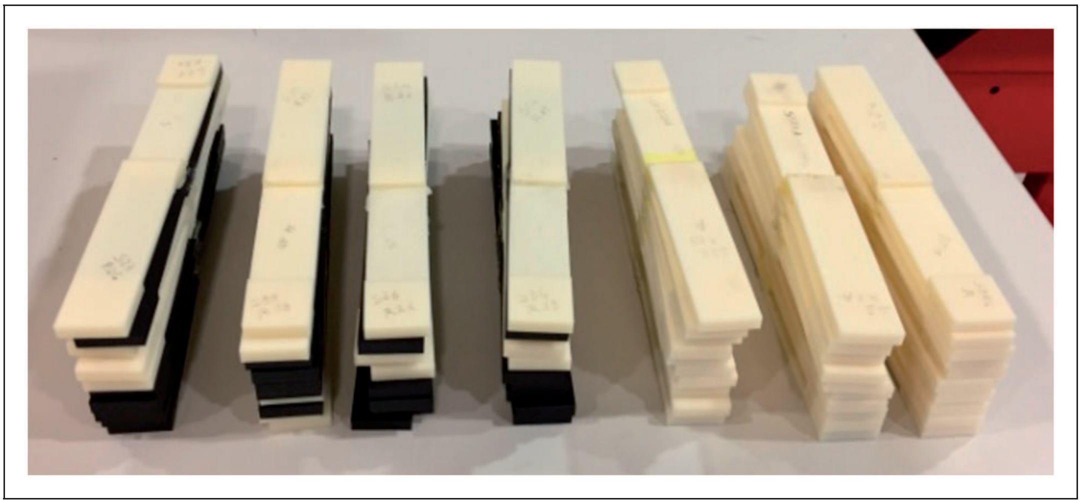

Figure 2. 3D printed specimens.

Figure 3. Experimental tensile test on bonded joints.

Hybrid 4090 exhibited a substrate failure, as shown in Figure 7.

The prevalent failure mode for Hysol 3422 specimens is a cohesive failure of the adhesive, which happens in all the configurations except the 90° high tooth profile. The most frequent failure mode for the Hybrid 4090 specimen on the other hand is a substrate failure, which occurs in most cases except the 0° high tooth profile.

Discussion

Three main experimental responses were extracted by the analysis of the following results: the maximum load, the stiffness and the effective failure stress in the adhesive layer. We defined "effective stress" as the peak force measured divided by the real bonding area obtained by considering all the peaks and valleys due to the sawtooth profile. Obviously, this value is always lower than the nominal stress when a profile is present while for the flat surfaces is the same. In addition to these three responses the failure surfaces were examined to assess whether the surface morphology plays a role or not. In order to examine the three main outputs at a glance we reported the values in Figure 8. Figure 8(a) shows that the maximum output force is reached with the Hybrid 4090 adhesive, especially for flat specimens and 45° specimens with high tooth profile. The performance of the joints bonded with 4090 adhesive is not quite dependent on the profile chosen; the performance in terms of maximum force is within the error bands. Particularly interesting is the comparison with the MJ joints, which have a maximum force, averaged on the three specimens, of 1306.2 N. The performance of the 4090 bonded joints, regardless of the morphology of the surface, is always greater than the continuous material component. This behavior is remarkable and shows that bonded joints and adhesives, could work pretty well together. On the other hand, we could argue that the performance of the Hysol 3422 adhesive, in terms of maximum force, is lower than the MJ joints in all configurations except the 0° high profile tooth. This difference can be simply explained by considering the failure modes reported in Figure 7. The failure of the 3D printed substrate is quite likely due to the lower mechanical properties of the ABS and the stress concentrations caused by the geometry. Surprisingly the substrate failure occurred in the bonded joints have a maximum peak force higher than the MJ joints. This behavior is due to the quite flexible behavior of the Hybrid 4090 adhesive (Young's Modulus 565 MPa), which smoothed the stress peak around the corner typical of the bonded single lap joints.[7] In fact, when the joint is bonded with a stiffer adhesive such as the Hysol

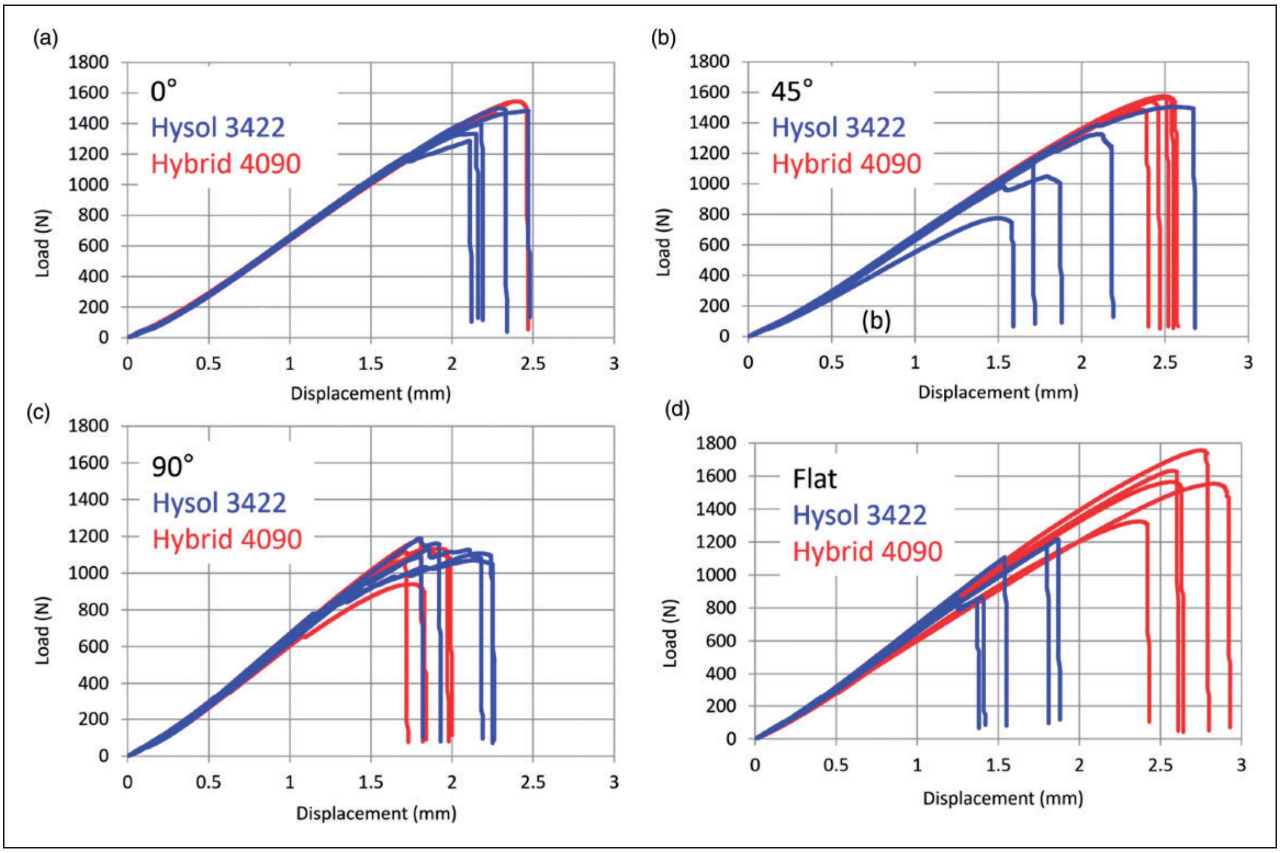

Figure 4. Experimental Load Displacement curves for profile depth of 0.6 mm. Blue curves report the results for the 2 K epoxy Hysol 3422 and red curves report the Hybrid 4090. The 0°, 45°, 90° and flat specimens are reported in (a), (b), (c) and (d) respectively.

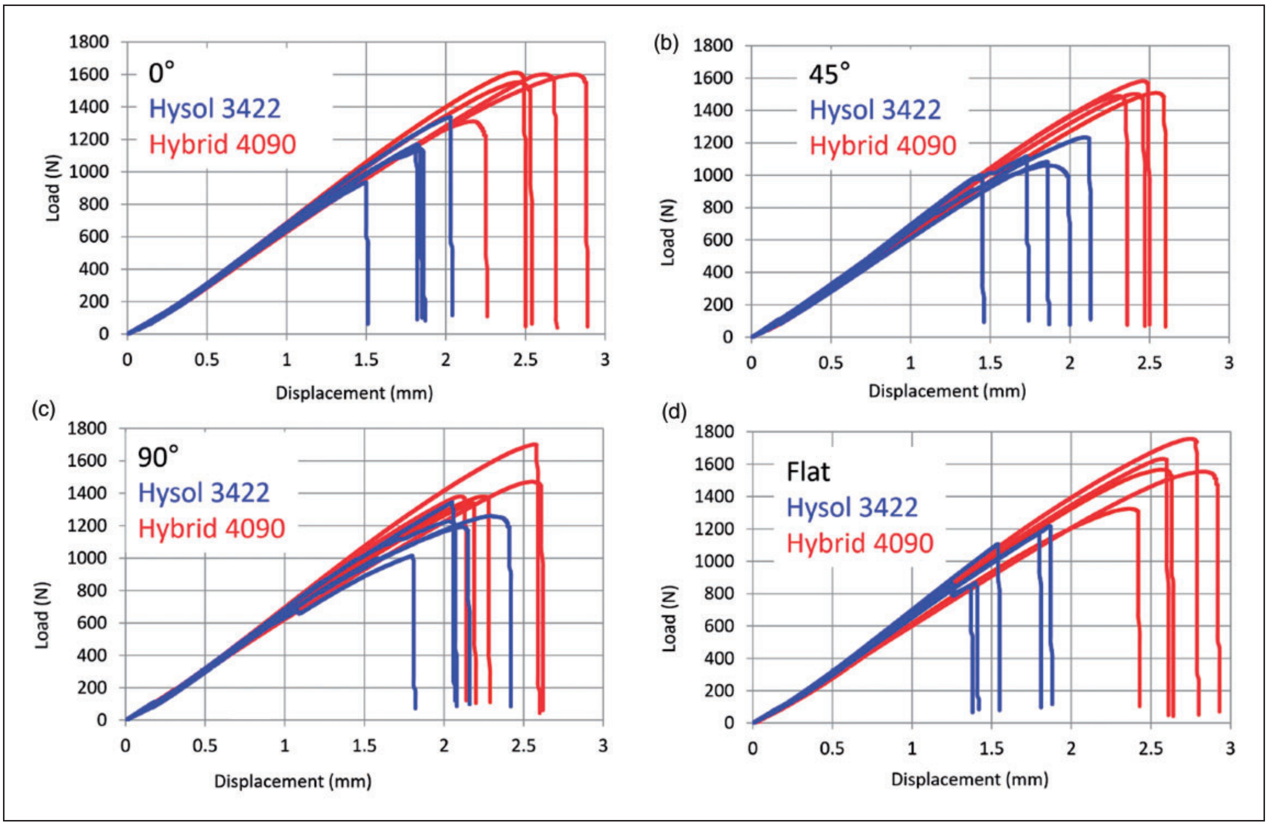

Figure 5. Experimental Load Displacement curves for profile depth of 0.3 mm. Blue curves report the results for the 2 K epoxy Hysol 3422 and red curves report the Hybrid 4090. The 0°, 45°, 90° and flat specimens are reported in (a), (b), (c) and (d) respectively.

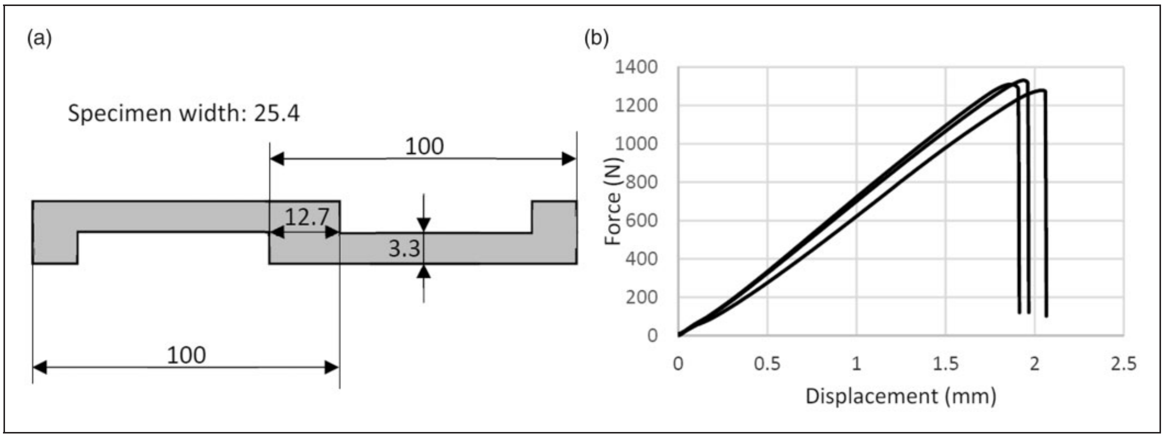

Figure 6. Geometry of the "monolithic joints" (a) with the same dimensions (in mm) of the bonded one, not to scale and Force displacement experimental curves (b) on three replicates under tensile tests.

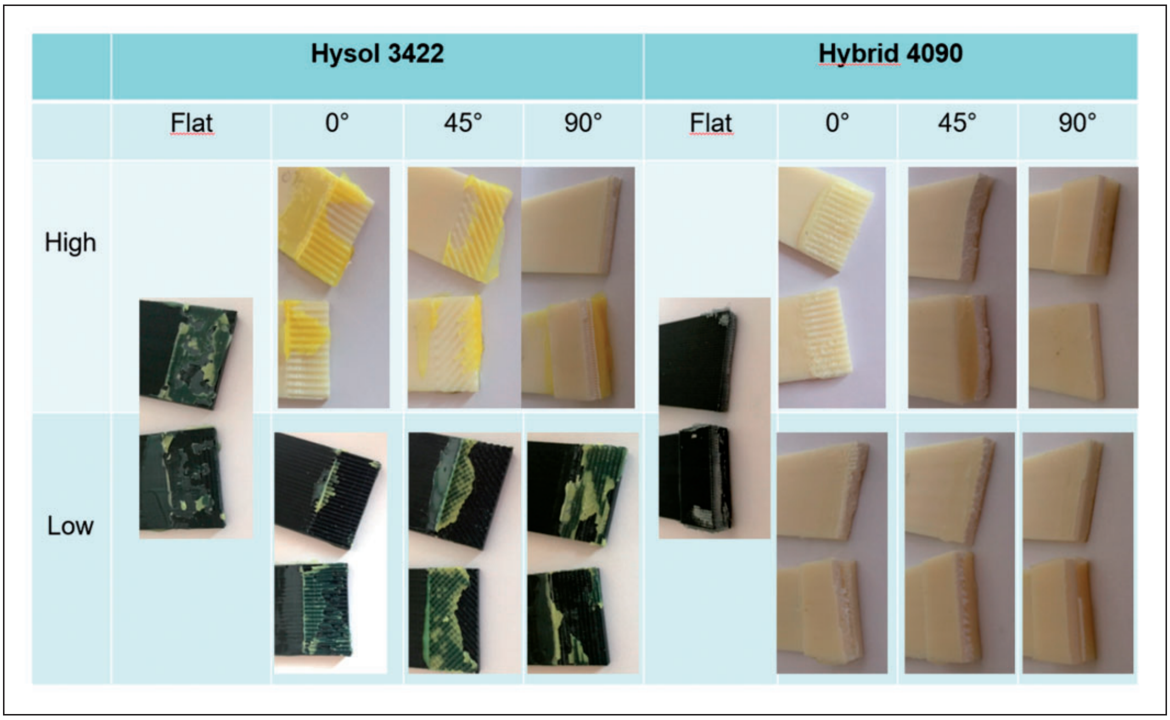

Figure 7. Different failure modes for the specimens considered for the high tooth profile 0.6 mm (upper row) and low tooth profile 0.3 mm (lower row).

3422 adhesive (Young's Modulus 1298 MPa), comparable to the ABS one (Young's Modulus 2200 MPa), there is no improvement of the performance compared with the MJ specimens. A preliminary finite element analysis test, not reported here for the sake of brevity, shows that the stress concentration due to the geometry does not depend on the tooth height or profile type as one could expect. Therefore, the different behavior of the joints is mainly due to the different mechanical properties of the adhesive selected.

Figure 8(b) shows the effective stress, which is much higher for the flat specimens. This behavior depends mainly on the lower area of the flat specimens, since the force, at least for the Hybrid 4090 joints, are comparable. The effect of the orientation of the sawtooth profile seems negligible and this is confirmed by an analysis of variance (ANOVA)[29,30] of the results. This statistical tool is a convenient way to examine the effect of the variables on the responses and it typically produces results in terms of half normal probability plot. Figure 9 shows the half-normal diagrams of the three responses considered, useful for estimating the variables that have an influence on the response at a glance. The stronger the influence, the larger the distance from the error line, extrapolated from the green triangles, which represent the normal stochastic variation of an experimental test.

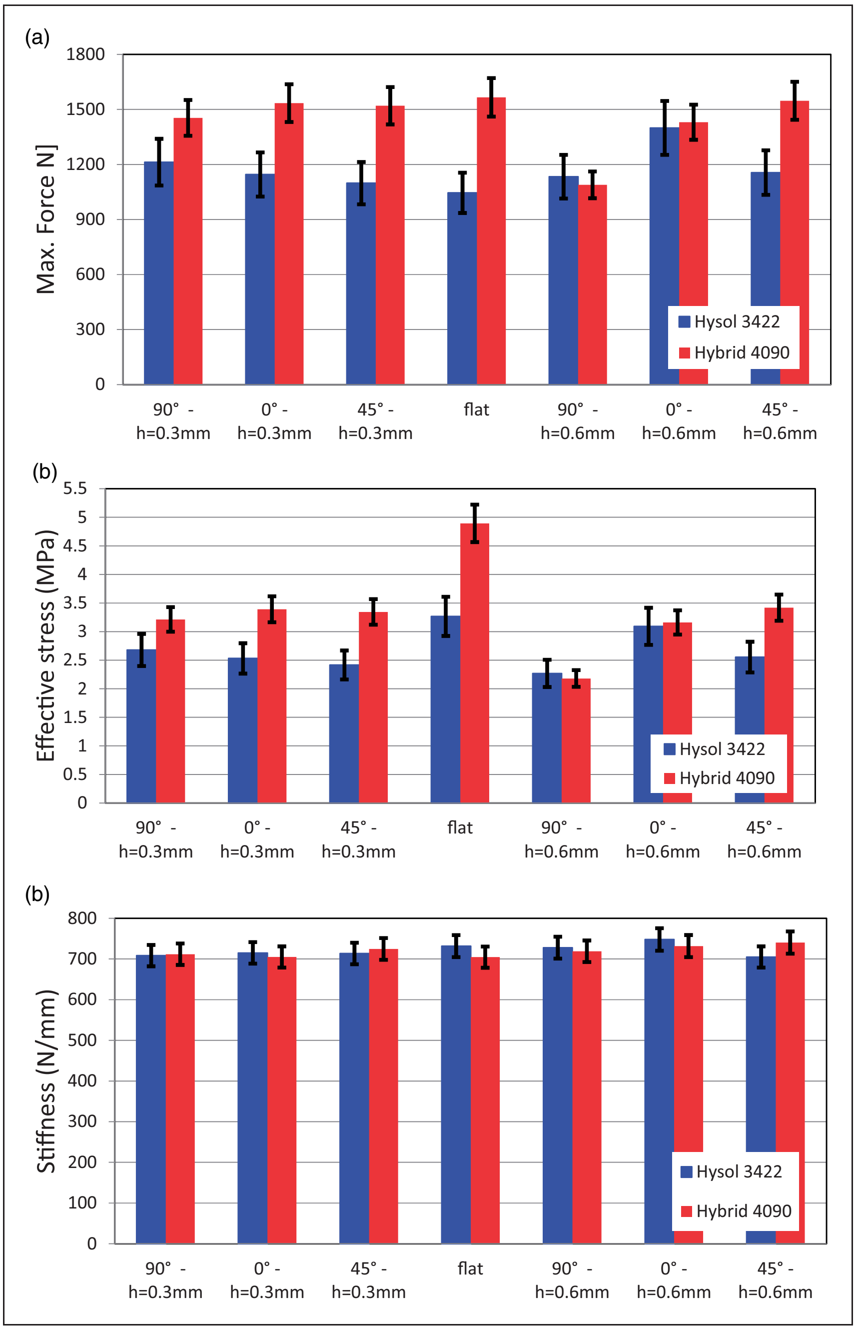

Figure 8. Results of the experimental test in terms of (a) maximum force, (b) effective stress and (c) stiffness for all the specimens considered. The black bars represent the standard deviation.

Figure 9 shows the variables that have a statistically significant influence on the response of the specimen. This influence is greater as they deviate from the error bar and the x-axis represents the influence on the response while the y-axis the confidence that the effect is not due to experimental noise. The plots confirm the qualitative findings of Figure 8, the main effect acting on the first two responses is the adhesive type and there is an interaction between the adhesive type and the morphology of the joint. The effect of the morphology alone is negligible and therefore it is not reported in the plot. As can be seen both in Figures 8(c) and 9(c) the stiffness of the joints is practically independent on the variable considered, since it remains unchanged in all configurations. This is a quite desirable behavior especially for the hybrid 4090 adhesive, which is quite flexible, and at the same time it does not affect the global behavior of the joint and improves the performance.

As a global comment on the experimental results, it is possible to observe that the bonding of an ABS 3D printed system could be done without any loss of performance, both in terms of stiffness of the joint and maximum load. In some cases, the bonded joints are performing better than the "monolithic joints" counterpart. A quite unexpected result is the missing effect

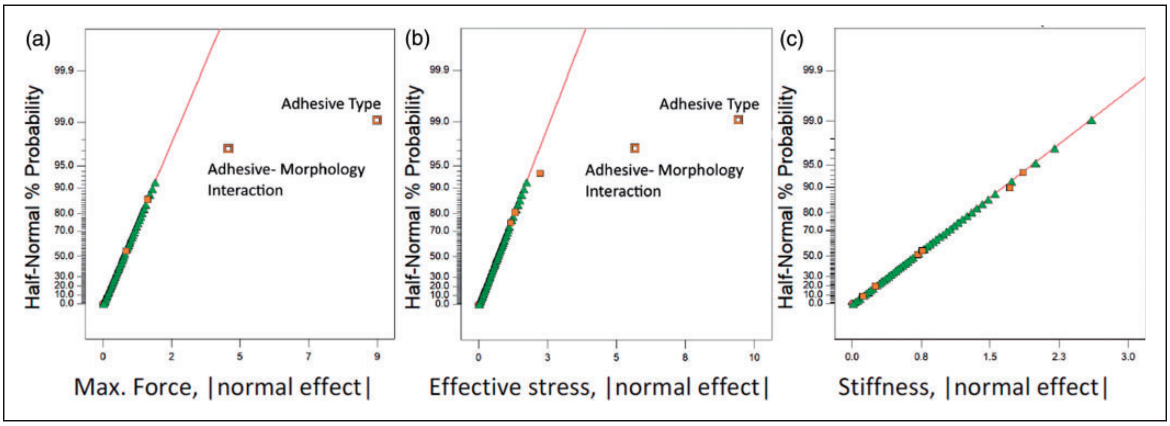

Figure 9. Half normal plot for the (a) max normal force, (b) effective stress and (c) stiffness.

of the morphology of the joint, which does not exhibit any improvement with respect to the flat surface. This could be motivated by three causes: first, no mechanical interlocking occurred, since the parts were manufactured to avoid any slot, in order to achieve a bonding only by placing the surfaces near each other, and with the peel stresses acting to separate the two adherends. Second the sawtooth profile beneficial aspects, which are the wider bonding area and the gripping due to the profile, are compensated by the higher stress concentrations caused by the corners. Third, both the low and high sawtooth profiles works at the macroscale and thus they are not capable to promoting any surface improvements as the micro or nano-pattering, as already demonstrated by other researchers.[35,36]

Conclusion

This paper shows the beneficial effect of combining the additive manufacturing techniques, such as fused deposition molding, and structural adhesives, to obtain strong and reliable bonded structures. This procedure overcomes the limitation in volume typical of the 3D printing techniques and also exploits the free form shape to increase the bonding area of the joints. By means of an extended design of experiment experimental campaign, a wide set of single lap joints combinations was tested, considering two adhesives, a rigid 2 K epoxy resin and a more flexible hybrid adhesive, and four different surface morphologies, a flat bonding area and three different sawtooth profile with different orientation and tooth height. The experimental results highlight that the adhesive bonding does not undermine the load carrying capacity, and in some cases it improves the performance compared with the same geometry in a single component with the base material. Moreover, the stiffness of the joints is not affected by the bonding typology. The experimental results do not highlight a high contribution of the morphology of the joint, since the mechanical interlocking does not occur due to the peel stresses in the adhesive which prevents another possible interesting feature obtainable with the additive manufacturing technique. In the future works we will investigate other more complex shapes of the bonded area which could increase both the performance of the joints and extend additive manufacturing range of applications.

Declaration of Conflicting Interests

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