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Abstract. The joint between different lightweight materials plays a significant role in multi-material design of structural components for the automotive industry, aiming to reduce the vehicle's weight without compromising performance or safety. Yet, conventional mechanical joining technologies between metals and Carbon Fibre Reinforced Polymers (CFRP) result in either a hole being drilled in the composite material, leading to damages which reduce the load bearing capacity, or the weight of the part being increased due to the incorporation of fasteners. At the same time, alternative mechanical joining methodologies involve complex and costly processing, hindering their industrial application. This work presents a new, simple, cost-efficient and non-weight penalizing mechanical joining technology between a metal sheet and fibre reinforced polymer prepregs consisting of a single-step punching process. In this process, the metallic sheet is completely perforated, while the prepreg is not. The punch pushes the carbon fibres through the metallic hole, with no, or minimal fibre breakage, generating a mechanical interlock. The shear strength and the absorbed energy of the co-cured joint increase with the incorporation of the mechanical interlocking joint.

1. Introduction

Nowadays, concern over fuel consumption and pollutant emissions is driving transport industry efforts towards vehicles weight reduction, powering a trend known as lightweighting. Such weight decrease is a key factor to lower CO_2 emissions in fuel powered vehicles and to increase the driving range in electric ones. An interesting strategy to achieve such weight decrease is Multi-Material Design (MMD) of structural components, consisting of combining materials with high specific properties such as advanced high strength steels, aluminium alloys, or Fibre Reinforced Polymers (FRP). MMD seeks to meet the mechanical and safety requirements at affordable costs and high production volumes.

Considering this, the joint between these dissimilar materials is usually the weakest point of the structure and it determines its structural efficiency. Traditional joining strategies for metal-FRP multi-material structures include mechanical fastening, adhesive bonding, hybrid mechanical-adhesive bonding and welding [1].

Mechanical fastening strategies consist of generating a mechanical interlock between two materials, with their main advantages being low cost, simply processing, easy maintenance and non-sensitivity to the working environment [2]. Conventional mechanical joining strategies for metals and CFRP include bolted joining [3], Self-Piercing Rivets (SPR) [4] and mechanical clinching [5]. However, these conventional methodologies either increase the weight of the structure due to fasteners employment or require to drill a hole in the composite, which can cause damage such as delamination or fibre breakage, thus reducing the load bearing capacity of the structure [6].

Modifications to such conventional mechanical joining strategies have also been proposed. Some examples are the incorporation of bonded metallic inserts in the composite to reduce the stress concentration factors at the hole in the composite [7] or steering the fibres onto the tacky prepreg to match the load path to improve the stiffness and strength of the bolted joint [8]. A post-curing SPR method to join CFRP and aluminium alloy sheets has also been proposed to reduce the damage generated in the composite material [4]. Conventional clinching has also been adapted to extend its suitability to materials with low ductility, as CFRP are. For instance, using a spring die [9], Friction Assisted Clinching [10], or softening the polymeric matrix in thermoplastic composites to increase composite toughness and formability [11].

Alternative mechanical joining procedures have also been developed in order to overcome the previous drawbacks, such as pin joints [12] or loop joints [13] among other joining methodologies.

However, all these methods imply extra process steps or high complexity, which hampers their implementation in high volume production industries [14]. Aimed at boosting the deployment of MMD in the automotive industry, this work presents a straightforward, cost-efficient, non-weight penalizing mechanical joining technology for metal and FRP based on a single-step punching process of the metal sheet and the uncured prepreg. Such technology can be easily implemented in automotive production lines, where punching operations are commonly used. It does not increase the weight of the part with the addition of fasteners, on the contrary, it removes part of the metallic material, making the part even lighter. In addition, the hole created in the metallic material relives stress concentrations more efficiently than the composite due to its plasticity [15]. Therefore, damage on the composite is minimized without adding weight to the structure or complexity to the joining process. Moreover, the joint does not generate any protrusion, making it suitable for completely flat applications.

2. Materials and methods

2.1. Materials

Rolled sheets of 1.5-mm-thick AA5754 H111 aluminium alloy were used in this work. The high formability and corrosion resistance of this alloy makes it one of the most common non heat treatable aluminium alloy used in automotive industry to produce medium strength parts. Aluminium sheets were waterjet cut perpendicular to the rolling direction and joined with CFRP sheets of 0.65 mm thickness, which consisted of one layer of a Twill 2x2 prepreg of 650 g/m^2 with the MTC275 toughened epoxy resin.

2.2. Microstructural and mechanical characterization of the joint

The cross-section of the generated joint was inspected through stereomicroscopy using an Olympus SZX10.

The mechanical performance of the joint was evaluated with the Single Lap Shear (SLS) test performed at room temperature using a universal testing machine at constant crosshead speed of 1mm/min. Specimen geometry and dimensions were the ones depicted in Figure 1. A discontinuity is present in each one of the substrates, equidistant from the specimen centre and in opposite directions for each substrate, so that the area between both discontinuities is the area of the joint which is being tested. The maximum shear load, shear strength and absorbed energy were evaluated from the load-displacement curves.

The used SLS configuration introduces peeling (mode I) and non-linear geometric effects due to the slight curvature of the specimens, which is caused by the difference on the Coefficient of Thermal Expansion between aluminium and the carbon fibres. However, this mode-mixity was considered to be representative of industrial applications and no effort was devoted to avoiding it.

Two different types of specimens, with five specimens per each type, were manufactured to analyse the mechanical performance of the joint (Table 1). Co-cured specimens (CO) were used as reference specimens, and they were prepared with no mechanical interlock with the aim to characterize the joint strength given by the adhesion of the epoxy resin on the aluminium substrate when co-curing.

Mechanically interlocked (MI) specimens were prepared with the mechanical joining procedure developed in this work.

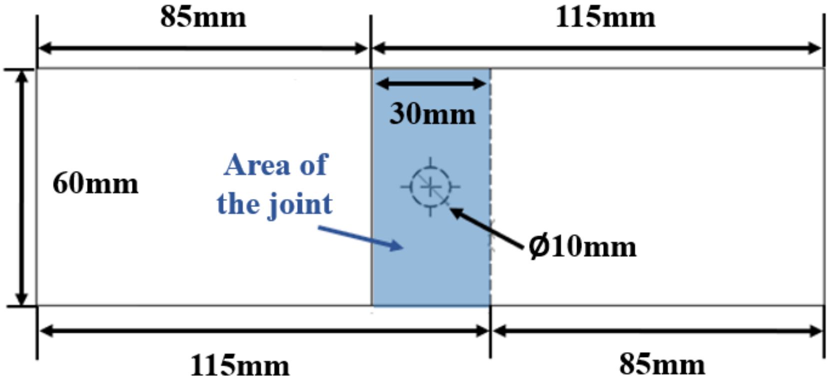

Figure 1. Dimensioned drawing of Single Lap Shear specimens.

Table 1. Types of specimens and process parameters.

	Punched materials	d_d (mm)	Clearance (%)	Stroke (mm)
Co-cured specimens (CO)	None	-	-	-
Mechanically interlocked (MI)	Al+CFRP	11.7	38	2.3

3. Developed joining procedure

The mechanical joining procedure consists of laying up uncured CFRP prepreg layers on top of an aluminium sheet and punching the whole system with the CFRP facing the punch side of the set-up. The aluminium surface was cleaned with acetone using a wipe cloth to remove any surface contamination before adding the prepreg. To avoid the prepreg from sticking to the punch, a silicon paper was placed between the uncured CFRP prepreg and the punch.

By adjusting the cutting clearance and the punch stroke, the aluminium sheet is completely punched through while the carbon fibres are not (Figure 2). Instead, the carbon fibres are pressed against the hole walls in the aluminium, generating a mechanical interlock between both materials. As joining takes place in an uncured state, delamination of the CFRP does not occur when punching.

The mechanical joints were achieved mounting a punching tooling on a universal testing machine. The specimens were cured afterwards by thermoforming. Co-curing of the composite epoxy resin on the aluminium sheet takes place and therefore, adhesive bonding between both substrates is present apart from mechanical interlocking.

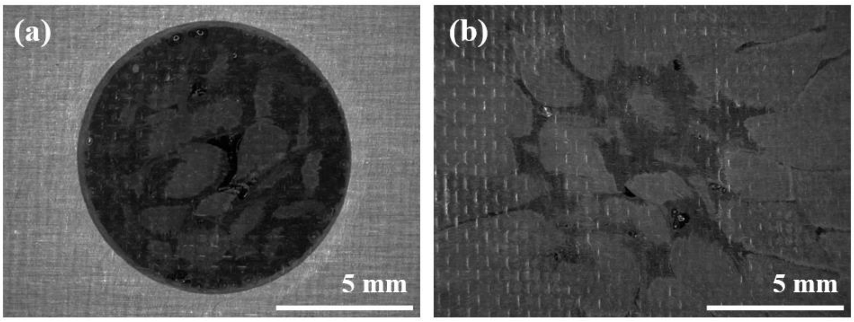

Figure 2. Mechanical interlocking joint (a) from the aluminium sheet side and (b) from the CFRP side.

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The cutting clearance, c equation (1), is defined as the ratio between the punch (d_p) and the die (d_d) diameters gap and the thickness of the punched material, t [16].

$$c = \frac{d_d - d_P}{2t} \cdot 100 \tag{1}$$

Typical clearance values in the sheet metal forming industry range from 5% to 20%, with 10% being the most common. However, higher cutting clearances have been used in this work to allow the carbon fibres to slide between the punch and the die without being completely cut. Another relevant punching parameter is the punch stroke (s), which is the penetration of the punch on the substrate being punched.

In the present work, the joints were performed at a constant punching speed of 10 mm/min. The punch diameter was 10 mm, as is commonly found in automotive body-in-white parts, and the fillet radius was 0 mm. Three die diameters were used for joint geometry characterization, 11.7 mm, 11.3 mm and 10.8 mm, which correspond to clearance values of 18%, 29% and 38%, respectively. Mechanical performance was evaluated for CO specimens and MI specimens performed with 11.7 mm die diameter (table 1).

During the punching process, load vs stroke curves were recorded (Figure 3). When punching a metallic sheet (Figure 3a), three different regimes were observed [17]. The first (A) corresponds to the deformation and strain hardening of the aluminium sheet. The second (B) corresponds to the cutting of the aluminium and the third (C) corresponds to the complete punching of the aluminium sheet.

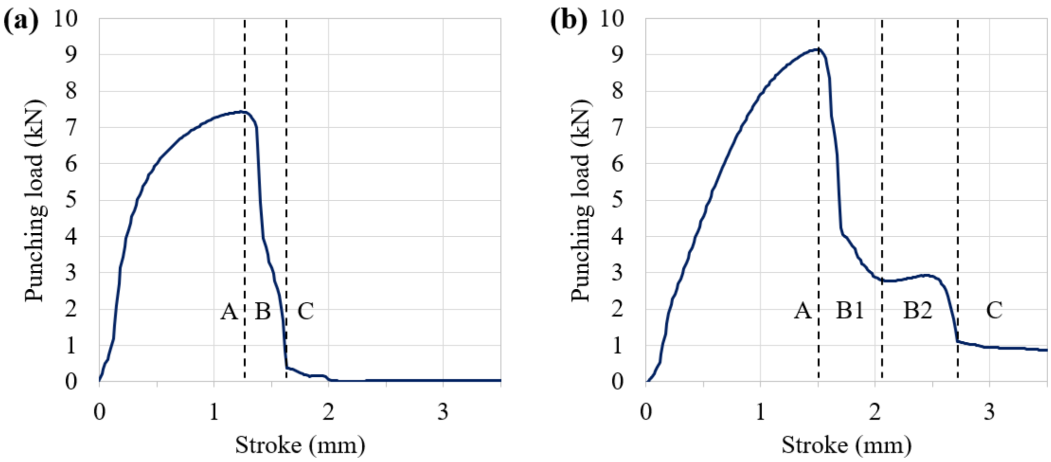

Figure 3. Load-stroke curves when punching with d_p =10 mm and d_d=11.7 mm (a) a 1.5-mm-thick aluminium sheet, and (b) a 1.5-mm-thick aluminium sheet with CFRP prepreg.

When punching a metallic sheet with a CFRP prepreg (Figure 3b), the same punching regimes are observed, but regime B is divided into two differentiated regions: B1 and B2. Region B1 corresponds to the cutting of the aluminium sheet. On the other hand, region B2 initiates with complete punching of the aluminium without fibre breakage and, as the punch stroke increases, carbon fibres progressively break until maximum fibre breakage is reached at end of regime B2.

Thus, the process parameters to completely punch the aluminium sheet while avoiding or minimizing the cutting of the carbon fibres were selected for this study. Such conditions fall into regime B2 of the punching load vs stroke curve and are the ones which allow the generation of the developed joint (Figure 3b).

4. Results

The cross-section of the joints was inspected with stereomicroscopy (Figure 4). The carbon fibres were pressed against the roll-over depth of the aluminium cut edge, while the area of the hole in contact with the fracture depth was resin rich. The carbon fibres filled the rest of the aluminium hole.

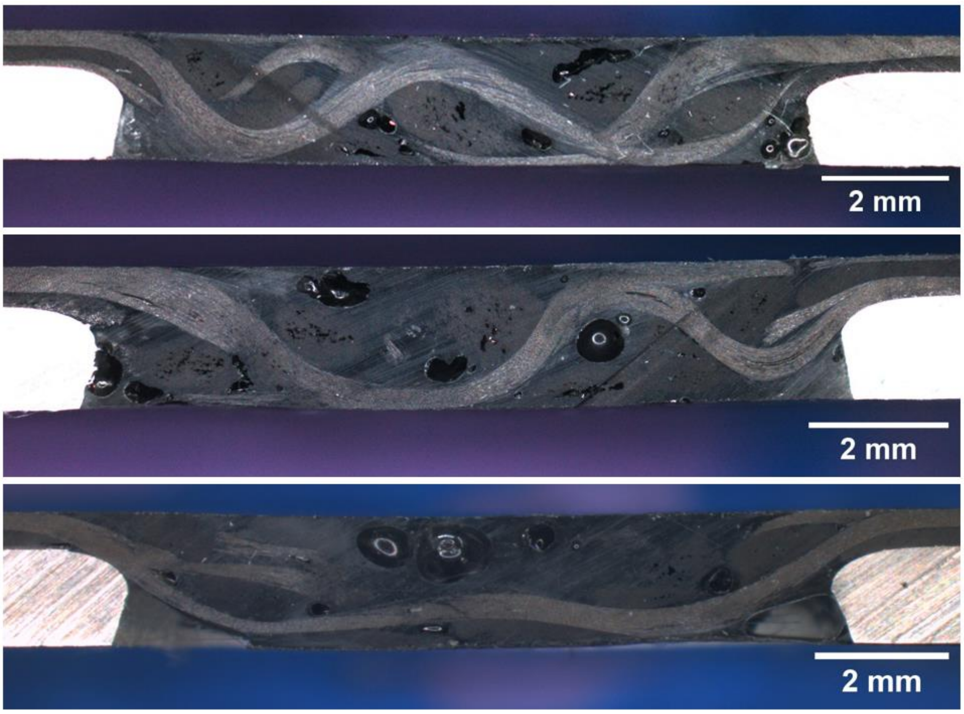

Figure 4. Cross-sections of the developed joint.

The cross-sections of punched aluminium sheets and MI specimens were also inspected (Figure 5). The morphology of the Al sheet cut edge was modified with the incorporation of the CFRP prepreg in the punching process. Punched aluminium sheets without CFRP present four different regions at the cut edge: roll-over depth, smooth-sheared depth, fracture depth and burr (Figure 5). On the other hand, when incorporating the carbon fibre prepreg in the punching step (MI specimens), the burr and the smooth-sheared depth disappear. Therefore, only the roll-over depth and fracture depth are present in the cut edge, regardless of the clearance.

Load-displacement curves obtained for the SLS tests of CO and MI specimens are shown in Figure 6. Average shear strength and absorbed energy are plotted in Figure 7a and Figure 7b, respectively.

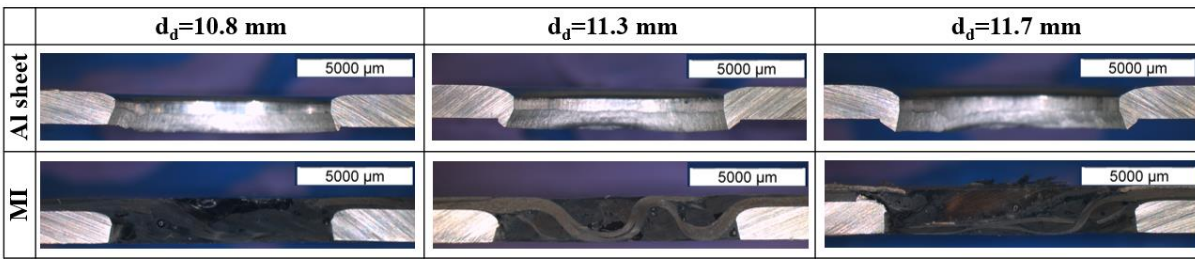

Figure 5. Cross-section of aluminium sheets and MI specimens generated with different die diameters.

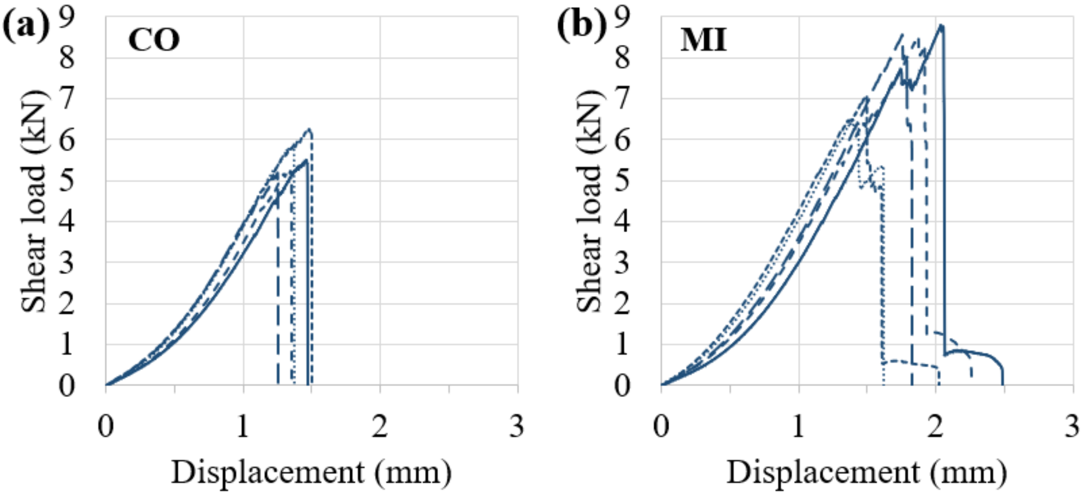

Figure 6. Load-displacement curves obtained in the SLS test for (a) co-cured samples (CO) and (b) MI specimens.

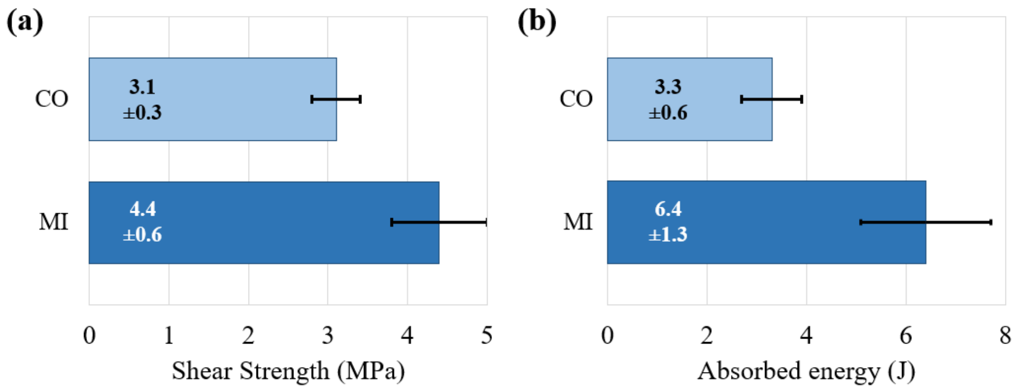

Figure 7. SLS average results with standard deviation regarding (a) shear strength and (b) absorbed energy.

CO specimens showed adhesive failure between the CFRP and the aluminium substrate (Figure 8a). On the other hand, MI specimens failed by complete pull-out or unbuttoning of the CFRP bulge from the aluminium hole (Figure 8b). Catastrophic failure occurred for CO specimens, whereas a more progressive failure was observed for the MI specimens, with several small drops before the load peak and a non-zero load queue after the main load drop (Figure 6b).

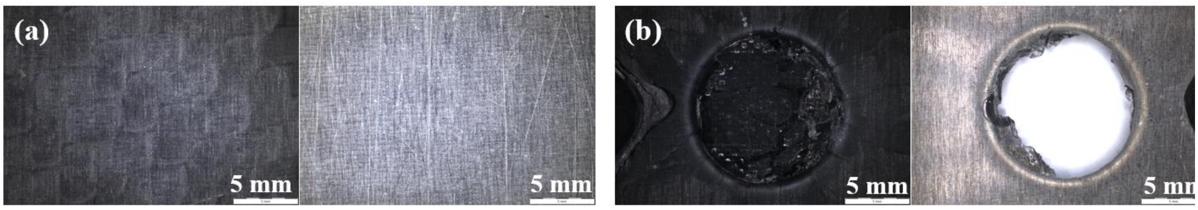

Figure 8. Joint region of SLS specimens after failure (a) CO specimens and (b) MI specimens.

5. Discussion

The present work describes a new type of joining methodology which is not intuitive, since the aluminium sheet, which is in contact with the die, can be punched without completely cutting the carbon fibres, which are in contact with the punch. This is possible because the punch penetrates the material slightly before the actual cutting, and compresses the aluminium surface near the punch inducing strain hardening on the material. Therefore, the resistance of the material to penetration rises and material fracture does not start on the edge close to the punch, but rather occurs on the soft area close to the die, which is not hardened [18].

As the punching is performed with the uncured prepreg, the polymeric resin is in a viscous flow state, and therefore delamination and CFRP tear around the joining area are reduced. When curing, the epoxy resin flows inside the aluminium hole and fills it up. Consequently, there is a resin-rich region near the fracture depth of the aluminium cut edge (Figure 4) and the fibres are less compacted inside the aluminium hole than on the rest of the specimen.

Regarding the process window, the punch strokes that allow the generation of the joint are those that fall within punching regime B2, where the aluminium is completely punched, but the CFRP is not.

When punching an aluminium sheet together with a CFRP prepreg (MI specimens), the cut edge geometry is changed with respect to when only punching aluminium sheets. The smooth-sheared depth and the burr vanish due to the presence of the carbon fibres (Figure 5), which fill the gap between the punch and the die during the punching process, reducing the effective clearance and leaving no free space for burr formation. In addition, burnishing does not take place and, therefore, the smooth-sheared depth cannot be formed.

With respect to the mechanical properties MI specimens increased the mechanical performance of the co-cured CO joints in terms of shear strength and absorbed energy. When punching the specimen to generate the mechanical interlock, the punch pushes the carbon fibres all the way down through the aluminium hole. Because of this, failure of the specimen is delayed with respect to CO specimens, thus higher shear strength and absorbed energy are obtained. In addition, MI specimens fail by CFRP bulge unbuttoning (Figure 8b), leading to a less catastrophic failure, which also contributes to the increase of the absorbed energy at failure. Another contribution to the higher mechanical properties of these specimens can be the strain hardening caused in the hole surroundings, which is due to the aluminium compression caused by the tension introduced into the carbon fibres when punching.

The mechanical behaviour of the developed joint was compared to other similar joining methodologies between composites and sheet metals found in the open literature (Figure 9) [9], [19]–[25]. Mechanical clinching and its variations give maximum shear loads ranging from 0.8 to 5.3 MPa when joining aluminium and CFRP [11]. The highest shear loads were found for hole clinching. However, this process requires to drill a hole in the composite material and then align this hole with the clinching device to generate the joint. Mechanical clinching of thermoplastic composites, where there is also adhesive bonding in addition to mechanical interlocking, show maximum shear loads ranging from 0.8 MPa to 3.9 MPa [11]. Therefore, considering the maximum joint force of 4.4 MPa, and an improvement of 1.3 MPa with respect to adhesive bonding resulting from the co-curing of the CFRP with the aluminium, the joint procedure presented in this work can be postulated as an interesting alternative to join dissimilar materials in engineering applications.

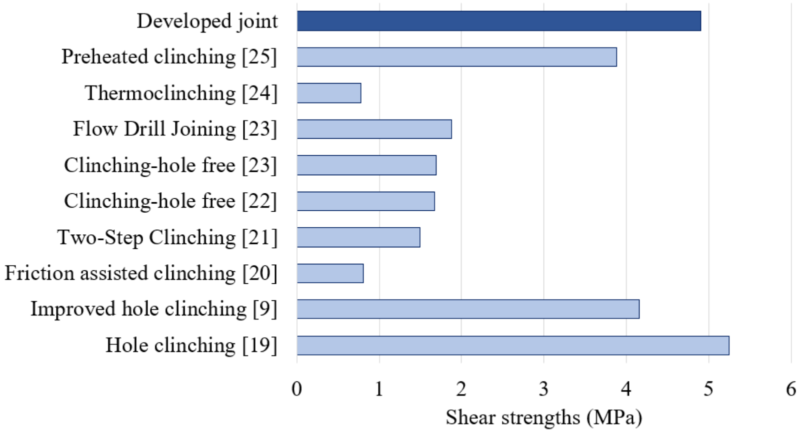

Figure 9. Shear strengths calculated from maximum shear loads and the joint area for different clinching technologies [9], [19]–[25].

6. Conclusions

A new mechanical joining methodology for a metal sheet and FRP based on a single-step punching process was developed in this work. Such technology is new, simple, cost-efficient and does not penalize in the weight of the part. In addition, it avoids damage in the composite material and does not add complexity to the joining process.

The resulting mechanical interlocking joint improved the shear strength of the co-cured joint in a 41% and the absorbed energy a 94% with respect the co-cured joint for the studied materials.

Moreover, the mechanical performance of the joint was found to be within the same range as other mechanical metal-composite joining methodologies such as clinching, indicating its potential to be used to join dissimilar materials in practical applications.

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