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Fast joining of aluminum sheets with Glass Fiber Reinforced Polymer (GFRP) by mechanical clinching

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ABSTRACT

The suitability of mechanical clinching (press joining) to join fiber-reinforced plastics with aluminum sheets was investigated. To this end, different types of tools were tested, including split, grooved, flat dies, as well as rectangular ones. The influence of sheet thickness (thin sheets of 2 and 3 mm in thickness) and alloy composition (AA6082-T6 and AA5086) on joinability and mechanical behavior of the joints was analyzed. Single lap shear tests were conducted to characterize the joints, and fracture produced after joining and testing was performed. In addition, the geometry evolution of the joints during clinch joining was studied to understand the material flow and damage evolution of both aluminum and Glass Fiber Reinforced Polymer (GFRP) sheets. The study demonstrates the feasibility of the process, which has great potential for shortening the joining time dramatically as compared to conventional processes (riveting, adhesive bonding). According to the achieved results, round grooved tools are not suitable for this purpose since the formation of GFRP crumbles, which fills the die cavity, thus requiring a long restoration time. On the other hand, the other types of tool enabled joining aluminum with the GFRP sheets successfully. Such joints fractured in the aluminum bulge or in the GFRP sheet by bearing failure; in both the cases, the failure modes developed progressively rather catastrophically. The best performance was achieved by the joints produced by the split die. Such joints were also characterized by limited composite damage in the joint's neighbors, since the damaged composite material was separated from the joint.

1. Introduction

The adoption of multi-material assemblies represents a key solution for reducing weight and fuel consumption, and improving vehicle performances. Lightweight design concepts exploit the characteristics of different materials characterized by different physical and mechanical behavior. For example, metals exhibit good mechanical properties (ductility, strength, isotropic behavior), enables high production flexibility and easiness of automation. Thus, they are particularly suitable for complex components, which are subjected to three-dimensional stress states. On the other hand, Fiber-Reinforced Polymers (FRP) are lightweight materials with high specific stiffness, giving the possibility of designing the material by arranging the fibers in a given direction, in order to enhance the mechanical behavior of the component in that direction. Nevertheless, the production of such materials is more time-consuming, less standardized, and requires extensive manual operations. The presence of multiple materials can potentially improve the mechanical and thermal behavior of the assembly, reduce the weight and the production costs, as well as the fuel demands of automotive vehicles and aircraft. However, the presence of different materials implies specific requirements in terms of joining processes, owing to the difference in the mechanical, physical, and thermal behavior of metals, polymers, and Fiber-Reinforced Plastics (FRP).

Welding processes, with few exceptions, e.g. laser joining (Farazila et al., 2012), are generally not suitable for connecting metal to FRP sheets, because of chemical incompatibility, thermo-physical differences, e.g., melting, coefficient of thermal expansion, thermal diffusivity. Thus, hybrid FRP-metal joints are generally produced by adhesive bonding (Bouchikhi et al., 2013), or mechanical joining processes involving rivets or bolts (Girão Coelho and Mottram, 2015). Owing to the long curing time and surface preparation of both the metal (elimination of grease, oil, oxide layer) and the FRP parts, adhesive bonding is affected by a long processing time as well as having high environmental impact (due to the employment of solvents, etc.). In addition, the strength of the bonded joints is affected by aging, environmental, either thermal

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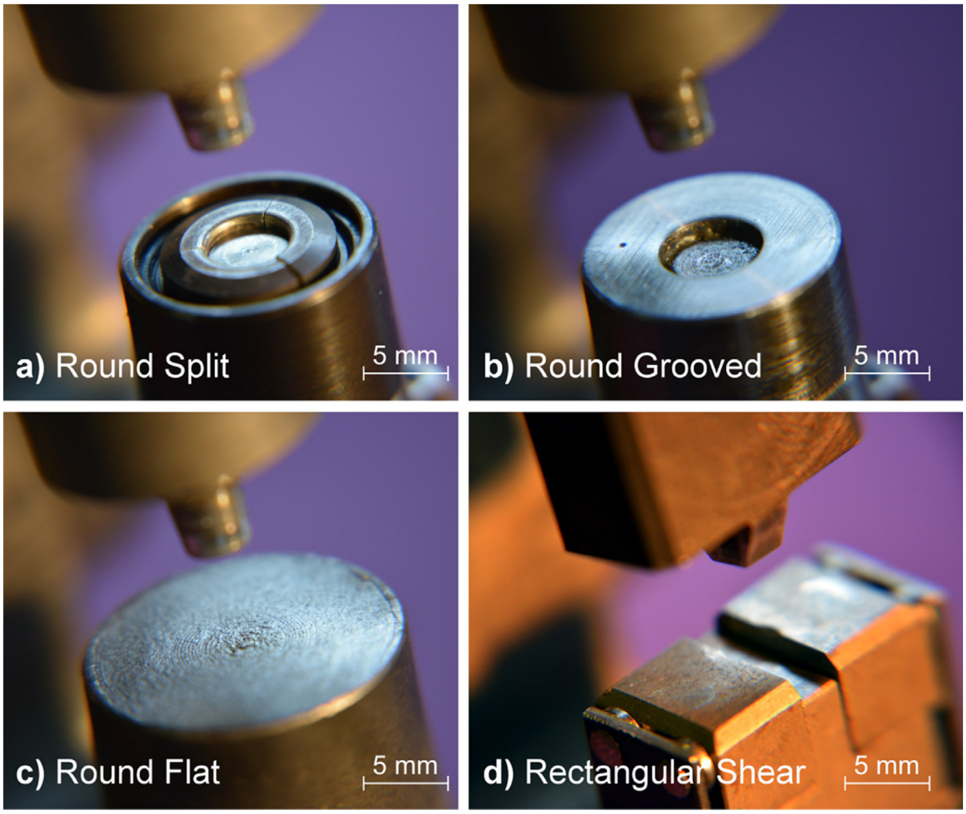

Fig. 1. Macrograph of clinching tools: (a) round split; (b) round grooved; (c) round flat; and (d) rectangular.

agents. On the other hand, mechanical joining processes generally involve spot fasteners, such as screws or rivets, which lead to a stress concentration around the joint, and produce undesired interruption in the fibers, which affects the mechanical behavior of the FRP. Although such interruption can be avoided, e.g. by a mold-in technique (Durante and Langella, 2009), a predrilled hole in the metal part is still required.

Fast mechanical joining methods such as Self-Pierce Riveting (SPR) and Mechanical Clinching (MC) have been employed to join a wide variety of materials, in order to substitute spot joining, riveted and bolted joints. Actually, both these processes do not require predrilled holes, thus reducing the overall joining time significantly. MC offers additional advantages since the absence of external fasteners that leads to reduction of the assembly weight other than cost reduction, reduced joining forces and comparable fatigue strength (Mori et al., 2012). However, the main limitation of clinching lies in the high strain developing during joining; thus, the materials being joined should show a certain ductility (Lambiase et al., 2015). Fractured regions should be avoided in clinched joints since they reduce the static and dynamic mechanical properties of the joints. To this end, a number of works have been conducted to predict the fracture onset by numerical investigations. A kriging metamodel was proposed in (Roux and Bouchard, 2013) to optimize the design of clinching tools and maximize the mechanical behavior of clinched joints. A numerical model involving a damage criterion was introduced in (Zhao et al., 2014) in order to predict the mechanical behavior of clinched joints during single lap shear tests. The influence of the clinching tools on the stress developing during clinch joining of aluminum with low ductility was investigated in (Lambiase and Di Ilio, 2016) to prevent fractures in clinched joints.

Owing to the great advantages of the process, clinch joining has been extended to a variety of materials other than steel and aluminum alloys. The mechanical performances of clinched and SPR joints produced on copper alloy H62 sheets were compared in Xing et al. (Xing et al., 2015). Flat clinching with pre-heating was employed in (Neugebauer et al., 2008) to join magnesium sheets. In the recent years, a number of researches have dealt with clinching of non-metallic sheets. The suitability of mechanical clinching used to join aluminum with wood and polymer materials using a flat die was proved (Lüder et al., 2014). Sound processing window (varying the geometry of the tools and the duration of preheating) to join polystyrene (PS) with aluminum AA5053 was identified in (Lambiase and Di Ilio, 2015). Then, the joinability while clinching different thermoplastics, including polystyrene (PS), polymethylmethacrylate (PMMA), and polycarbonate (PC) with aluminum AA6082 sheets was compared in (Lambiase, 2015a). Numerical simulation of clinching of short fiber reinforced thermoplastic coupled with aluminum sheets was performed in (Behrens et al., 2014a). However, accurate material characterization is required for development of a reliable FE model of clinching of such materials (Behrens et al., 2014b). Hole clinching (Lee et al., 2014b) was developed to join aluminum alloys to Carbon Fiber-Reinforced Plastics (CFRP). In a subsequent study, some of the problems concerning hole clinching were pointed out (Lee et al., 2014a). Indeed, despite the feasibility of the process, two limitations were found: i.e. the presence of a predrilled hole on the CFRP; and problems concerning the coaxially of the CFRP hole and the punch during the clinch-joining, which can affect the geometry and mechanical behavior of the joint.

In the present investigation, different clinching tools, commonly used for joining metals, were adopted to join aluminum sheets with Glass Fiber Reinforced Plastic sheets by mechanical clinching, using round (including grooved dies, split dies, and flat die) and a rectangular tools. Since clinching is limited by the materials' toughness,

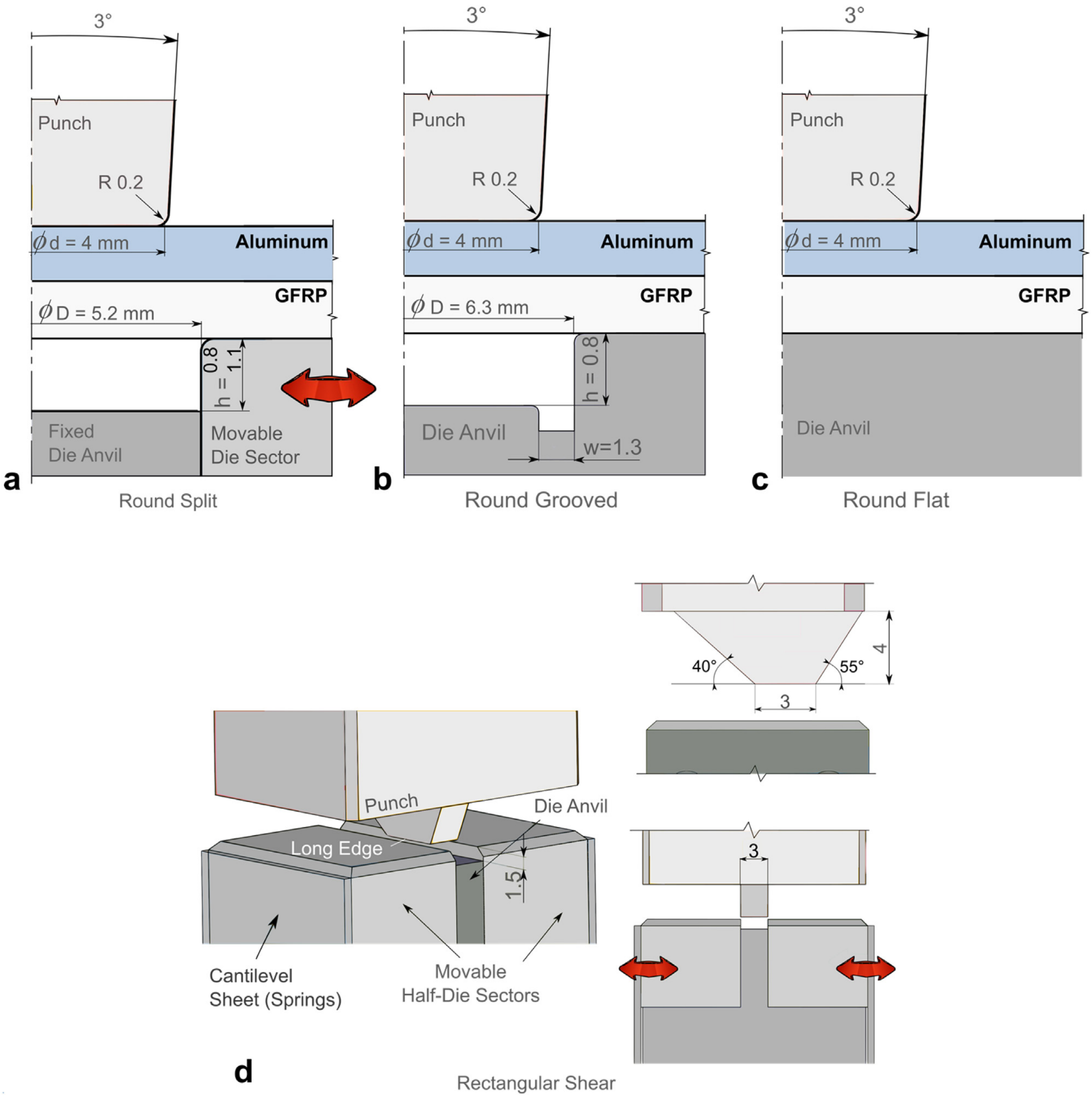

Fig. 2. Schematic of clinching tools: (a) round split; (b) round split; and (c) round grooved and (d) rectangular.

Table 1
Mechanical behavior of involved materials as determined by means of tensile tests.

Material	AA6082-T6	AA5086	GFRP	AISI304
Yield Strength, $\sigma_{0.2}$ [MPa]	172	92		255
Tensile Strength [MPa]	340	211	299	535
Flow Stress [MPa]	$\sigma_p = 467\varepsilon^{0.098}$	$\sigma_p = 414\varepsilon^{0.27}$		$\sigma_p = 1551(\varepsilon+0.078)^{0.63}$
Elongation at Break [%]	11	15	2.4	65

as well as the relative flow stress of the punch-sided and die-sided sheet materials, different types of aluminum alloys and thicknesses were studied. The composite panels were manufactured by means of a resin infusion under flexible tool (RIFT) technique, characterized by low cost and the possibility of manufacturing an element of high dimension, because high quality and nonautoclave-based composite fabrication technologies have encouraged their greater and more competitive use in recent years. For each configuration, the joinability window, main characteristic dimensions, and damage on GFRP, were investigated. In addition, single-lap shear tests were performed to compare the mechanical behavior of the performed joints.

Table 2
Joinability table of different metal materials and thicknesses using different dies (blue shows unsuccessful conditions).

Metal	Thickness, s [mm]	Flat Die	Split Die		Rectangular
			h = 0.8 mm	h = 1.1 mm	
AA6082-T6	2.0				
AA5086	2.0				
AA5086	3.0				

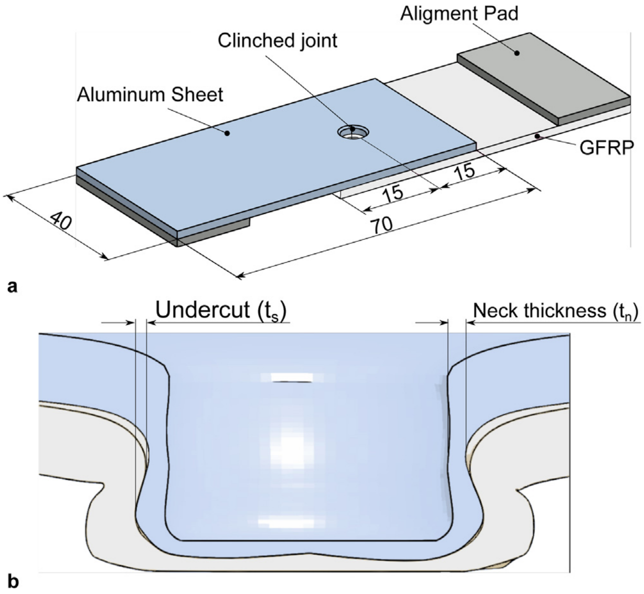

Fig. 3. Schematic of (a) single lap shear specimen (all dimensions are given in millimeters) and (b) geometrical characteristics of a clinched joint.

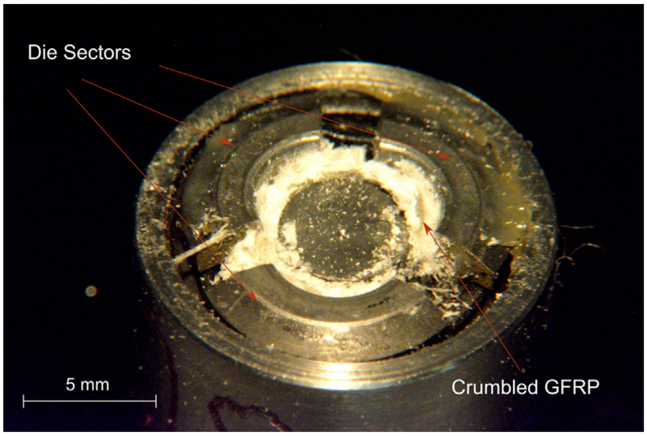

Fig. 4. Presence of crumbles within die sectors interstices when using split die.

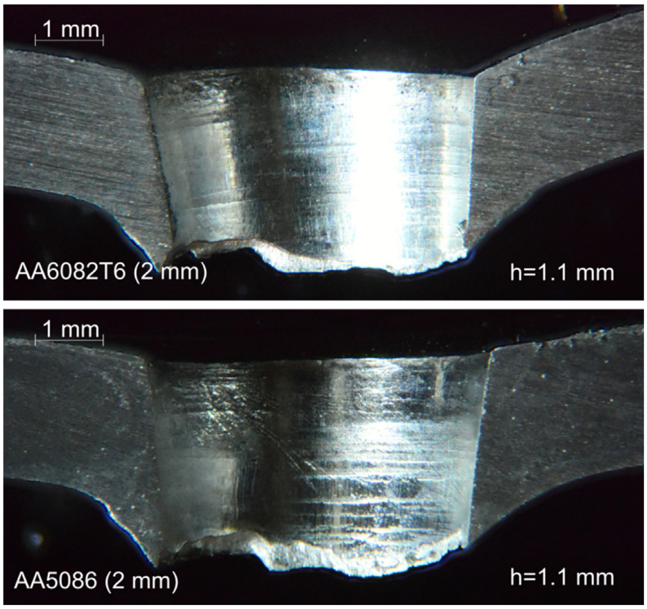

Fig. 6. Effect of material type on clinched joint profile (split die): (a) AA6082T6, s = 2 mm and (b) AA5086, s = 2 mm.

2. Materials and experimental setup

Clinched joints were realized on two types of aluminum alloys: AA6082-T6 and AA5086. The first is a high strength alloy with reduced elongation at a break, while the second is characterized by higher formability and lower yield strength. Two values of thickness (s) were adopted for AA5086, s = 2.0 and s = 3.0 mm, while only s = 2.0 mm was tested for the AA6082-T6 alloy. Tensile tests (conducted according to ASTM E08 standards for sheet type specimens) were performed to evaluate the main mechanical behavior of the AA5086 sheet, while the mechanical behavior of AA6082-T6 was determined in a previous work (Lambiase et al., 2015). A glass fiber woven fabric of 400 g/m^2 and SX10 epoxy resin system, of low viscosity and low toxicity, provided by MATES was used to manufacture composite laminates by resin infusion under flexible tool (RIFT). In the RIFT process the impregnation of a preform, constituting reinforcement layers with a thermosetting resin, is obtained by use of vacuum and a close mold, comprising a rigid part and a flexible tool. This tool, generally a polymeric bag, enables the production of complex and large components, thus reducing the manufacturing cost. Two laminates were produced by overlapping four layers of plain weave (fabric) with the fibers in the same direction (0–90) with dimensions of 300 × 300 mm^2 and 2 mm in thickness, with a volumetric percentage of reinforcement of about 40%. The direction of applied load in the tests was 0°.

A portable machine by Jurado (Perugia, Italy), Python model, with a maximum joining force of $F_j = 22$ kN, was used to join the sheets. When joining by clinching, it is preferable to place the

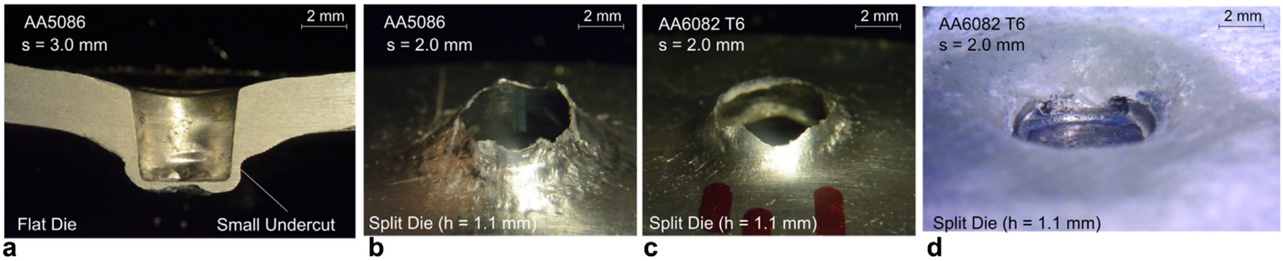

Fig. 5. Unsuccessful joining cases when joining GFRP by clinching: (a) small undercut; (b–c) fracture of aluminum bulge; and d) composite with fractured aluminum bulge.

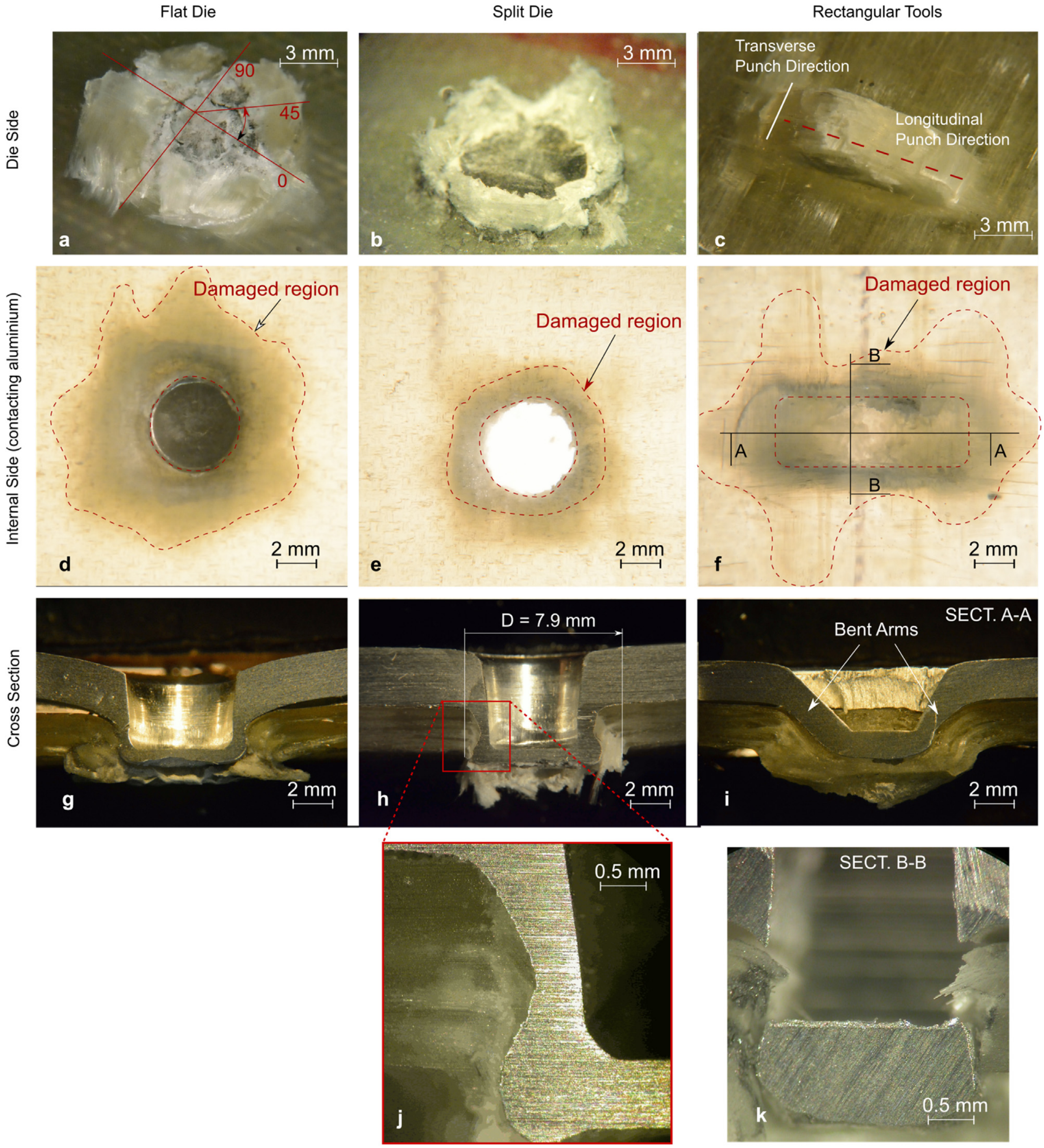

Fig. 7. Geometries, damaged regions, and cross-sections of clinched joints using different types of clinching tools.

higher-yield strength material (or the thicker sheet) on the punch-side. However, in preliminary tests, when the composite was placed on the punch-side, the GFRP sheared owing to its reduced formability. During clinching the punch-side sheet undergoes severe plastic deformation, thus, in subsequent tests, the aluminum sheet was placed on the punch-side, while the GFRP was placed on the die side.

Different clinching tools were employed in the experiments, including flat, round grooved, split (extensible), and rectangular shear dies, as shown in Fig. 1. The schematic representation and main dimensions of the clinching tools are reported in Fig. 2.

The mechanical behavior of clinched joints was studied by conducting single-lap shear tests performed on a universal testing machine by MTS model 322.31, at a constant velocity of 1 mm/min. The schematic of single lap shear specimen with main dimensions is depicted in Fig. 3a.

For each testing condition, five repetitions were performed. The tests were carried out with the maximum available joining force, $F_j = 22$ kN, to maximize the undercut dimension, since the undercut increases with the joining force (Mucha, 2011a). Clinched joints strength is greatly influenced by some characteristics dimensions of the joint cross-sections; namely, neck thickness, and undercut, which have been schematically depicted in Fig. 3b. Thus, optical

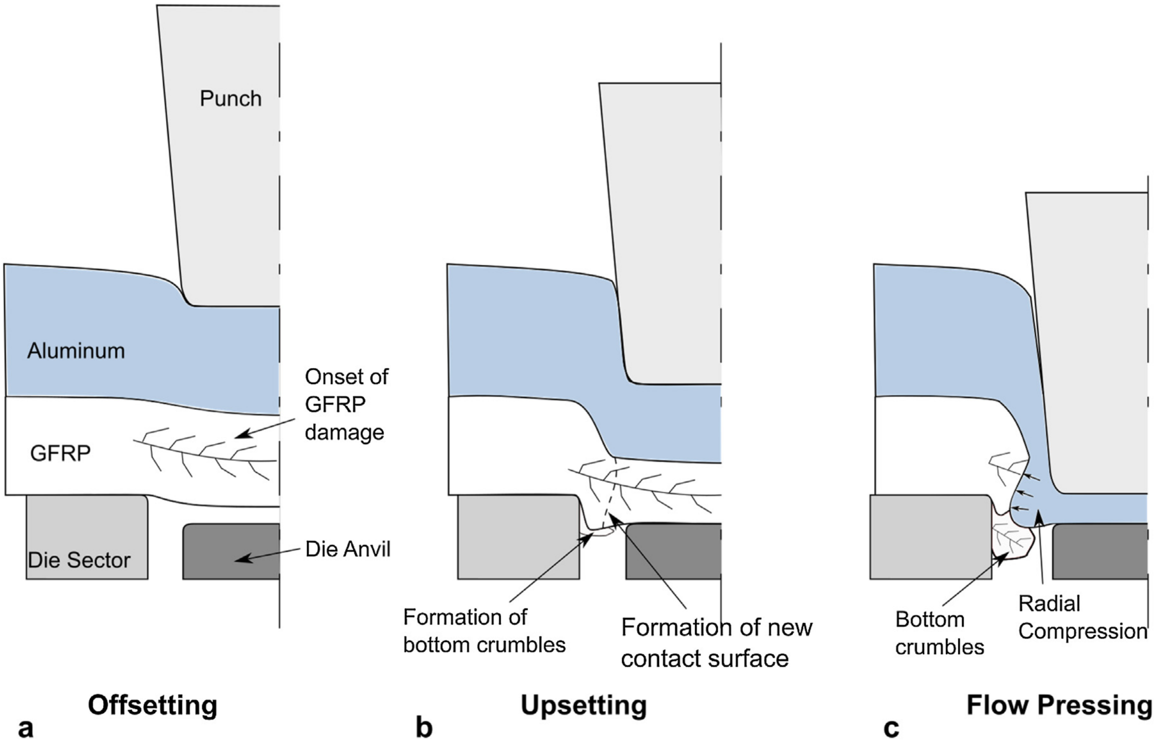

Fig. 8. Schematic representation of material flow during clinching with split die: (a) offsetting; (b) upsetting; and c) flow-pressing phase.

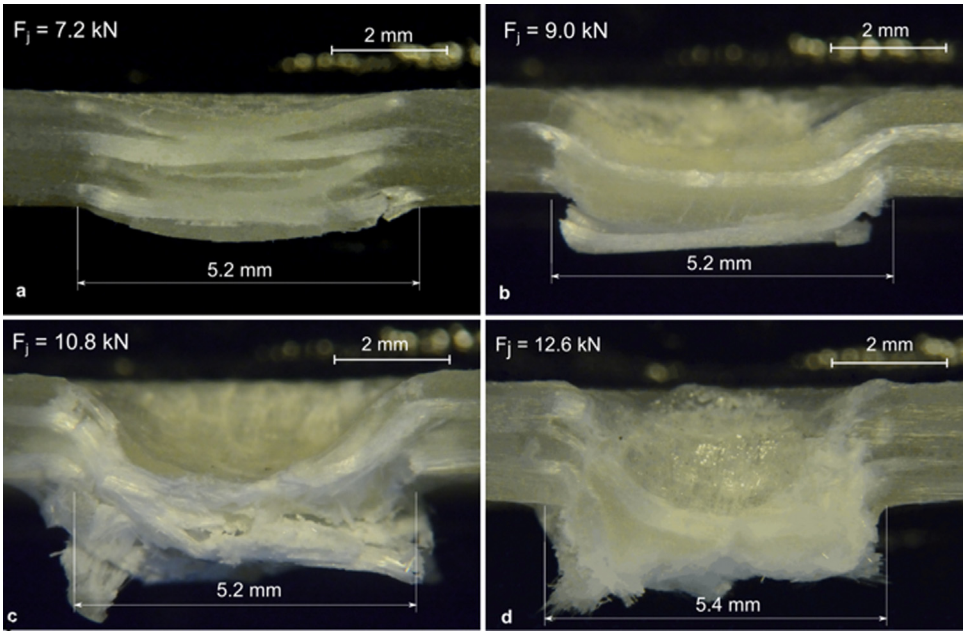

Fig. 9. Macrograph of GFRP flow produced with clinching using split die: a) F_j = 7.2 kN; b) F_j = 9.0 kN; c) F_j = 10.8 kN; and d) F_j = 12.6 kN. (AA5086, s = 3 mm).

microscopy was used to measure the abovementioned joint dimensions, as well as to evaluate the extension of the damaged area on both the aluminum and the composite sheets.

3. Results and discussion

3.1. Mechanical behavior of the sheets

The mechanical properties of the materials, determined by means of tensile stress, are summarized in Table 1. As can be observed, the AA6082-T6 alloy is characterized by higher yield strength and flow stress, and lower elongation at the break, as compared to the AA5086.

3.2. Preliminary problems when using fixed and extensible dies

Preliminary experiments were carried out to assess the suitability of the clinching tools for joining aluminum and GFRP sheets. Since clinching involves great strain in the joining area, materials with fragile behavior may be damaged, or even show large frac-

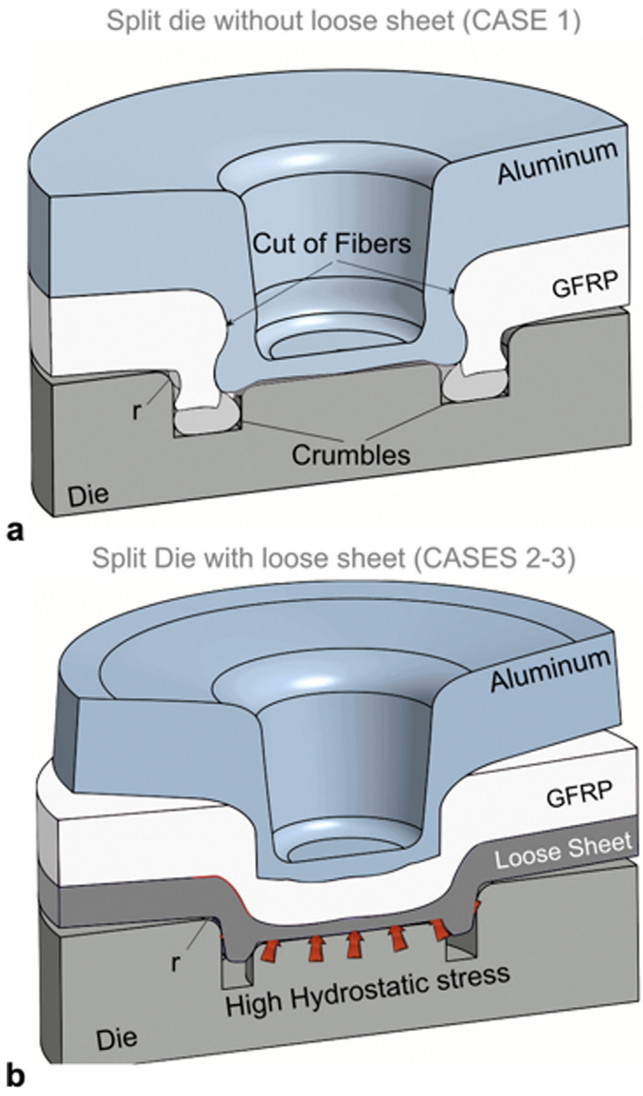

Fig. 10. Schematic representation of material flow and stress developing during clinching using: (a) split die without loose sheet; and (b) split die with lose sheet.

tured regions (Lambiase, 2015a). During the experiments involving round grooved and split dies, part of the GFRP matrix fractured and was trapped within the die interstices, leading to crumbling of the GFRP, as shown in Fig. 4. When round grooved dies are employed, the removal of crumbles from the die is time-consuming and not compatible with production joining times. Therefore, grooved dies were excluded from further investigation. On the other hand, the radial sectors sliding in split dies facilitated the extraction of the crumbles, and consequently, the die restoration. To solve the problem concerning the entrapment of crumbles within the die sectors, the adoption of a loose sheet between the GFRP and the die was also investigated.

3.3. Joinability

Mechanical clinching develops in three main phases (Eshtayeh et al., 2015) namely, offsetting, upsetting, and flow-pressing. During the offsetting phase, the two sheets are drawn within the punch-die cavity volume, which becomes thinner. If the strength of the die-sided material is higher than that of the punch-sided sheet, a higher thinning effect arises on the punch-sided sheet. The formation of the undercut develops in the upsetting and flow-pressing phases, during which the material of the die-sided sheet restrains the material flow of the punch-sided sheet, limiting the undercut development. The material flow during these phases is still influenced by the tool's geometry, the sheet thickness, and the thinning effect during the offsetting phase and the material flow stress. When round split tools are used, the adoption of deeper dies involves a reduction in the hydrostatic stress during upsetting (since the reduced material flow), which leads to lower restricting action on the material flow (Lambiase and Di Ilio, 2014), and consequently, larger undercuts. In addition, joints characterized by deeper bulges undergo to lower bearing stress acting on the die-sided sheet (Lambiase, 2015b). Nevertheless, deeper dies involve higher thinning on the punch-sided sheet, which may also affect the mechanical behavior of the joints. Indeed, excessively deep dies may result in bulge fracture, as shown in Fig. 5b–c.

Thus, the optimal die anvil depth represents a trade-off between the dimension of the undercut and the neck thickness. The successful and unsuccessful joining conditions are summarized in Table 2. As can be observed, all three types of clinching tool enabled the production of sound AA6082/GFRP joints. Nevertheless, when the split die with the deepest anvil was used, a fracture in the aluminum bulge developed, owing to the limited formability of the material, as shown in Fig. 5c–d.

The joining tests performed on the AA5086 sheets of 2 mm of thickness revealed that all the round split tools failed to join this alloy, as a result of excessive thinning leading to a fracture in the aluminum neck, as depicted in Fig. 6. During the offsetting phase, the plastic strain is relatively small (leading to a limited strain hardening). Hence, a pronounced thinning develops on the AA5086 sheet until the development of a fracture around the punch corner.

Flat and rectangular clinching tools allowed the joining of both aluminum alloys to the GFRP, regardless of the material type and metal sheet thickness. However, flat dies can be regarded as round tools with anvil depth of $h = 0$ mm. In this case, the offsetting phase is negligible; thus, the neck thinning is reduced as compared to split dies with $h = 0.8$ mm and $h = 1.1$ mm. Nevertheless, a high thinning effect was observed on the AA5086 alloy with $s = 2.0$ mm, compared to the joint performed with a flat die on the higher strength aluminum alloy AA6082. Owing to the relative softness of AA5086, with respect to the die-sided material (GFRP) for low strain amounts, high thinning is experienced by the aluminum sheet neck. On the other hand, when rectangular tools were used, a fracture in the punch-sided sheet was induced intentionally in the longitudinal punch direction, and the "bent arms" sustain the external loads (Mucha, 2011b).

Increasing the thickness of the punch-sided sheet had beneficial effects on the joinability. When thicker aluminum sheets made of AA5086 alloy were used ($s = 3.0$ mm), all types of clinching tool enabled the production of sound hybrid aluminum/GFRP joints. As a matter of fact, when thicker aluminum sheets were used, the thinning effect produced during offsetting did not lead to the onset of cracks, since the higher material flow resulted in higher residual neck thickness.

3.4. Analysis of joints and material flow

The proper selection of process parameters and clinching tools is aimed at increasing the main quality criteria; namely, undercut and neck thickness. In addition, optimal process conditions should prevent any onset of cracks on the sheets or minimize the damage induced on the composite sheet. Fig. 7 shows the joints performed with different clinching tools i.e. flat, split and rectangular tools. The joints produced with rectangular tools showed a large undercut and neck thickness, and a confined damaged region, concentrated around the extremities of the "long edges". In this region, bending is predominant, leading to a large delaminated area, as depicted in Fig. 7f. On the other hand, in the central part of the joint, high shear

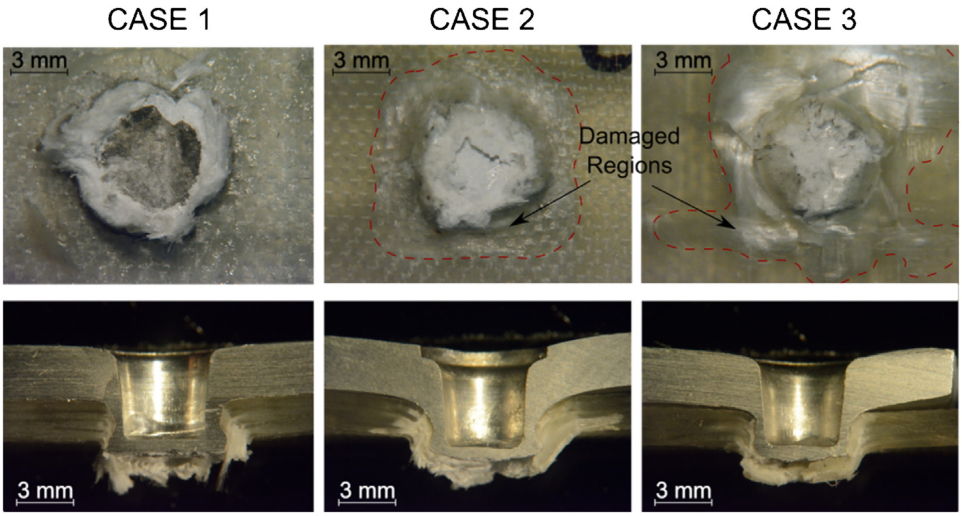

Fig. 11. Effect of material placed between GFRP and the split die: damaged areas and cross-sections (AA5086 s = 3.0 mm).

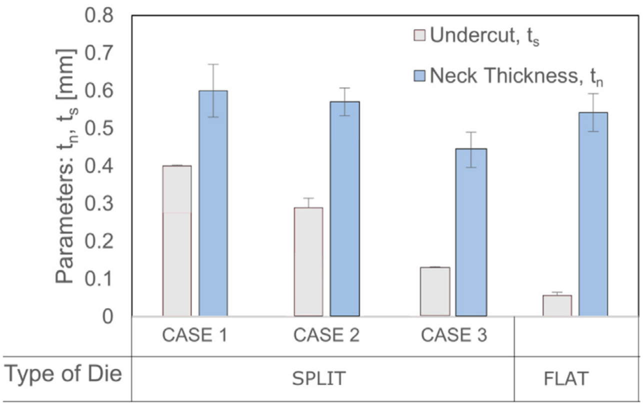

Fig. 12. Effect of material placed between GFRP and the split die: characteristic dimensions (AA5086 s = 3.0 mm).

stress developed, leading to a cut of the fibers (as shown in Fig. 7i and k), which prevented delamination in the surrounding material. Flat dies generally produced joints with relatively large neck thickness, but with small undercuts and a large damaged area surrounding the joint region. The flat die promoted high hydrostatic stresses during joining, which restrain the material flow, and consequently, the undercut dimension. The large neck thickness of such joints is due to the reduced offsetting phase. Nevertheless, as can be seen in Fig. 7d, a large damaged area surrounds the joint region. In the composite laminate, this area, due to initial hydrostatic stress resulting from the aluminum upsetting, and a successively compression stress in the radial direction, generated buckling with the removed material in a direction of 45° with respect to the fiber direction.

The joints produced with the split die show a larger undercut, a thinner neck, and confined damage of the GFRP. In such joints higher shear stress develops on the GFRP during joining, leading to cut-off fibers. As a result, lower hydrostatic stress state occurs during subsequent phases, leading to the formation of larger undercuts. In these joints, minor damage to the composite sheet is observable, since the cut of the fibers attenuates the delamination effect. Fig. 7j shows a higher magnification of the contact region between the aluminum and the GFRP. It is evident that the composite is perfectly sheared and free from fractures, along with some crumbled material compacted against the aluminum sheet. A schematic representation of the material flow produced with the split die is depicted in Fig. 8.

During the offsetting phase (also shown in Fig. 9a–c), the GFRP bends since it is pressed by the aluminum sheet. Such displacement comes with a wide damaged region, with delamination and fiber fracture, which produces an irregular bottom surface of the GFRP sheet. The beginning of clinch-joining ($F_j < 10.8$ kN) comes with a negligible displacement of the die sectors, as highlighted by the slight variation of the GFRP protrusion diameter. However, as the process proceeds (see Fig. 9d), the die sectors slide radially, leading to an increase in the shear stress acting on the regions surrounding the GFRP protrusion. A fracture develops within the GFRP sheet surrounding the aluminum bulge leading to the formation of a hole. As the fracture propagates, any further bending is produced in the GFRP material surrounding the developing joint preventing from further GFRP delamination. Then, the aluminum spreads radially and pushes the fractured peripheral regions of the GFRP within the die interstices. Finally, during the flow-pressing phase, the aluminum sheet is pushed against the inner surface of the GFRP hole, which becomes highly compressed.

To better understand such behavior, the material flow produced with the split die was investigated more in depth by varying the joining force as shown in Fig. 9. Initially the GFRP delaminates due to the bending stress, and then the fibers are cut since the increase in the shear stress. The displacement of the die sector is very small, which confirms the hypothesis that the flow of aluminum sheet eliminates the damaged material crumbles, and compacts the surface of the hole in the GFRP.

3.4.1. *Influence of loose sheet between composite and split die*

In order to prevent the entrapment of composite material within the die interstices, different configurations were tested, involving the presence of a loose sheet between the GFRP sheet and the die, as schematized in Fig. 10. Fig. 11 shows the macrographs of the GFRP sheet and the cross-sections of joints performed without the loose sheet (CASE 1), an aluminum alloy AA5086 sheet with thickness of 1.0 mm (CASE 2), and a sheet of AISI304 stainless steel with thickness of 0.5 mm (CASE 3). As can be inferred, the presence of the loose sheet has a detrimental effect on the joint quality since it results in enlarging the damaged area on the GFRP and a reduction in the undercut dimension.

The use of a loose sheet restrained the material flow of the punch-sided sheet because of the increase in the hydrostatic stress. In addition, comparing the results from CASE2 and CASE3, it is evi-

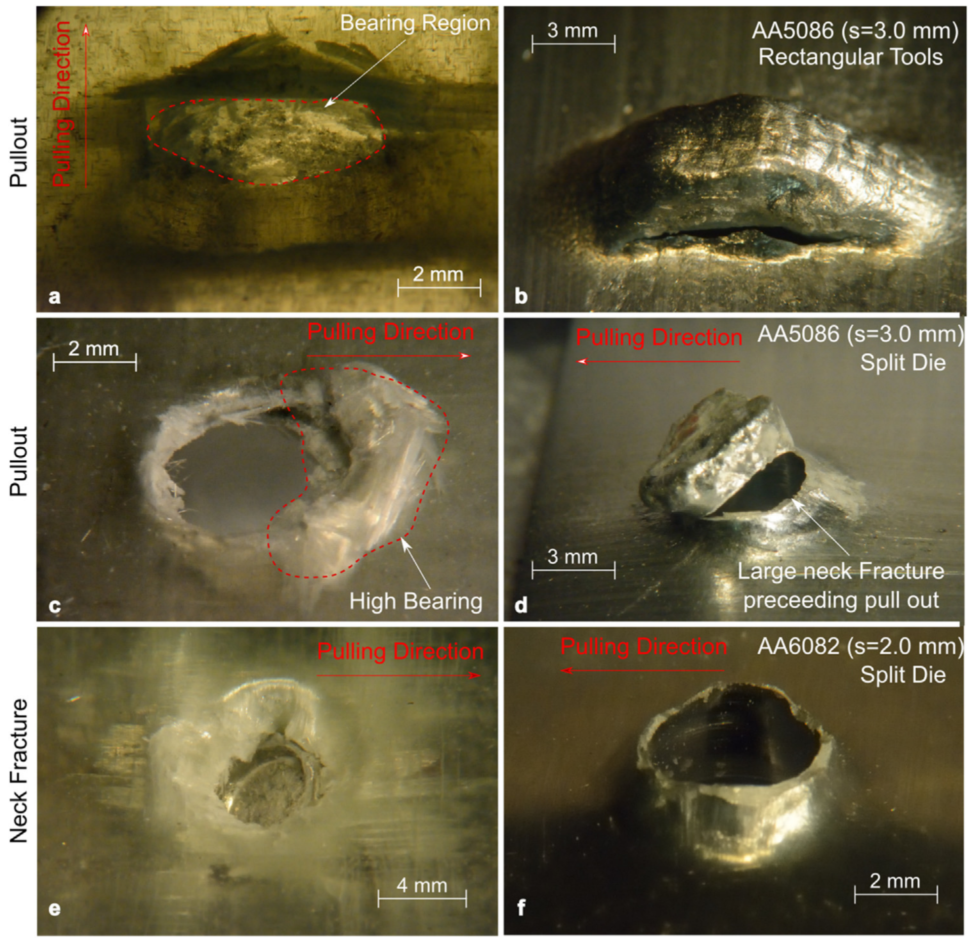

Fig. 13. Failure modes in hybrid aluminum-GFRP joints: (a–b) pull-out; (c–d) neck fracture with large GFRP bearing; and e–f) neck fracture.

dent that, even though the loose sheet made of AISI304 (s = 0.5 mm) is thinner than that made of AA5086 (s = 1 mm), the employment of AISI304 as loose sheet exerts higher constraint to the material flow during the joint formation because of the much higher yield strength (for AISI304, $\sigma_{0.2}$ = 255 MPa). This results in the development of smaller undercut, as can be seen by comparing Fig. 11 b and c. Conversely, when the sheet between the GFRP and the die was avoided, a lower hydrostatic stress developed, leading to an increase in the undercut dimension, as shown in Fig. 12. The presence of the loose sheet also induced greater delamination of the GFRP, since it delayed the above-mentioned fracture development.

3.5. Mechanical behavior of clinched joints

Hybrid aluminum-GFRP clinched joints failed in the aluminum bulge by two mechanisms: namely, pull-out, or neck fracture (Mucha and Witkowski, 2013), other than in the GFRP sheet by bearing. During the tests, the aluminum bulge is subjected mainly to shear stress. Initially, the load increases steeply, owing to the compression of the aluminum bulge over the GFRP. Then the aluminum bulge starts rotating and translating, leading to a reduction in the contact surface. During the rotation, the base of the aluminum sheet bears the load, and higher shear stress develops in such a region. Depending on the neck thickness and undercut dimensions, the clinched joint may fail by pull-out or neck fracture (or a combination of the two).

Clinched joints characterized by thicker neck or small undercut, results in the joint failing as a result of pull-out; that is, the ejection of the aluminum bulge from the composite housing, as depicted in Fig. 13a–b. Under such condition, the load decreases steeply after reaching the peak and both the aluminum bulge and the composite housing region deform plastically. On the other hand, joints with thinner necks and larger undercuts fail as a result of neck fracture, which consists of the onset and development of fracture at the base of the aluminum bulge, as shown in Fig. 13e–f. On the other hand, joints characterized by thick necks and large undercuts fail owing to competitive behavior between both failure modes of pull-out and neck fracture, as shown in Fig. 13c–d. Herein, the neck fracture can be seen propagating well into the formed region, but probably the GFRP plate detached before the neck crack could be completed.

Fig. 14 depicts the load-displacement curve recorded during single-lap shear tests, and the shear strength of joints produced with different tools on different materials and sheet thicknesses. As can be observed for each material, the joints produced by the split die showed the highest mechanical strength, followed by those produced by rectangular tools, while the ones produced with flat tools were characterized by the weakest mechanical performances. Such a difference can be ascribed mainly to the dimension in the undercut, which is much higher in the former joints (split die), compared to the latter ones (produced with flat dies). The only exception is represented when joining AA6082-T6 sheets (s = 2.0 mm). In such a case, the joints produced with rectangular tools showed lower mechanical performances compared to those performed using a flat die, owing to the presence of a crack on one of the bent aluminum arms (as reported in Fig. 15).

Comparing the joints performed with the same tools, but on different materials—i.e. AA6082 (s = 2.0 mm) and AA5086 (s = 2.0 mm)—it is evident that, the joints performed on the alu-

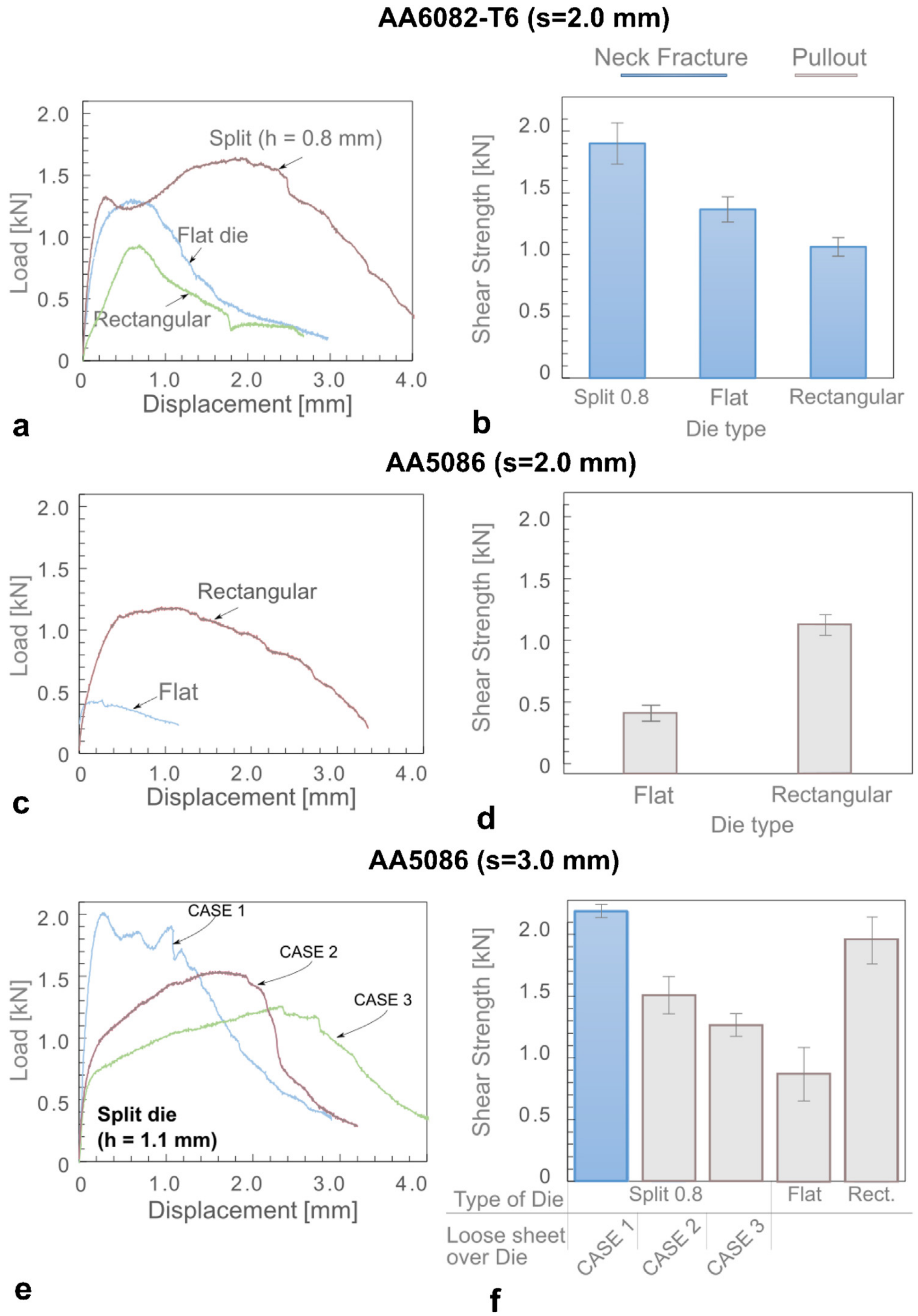

Fig. 14. Mechanical behavior of clinched joints: (a–b) AA6082, s = 2 mm; (c–d) AA5086, s = 2 mm; and e–f) AA5086, s = 3 mm.

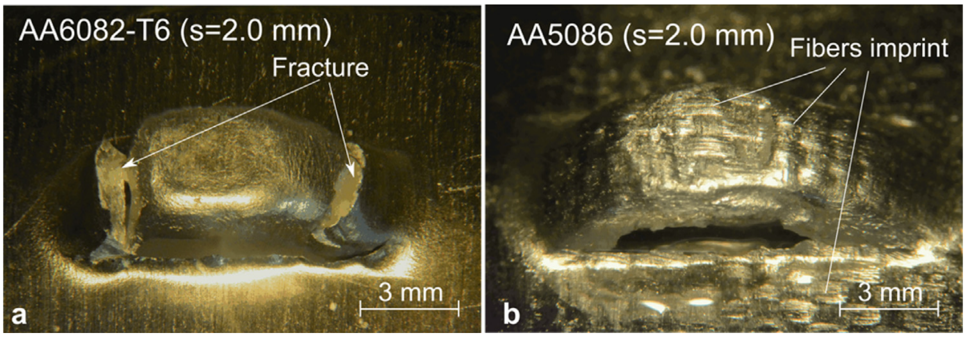

Fig. 15. Fracture produced by clinching process on: (a) more brittle (AA6082); and (b) more ductile (AA5086) aluminum alloys using rectangular tools.

minum with higher yield stress were characterized by higher shear strength. Such a characteristic is even more evident in joints made using round tools. Indeed, in such joints, a higher strength of the aluminum enables a reliance on the neck thinning effect, thus contributing to an improvement in the mechanical behavior of the joint.

The thickness of the aluminum sheet also played a crucial rule, since it greatly influenced the material flow, and the characteristic dimensions of the joint. Thicker sheets were characterized by larger undercut and neck thickness resulting in higher mechanical behaviors.

4. Conclusions

The present investigation has demonstrated the feasibility of mechanical clinching (using conventional dies) for joining metals and Fiber-Reinforced Plastic sheets. To this end, different types of dies were employed, and the mechanical behavior of the joints, as well as the damage to the composite sheets, were compared. According to the achieved results the following conclusions were drawn:

- Mechanical clinching can be used to join GFRP to metals sheets.
- The mechanical behavior of the joints is greatly influenced by the mechanical behavior of the parent material, and the relative metal/GFRP sheet thickness. Comparing the joints performed on AA5086 alloy, the joints produced on thicker aluminum sheets were characterized by larger undercuts, thicker necks, and greater shear strength.
- The tools involving high hydrostatic stress (such as flat dies) produced small undercuts (leading to weak strength of the joints), and severe damage to the composite sheet.
- Split dies allowed the production of the largest undercuts, and less damage in the GFRP, owing to the cut of the composite in the joint area. In addition, the cross-section of such joints showed that the largest part of the composite's damaged area was removed from the joint during the last phases of clinch-joining.
- The joints produced with rectangular clinching tools were characterized by intermediate mechanical behavior. In such joints the damage to the GFRP sheet was localized at the extremities of the longitudinal edges.
- In all hybrid GFPR/aluminum joints the failure came with a smooth reduction of the load; such a condition is often desirable despite a sudden load decrease.

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