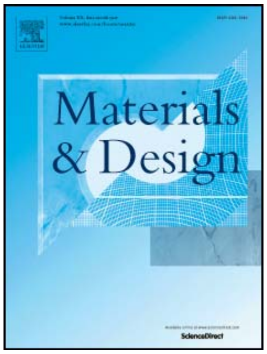

Mechanical behaviour of polymer-metal hybrid joints produced by clinching using different tools

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Mechanical behaviour of polymer-metal hybrid joints produced by clinching using different tools

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Abstract

In the present study, the mechanical behaviour of polymer-metal hybrid connections produced by clinching is investigated. Thin sheets were joined using different tools including grooved, split and flat dies as well as rectangular tools. The effect of the joining force on joinability was also analysed. Polycarbonate was used as the polymer partner since its high strength and toughness, while aluminium alloy AA6082-T6, which is characterized by a high yield stress but low ductility, was used as the metal sheet. Mechanical characterization involved single lap shear tests and peeling tests. According to the achieved results, grooved dies are not suitable for joining polymers. Rectangular clinching tools required lower joining forces and produced the highest peeling performances; however, because of the low ductility of the aluminium alloy, the joints were partially damaged resulting in weakest shear strength. Round clinching tools required higher joining force as compared to rectangular ones. The joints produced by flat dies were characterized by higher shear strength; however, because the small interlock produced, they were characterized by small values of peeling strength. Round split dies allowed producing the joints with highest performances in shear and peeling tests.

Keywords: thermoplastic; aluminium alloy; joining; thin sheet; mechanical characterization; strength

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1. Introduction

The employment of polymers is increasing in a number of manufacturing fields including automotive, aerospace, building and electronics. The adoption of hybrid structures involving polymers, composites either metal parts is aimed at exploiting the peculiarities of each material. Nevertheless, coupling such materials represents a challenging issue since they show different thermal, mechanical and physical behaviour. Conventional welding processes, which are widely employed for joining similar materials, (metal-metal, thermoplastic polymers) are not useful for the purpose since the different melting temperature of polymers and metals. The methods for joining polymers to metals are mainly based on adhesive bonding and mechanical fastening, as reported in [1-3]. Driven by such requirements, recent developments have been achieved in this field and emerging techniques are available such as ultrasonic welding, laser welding, friction spot welding and friction stir welding. Balle et al. [4] used ultrasonic welding to join aluminium to carbon fibre reinforced thermoplastic. During the process, plastic welding involves temperatures lower than those experienced during arc or laser welding processes. Laser joining can be employed for production of polymer–metal hybrid joints [5], as well as Reinforced-Plastic/metal sheets [6]. In addition, laser can be used to assist mechanical process and improve joinability as reported by Durantet et al. [7]. Blaga et al. [8] employed friction riveting process to join Glass-Fibre Reinforced-Plastic with titanium sheets. Subsequently, Altmeyer et al. [9] optimized the process for joining short carbon fibre-reinforced PEEK and grade 3 titanium.

Although a number of investigations focused on Friction Spot Joining (FSJ) of polymers (including polypropylene [10], polyethylene [11, 12] and high density polyethylene [13]), Amancio-Filho et al. [14] demonstrated the feasibility of FSJ to produce magnesium/fibre-reinforced polymer composite and aluminium/Carbon Fibre Reinforced-Plastics [15]. According to their results, the joints were characterized by relatively high performance ranging from 28 MPa to 43 MPa. Abibe et al. [16] developed the Injection Clinching Joining, which is a thermoforming process, to produce hybrid polymer-metal joints. Nevertheless, this process suffers of some complications such as requirement of a pre-hole on the metal sheet, the presence of a protruding stud pre-assembled on the polymer sheet and relatively long process duration. Liu et al. [17] demonstrated the feasibility of Friction Lap Welding, which is a modification of friction stir welding, to join polymers and metal sheets, other than Fibre-Reinforced Plastics to metal sheets [18]. In this process, a pin-less tool is adopted despite of that used in friction stir welding, and the materials being joined are not mixed.

Besides the above-mentioned processes, fast mechanical joining processes such as Self-Pierce Riveting (SPR) and mechanical clinching represent an interesting alternative for joining dissimilar materials. These processes combine the advantages of mechanical joining processes as compared to adhesive bonding (which requires substrate preparation, long curing time, involves significant environmental impact and specialized worker) and welding processes (which are limited by chemical, physical and thermal compatibility of the materials to join, substrate preparation and cleaning, specialized workers), with additional features. Self-pierce riveting is suitable to join a wide variety of materials as well as different materials. He et al. [19] used SPR to join aluminium with copper alloy sheets, while Di Franco et al. [20] joined Carbon Fibre Reinforced Plastic to aluminium sheets. Because the effectiveness and flexibility of this process, a number of variation have been proposed such as the employment of solid rivets [21].

Mechanical clinching offers additional advantages over SPR since it does not require pre-drilling, the employment of additional elements such as screws or rivets, it can be easily automated, and above all, it is characterized by a fast joining time (one joint per second, indicatively). Mechanical clinching is a bulk-sheet metal-forming process aimed at producing a mechanical interlock between two or more sheets. The process involves a portable gun or a fixed servo-press, a punch, (mainly circular or rectangular), and a die, (round grooved, round flat, round split or rectangular). Mechanical clinching has been widely employed to join steels and aluminium alloys. Nevertheless, it has also been employed for copper, magnesium and titanium alloys. Abe et al. [22] analysed the material flow in clinching with grooved dies of ultra-high strength steels. Lambiase et al. [23] employed numerical simulation for optimization of clinching tools while joining mild steel sheets. He et al. [24] analysed the static and dynamic characteristics of the clinched joints performed on aluminium alloys by means of experimental tests and finite element simulations. Lee et al. [25] proposed a new design method for mechanical clinching and developed an analytical model to predict the strength of clinched joints performed on aluminium sheets. Lambiase et al. [26] employed an external convective heater gun to pre-heat aluminium sheets in order to increase the formability of the material before joining. Gao et al. [27] evaluated the influence of mechanical properties of aged aluminium alloy on the strength of hybrid clinched connections made of Galvanized SAE1004 Steel-to-Aluminium AA6111. Xing et al. [28] compared the mechanical behaviour of copper alloy H62 sheets joined by high-speed mechanical fastening techniques such as self-piercing riveting and clinching. Neugebauer et al. [29] developed dieless clinching with a resistive heating cartridge (under the flat die anvil) to heat-up (up to 200 °C) magnesium sheets before clinching. He et al. [30] joined different titanium sheets by pre-heating the material (up to 700 °C) by means of oxyacetylene flame gun. In order to deal with new types of materials as well to achieve the best mechanical performance either reduce the joining force, different types of tools have been developed in the recent years including rectangular, round grooved, round flat and round split dies. Lambiase and Di Ilio [31] compared the mechanical performances of clinched connections (on mild steel sheets) performed with round grooved and round split dies. The research turned out that, extensible dies allow reducing the joining force and increase the mechanical behaviour of clinched connections. Zhao et al. [32] compared the mechanical behaviour of clinched joints performed on aluminium sheets using round and rectangular clinching dies. The authors found that the mechanical strength of clinched connections performed with rectangular tools was almost twice of those joined by means of round tools. The above-mentioned advantages have encouraged researchers to explore and extend the frontier of clinching employability. Lüder et al. [33] joined wood materials with aluminium using flat die clinching while Lee et al. [34] used hole-clinching to join different materials including aluminium, steel alloys as well as carbon fibre reinforced plastics. The suitability of clinching to join metal with polymer sheets has been also demonstrated only recently. Thus, only a few woks have been performed in this field. Lambiase and Di Ilio [35] performed an experimental investigation on the joinability of aluminium with thermoplastics polymers using a round split die and an external heat source. Gerstmann T, Awiszus [36] joined aluminium and polystyrene sheets using a flat die configuration. Lambiase [37] determined the main characteristics of polymers suitable to be joined with metal sheets by mechanical clinching using a round split tool set. However, the above-mentioned works were mainly aimed at analysing the influence of the joining force and process temperature on Joinability and mechanical behaviour using a single clinching tool set configuration.

On the contrary, the present work is aimed at investigating the mechanical behaviour of clinched connections produced by different types of tool. The influence of the processing conditions on the material flow, clinched joint profile and mechanical behaviour of the hybrid connections has been studied. In addition, in order to determine which clinching tool set can provide the best mechanical performance of the joints, the mechanical characterization of the joints included single lap shear tests and peeling tests (which have been never used for characterizing hybrid metal-polymer clinched joints). An experimental campaign, which involved different types of clinching tools, including, rectangular shear, round flat, round grooved and round split was carried out. The joining force and the tool geometry have been also varied. The analysis of the stressed regions during the mechanical tests has revealed that, the depth of the clinched bulge has great relevance to the shear strength of the connections in order to prevent from polymer bearing. Crossing the results from such analysis with geometrical characteristics of joints allowed understanding the difference in the mechanical behaviour of the joints produced with different clinching tools. As a result, flat dies produce joints with high bulge depth (thus high shear strength) but small interlock (which affect the joint toughness and peeling strength), while split dies produce the joints with the highest bulge depth and interlock, which result in high performances in both shear and peeling tests. Rectangular clinching tools produced high interlock that resulted in highest performances in peeling tests. However, since the reduced ductility of the aluminium sheet, a fracture was developed during clinching which limited the mechanical behaviour of the joint during the shear tests. Among the achieved result, it was turned out that polymer-metal clinched connections have mechanical properties comparable to those of clinched connections performed on metal sheets; in addition, when polymers with high toughness are employed (such as polycarbonate), pre-heating is not required. Therefore, for such materials, mechanical clinching is among the fastest and low-cost joining process available to produce hybrid polymer-metal joints.

2. Materials and Methods

Clinched connections were performed on aluminium alloy sheet AA6082-T6 with 2.0 mm of thickness and polycarbonate (PC) sheets of the same thickness. Aluminium alloy AA6082-T6 is increasingly replacing 6061 alloy, since it is characterized by a high strength and excellent corrosion resistance. Therefore, it is used as a structural alloy in different applications including automotive, transports, civil as well as drink vessels. Polycarbonate is thermoplastic polymer characterized by high impact resistance, high strength, durability and transparency. In addition, unlike most polymers, polycarbonate can undergo large plastic deformations that make typical cold metal sheet forming processes available to deform PC sheets. Polycarbonate is diffusely employed to substitute glass, in construction industry (e.g. for domelights), automotive, aircraft either security components.

Tensile tests according to ASTM E08 and ASTM D638 were performed on aluminium and polycarbonate specimens, respectively. The tests were performed at 2 mm/min and Digital Image Correlation (DIC) analysis was used to measure the true strain developing during the tensile test.

During the tests, the aluminium was placed at the punch side since its higher strength as compared to PC. Mechanical clinching was performed using an industrial portable machine model Python by Jurado srl (Rivotorto (Perugia), Italy), which can house different types of tools. Round and shear clinching configurations were tested. Different round dies including three grooved dies, three split dies (having different anvil depths, h) and a flat die were compared. The macrographs of involved clinching tools are reported in Fig. 1.

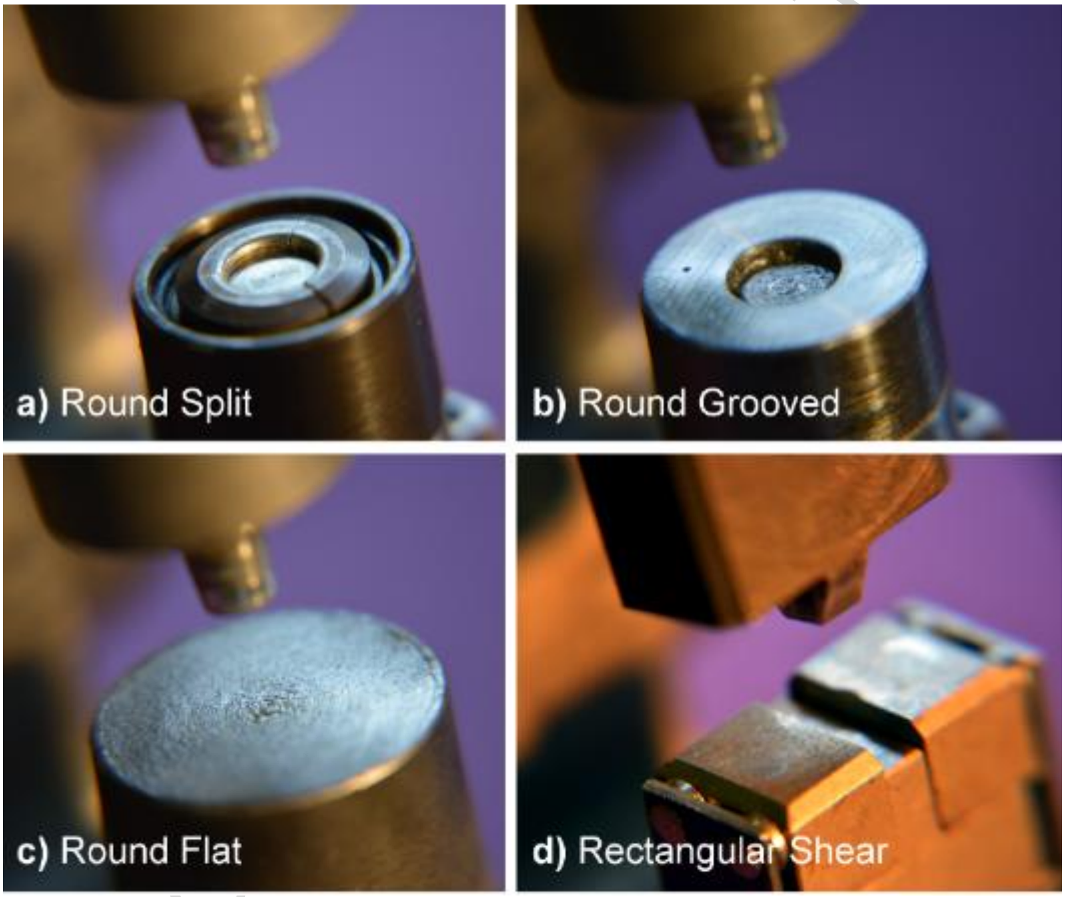


Fig. 1 Macrograph of the adopted clinching tools

The main dimensions of rectangular clinching tools are reported in Fig. 2. The rectangular die consists of a fixed die anvil and a couple of movable die sectors that are connected by two springs to the fixed die anvil.

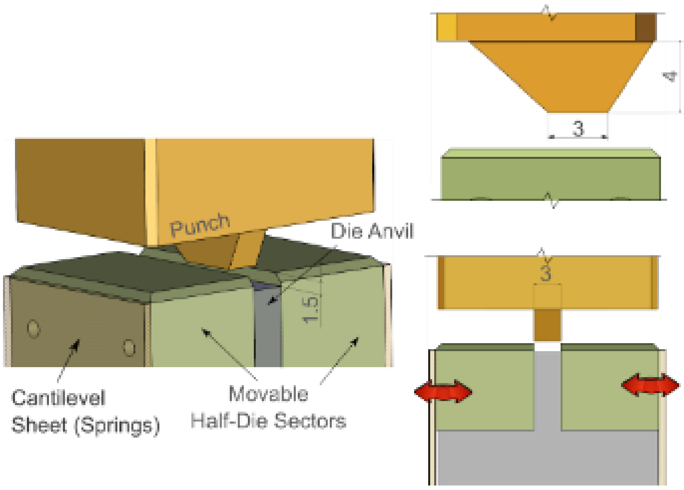


Fig. 2 Schematic Representation of Rectangular Clinching Tools.

The schematic representation and the main dimensions of adopted round split and round grooved dies are depicted in Fig. 3. To compare the joints produced by different round dies, the same punch with a diameter d = 4 mm was adopted. The punch is tapered to facilitate the extraction from the aluminium sheet after joining.

Three types of round split dies were employed having the same initial diameter D = 5.2 mm and different anvil depths (h = 0.6 mm, 0.8 mm and 1.1 mm). The round grooved dies have an intermediate die anvil depth h = 0.8 mm but different diameters (D = 6.1 mm, 6.4 mm and 6.7 mm). The anvils of grooved dies have the same diameter of those of the split ones (the difference among the grooved dies is the groove width, w: 0.45 mm, 0.6 mm and 0.75 mm).

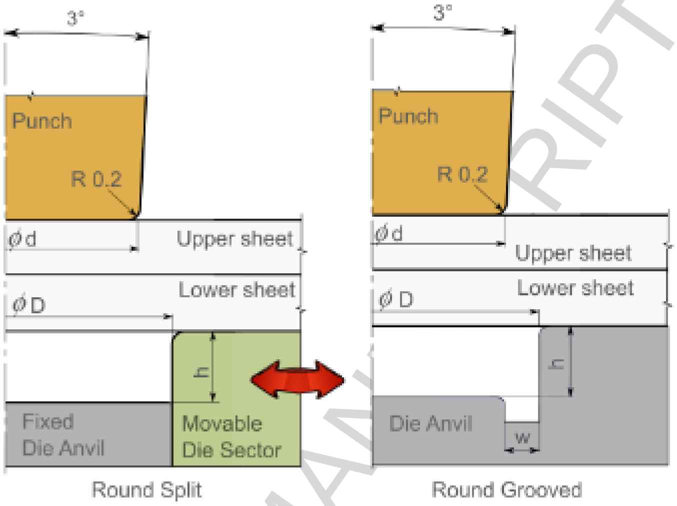


Fig. 3 Schematic Representation of Round Split and Round Grooved Clinching tools.

The joining force was varied between 7.2 and 21.6 kN to evaluate the threshold value of the joining force F_j required to fasten the sheets as well as the influence of the joining force on mechanical behaviour of clinched joints. The mechanical behaviour of clinched connections was evaluated by single lap shear tests and peeling tests performed at 0.5 mm/min on a Universal Testing Machine model 322.31 by MTS with 25 kN fullscale. The schematic representation of the specimens utilized in the single lap shear test and peeling test is reported in Fig. 4.

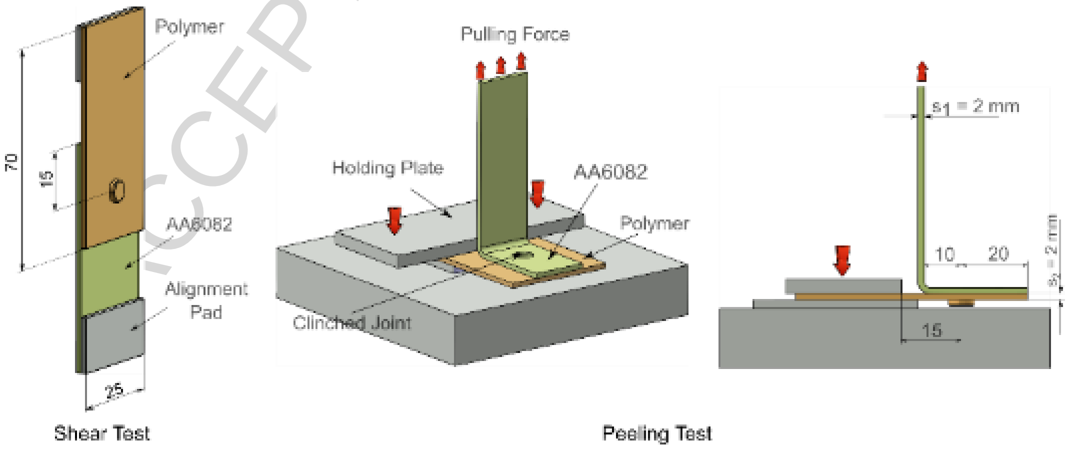


Fig. 4 Schematic representation of Shearing and Peeling tests.

Geometrical analysis of cross-sections of clinched connections was performed in order to better understand the effect of the joining force and clinching tool configuration on material flow and mechanical strength.

3. Results and Discussion

According to tensile tests results, the aluminium was characterized by yield stress of 170 MPa ultimate stress of 340 MPa and uniform elongation of 10.8%. On the other hand, polycarcarbonate (PC) was characterized by a much lower tensile yield stress of 60 MPa and a maximum elongation of 110% as depicted in Fig. 5.

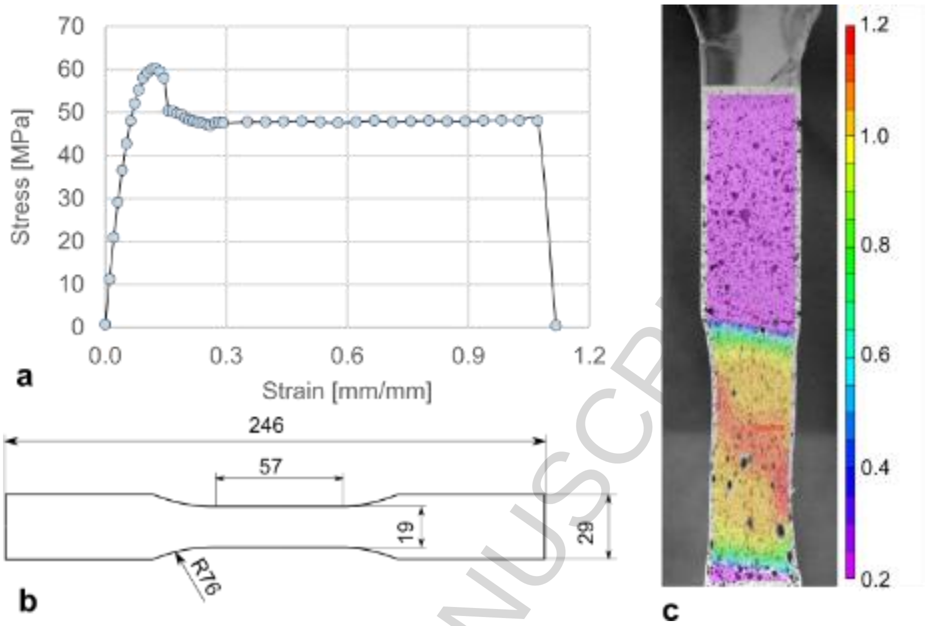


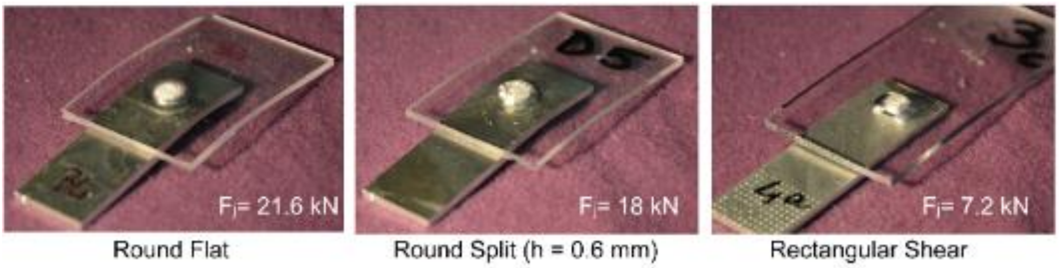
Fig. 5 Stress-Strain curve of PC material.

3.1 Joinabiltity

Mechanical clinching of hybrid aluminium-polymer sheets using round grooved dies failed (regardless the diameter of the die and joining force) since the PC bulge was torn out from the rest of the (polymeric) sheet as the punch was retracted. Fig. 6 depicts the grooved die (D = 6.7 mm) after joining.

Fig. 6 Macrograph of PC material entangled within a grooved die after joining

The macrographs of the joints produced with the other types of clinching tools are reported in Fig. 7.



Round Flat Round Split (h = 0.6 mm) Rectangular Shear

Fig. 7 Hybrid polymer-metal clinched connections produced with different types of tools

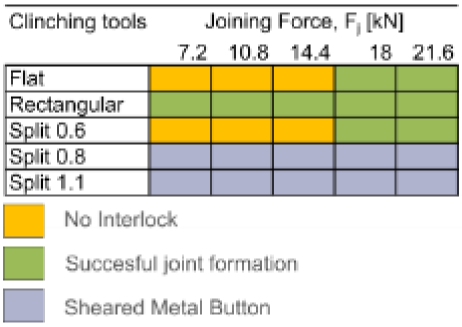
Mechanical clinching of polymer–metals hybrid joints may lead to unsuccessful joining owing to different causes. Indeed, as reported by Lambiase and Di Ilio [35], mechanical clinching of polymers may fail by brittle fracture of the polymer sheet, either polymer material ejection from the joining area (owing to high difference in the flow stress of metal and polymer materials) other than shearing of the metal button and no interlock formation reported in Fig. 8a. Nevertheless, as shown in Fig. 5, the polycarbonate sheet was characterized by high elongation at break and relatively high yield stress; in addition, no pre-heating was adopted as in [35]; consequently, brittle polymer fracture as well as polymer ejection effect were never experienced while joining PC sheets with aluminium AA6082 alloy at room temperature. When joining by clinching, the joining force being involved should be as high as to produce a material flow leading to the formation of the interlock between the sheets. Therefore, the threshold value of the joining force (below which the interlock is not formed) was investigated. Actually, other than depending on the materials flow stress and thickness of the sheets, the joining force threshold is highly influenced by the clinching tools configuration and mainly by the developing hydrostatic stress [31]. The second possible failure condition experienced while joining the analysed materials with split dies was the shearing of the metal button (see Fig. 8b) which is due to high strains at the punch-side sheet near the punch corner (e.g. small punch fillet radius, deep die anvils, small clearance between the punch and the die [22, 38]), either low ductility of the punch-sided material.


a No Interlock **b** Sheared Metal Button

Fig. 8 Unsuccessful joining conditions

Table 3 depicts the joining conditions resulting from the adopted clinching tools and joining forces. As can be noted, only the round flat, split round dies (with h = 0.6 mm) and the rectangular tools allowed to successfully join the PC and aluminium sheets. On the other hand, split dies with deeper anvils, i.e. h = 0.8 mm and h = 1.1 mm, failed to join the aluminium and PC sheets since the occurrence of shearing in the metal button. The analysis of the joining forces showed that when using the rectangular tools, the threshold value for the joining force was much lower (F_j = 7.2 kN) as that required by the round tools (F_j = 18 kN). Actually, with rectangular tools, a lower hydrostatic stress develops owing to the shearing effect on both of the metal and the PC sheets, as schematically reported in Fig. 10 and in cross sections shown in Fig. 11.

Table 1 Joinability conditions



Clinching tools	Joining Force, F_j [kN]				
	7.2	10.8	14.4	18	21.6
Flat	🟧	🟧	🟧	🟩	🟩
Rectangular	🟩	🟩	🟩	🟩	🟩
Split 0.6	🟧	🟧	🟧	🟩	🟩
Split 0.8	🟪	🟪	🟪	🟪	🟪
Split 1.1	🟪	🟪	🟪	🟪	🟪

🟧 No Interlock
🟩 Succesful joint formation
🟪 Sheared Metal Button

3.2 Material flow and quality criteria

The influence of the process parameters (clinching tools and joining force) on the material flow is analysed in this section. Fig. 9 depicts the macrograph of an aluminium bulge produced by means of rectangular tools. As can be noted, during the joining process, two parallel sheared surfaces develop on the aluminium and the PC sheets, as schematized in Fig. 10. In addition, ductile fracture occurs on one of the bent sides of the aluminium sheet bulge (the one corresponding to the higher punch slope) since the low ductility of this alloy.

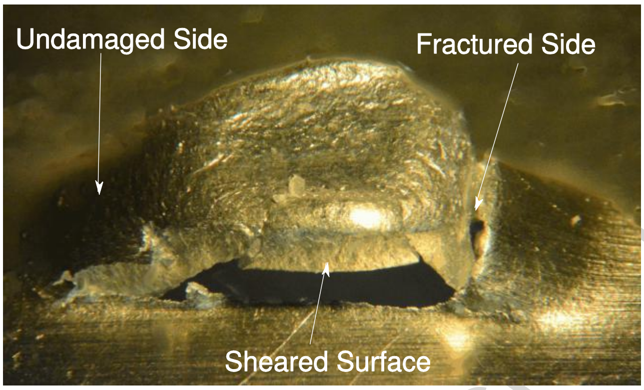


Fig. 9 Macrograph of a clinched joint produced with rectangular tools and joining force F_j = 21.6 kN.

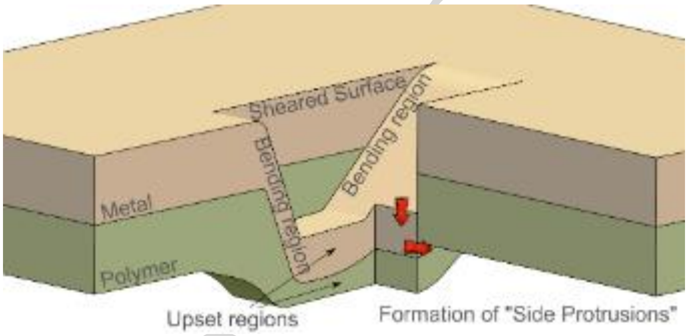


Fig. 10 Schematic representation of clinched connection produced with rectangular clinching tools

Fig. 11 shows the evolution of the material flow varying the joining force. When rectangular tools are adopted, the threshold of the joining force (F_j = 7.2 kN) should lead to the formation of the sheared surface in the aluminium and PC sheets. Higher joining forces (F_j between 10.8 kN and 18 kN) result in higher upsetting effect on the aluminium bulge with the formation of a side interlock while the PC material underlying the aluminium bulge becomes thinner. When high forming forces are applied, the aluminium flows in the less resistance (side) direction, which results in the formation of side protrusions, as schematically depicted in Fig. 10. Such bulges exert an additional fastening action between the aluminium and the PC sheet. The variation of the interlock t_s and bottom thickness X between the sheets with the joining force is reported in Fig. 12.

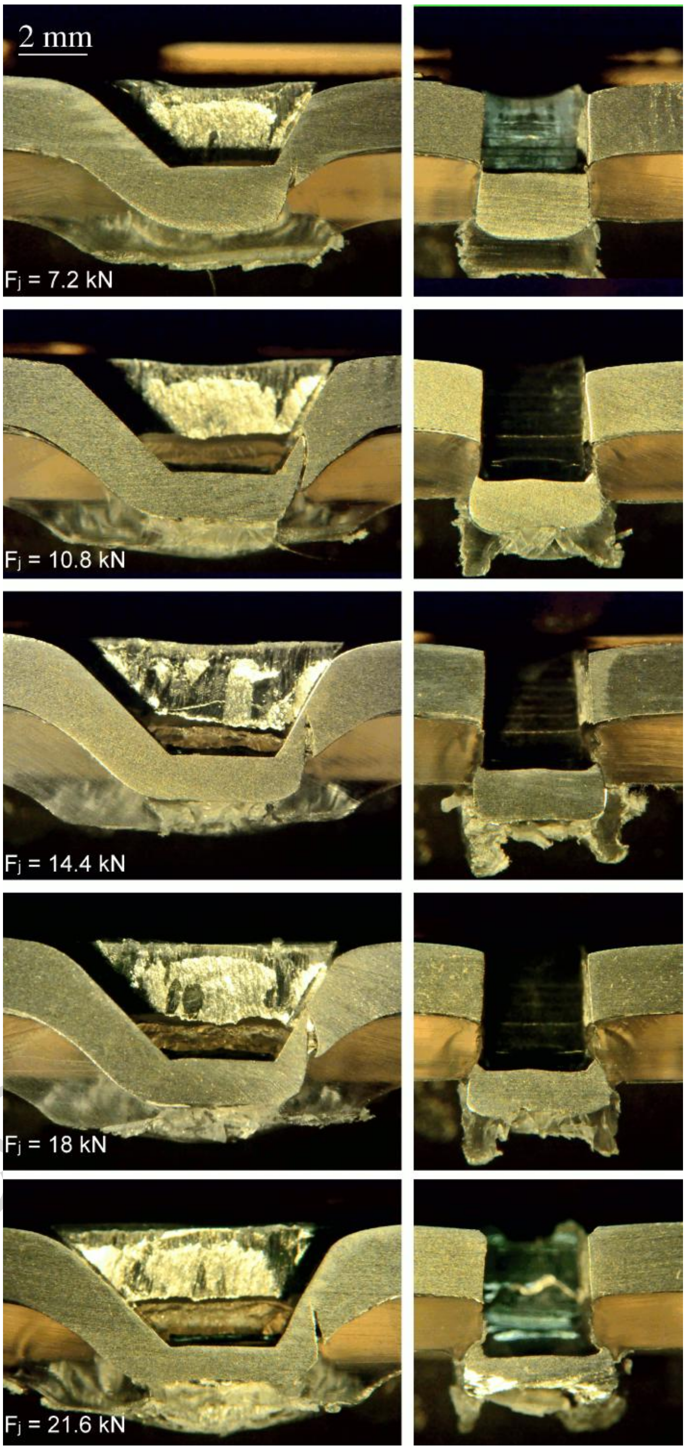


Fig. 11 Material flow produced with rectangular shear clinching tools.

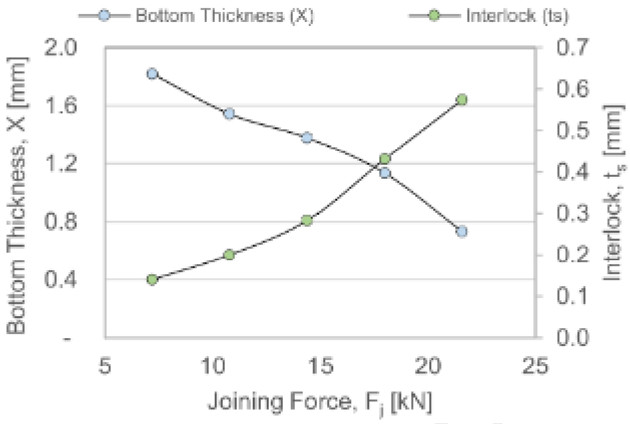


Fig. 12 Variation of bottom thickness and interlock with joining force for joints produced with rectangular tools.

The mechanical behaviour of clinched connections performed with round tools is influenced by the interlock and neck thickness [39], which will be referred as quality characteristics of clinched connections. Fig. 13 shows the variation of interlock and neck thickness of joints produced with flat and split dies. As expected, the interlock increased with the joining force regardless the type of die. The influence of the joining force on neck thickness was negligible when using the flat die; on the other hand, increasing the joining force produced a higher neck thinning when split dies were used. Comparing the quality criteria of joints produced with flat and split dies, it emerges that the interlock of joints produced with the split die is much larger than that of joints produced with flat dies.

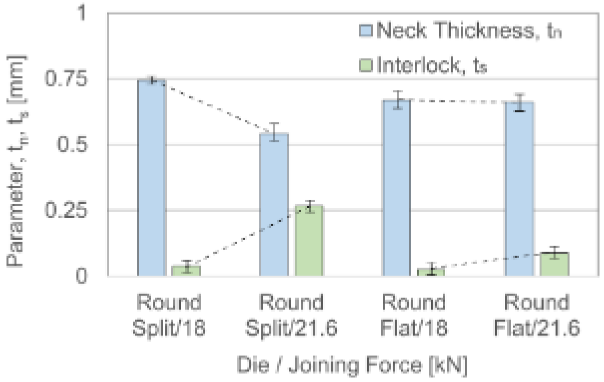


Fig. 13 Variation of interlock and neck thickness for joints produced with round split and round flat dies at different joining loads.

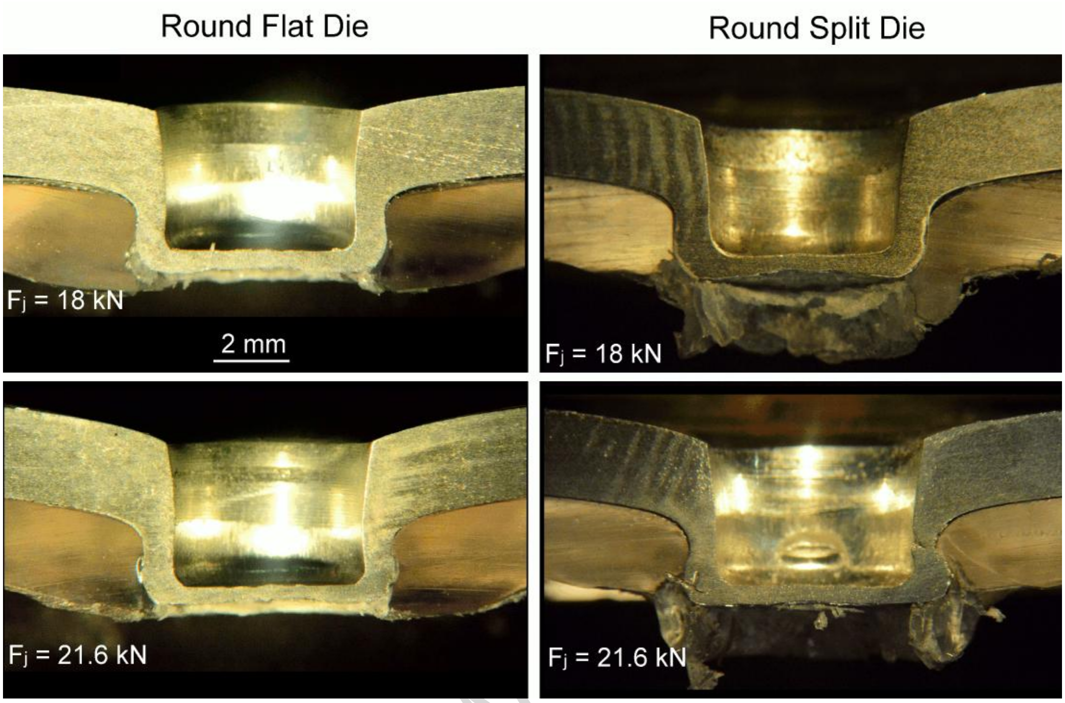


Fig. 14 Material flow of clinched connections produced with Round Flat and Round Split dies.

3.3 Mechanical behavior

In order to understand the differences among joints produced adopting different clinching tools, the stressed regions in the joints undergoing shearing and peeling stress were analyzed and the results were discussed by taking into account the geometrical characteristics of the joints.

3.3.1 Shear tests

Fig. 15a shows the main forces acting on a clinched joint undergoing a shear load. The punch sided sheet is subjected to an external shear load Fs acting in x-positive direction, the contact force P and the friction force $\tau = \mu P$, where μ is the coefficient of friction, while the die-sided sheet is assumed to be constrained. Since the slope of the contact surface α (shown in Fig. 15), is generally small, the external shear load Fs is mainly balanced by the horizontal component of the contact force P: $Fs \approx P_x = P \times \cos\alpha$. The contact force generates a clockwise “pulling moment” since P_x acts at a distance from Fs. Under equilibrium conditions, such a moment is balanced by that produced by the vertical components of the contact and frictional forces (P_y and τ_y) acting on the left side of the joint. Such a counter moment is proportional to the x-projection of the contact length $L_x = L \times \sin\alpha = t_s$, the yield stress of the die-sided material (PC), the diameter of the joint and friction coefficient; therefore, joints with larger interlocks offer a higher resistance to pull-out.

During single lap shear test, in the punch-sided sheet the stress mainly concentrates at the neck region. Indeed, the conjunction of the wall thinning effect (owing to the material flow during the joint formation) and the “u-shape” which acts as a stress raiser may produce the joint failure by neck fracture. The shear strength of the punch-sided sheet is thus proportional to the fracture stress of the material, the neck thickness and the diameter of the joint. Depending on the dimension of the interlock and the neck thickness, clinched joints performed on sheets having almost equivalent mechanical behaviour may fail by neck fracture, pull-out or a combination. On the other hand, hybrid aluminium-polymer clinched joints may also fail by large bearing preceding pull-out since the high difference in the strength of such materials. Actually, if the average bear stress σ_b, (given in eq. 1) exceeds the compression strength of the polymer, the joint fails by bearing.

$$\sigma_b \cong \frac{F_s}{H_R \times (d+2t_n+t_s)} \qquad \text{eq. 1}$$

As a result, the Maximum Bearing Load MBL that a clinched joint can undergo without onset of bearing is given in eq. 2.

$$MBL = \sigma_y \cdot H_R \times (d + 2t_n + t_s) \qquad \text{eq. 2}$$

where σ_y is the compression yield stress of the polymer. The value of MBL calculated by eq.2 provides a conservative guess of the effective bearing load (at which the polymer material starts bearing) since the entire external load (F_s) is supposed to be balanced by the bearing load neglecting the contribute of frictional forces at the sheets interface. According to eq. 2, the joints with deep protrusions (high values of H_R) can undergo higher loads before the onset of bearing other than higher rotation of the aluminium bulge before the joint failure (by pull-out). As a result, the onset of one or another of the failure mechanism is determined by the characteristic dimension of the joints: neck thickness (t_n), interlock (t_s) and joint bulge height (H_R).

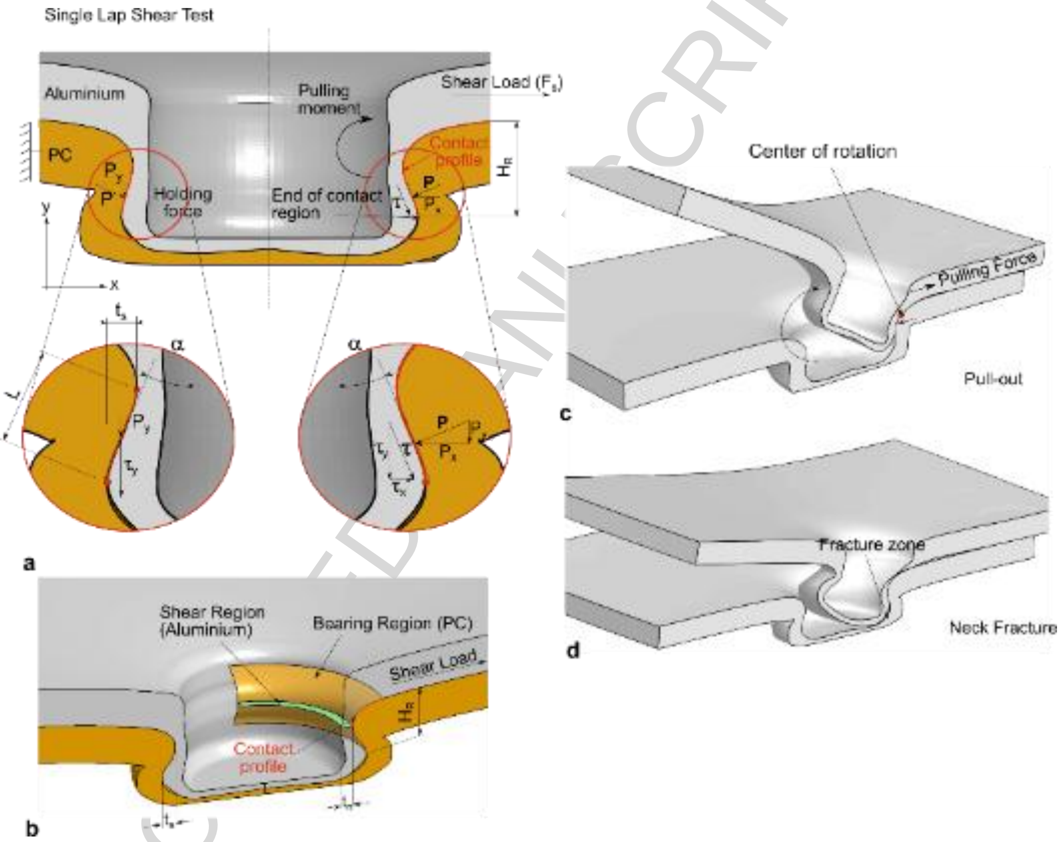


Fig. 15 Main forces and stress developing on a clinched connection during shear tests.

Fig. 16 shows the macrograph of a joint produced with rectangular clinching tools after the single lap shear tests. As can be seen, both of the bent sides of the specimen are fractured and the aluminium bulge remains embedded within the polymer. Actually, during the shear test, the whole load is born by only the undamaged side (since the other was fractured during joining), which results in significant reduction in the joint carrying load capability.

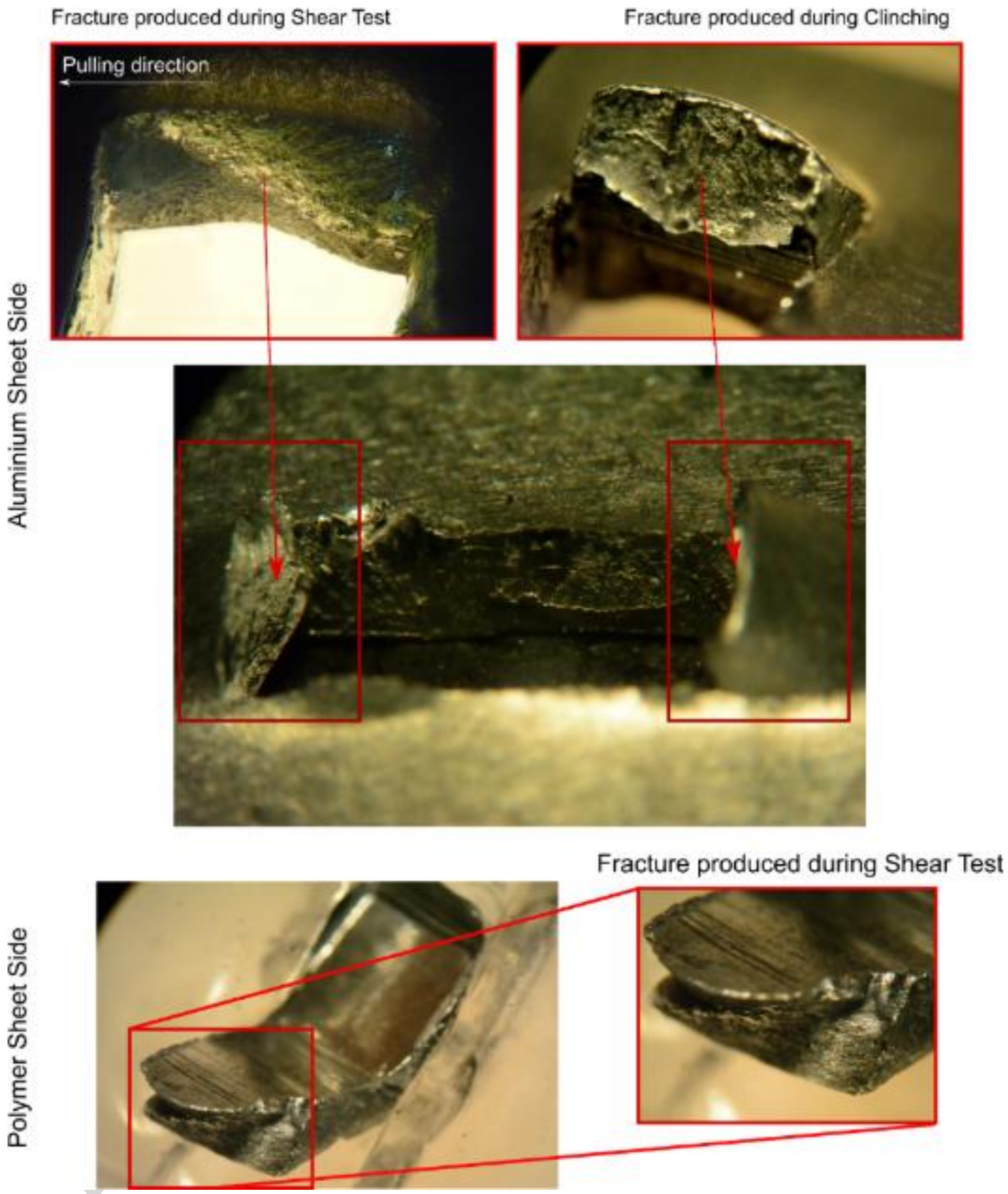


Fig. 16 Macrograph of clinched connection performed with rectangular tools (F_j = 21.6 kN) after the single lap shear test.

Fig. 17 shows the macrographs of clinched connections (polymer side) produced with round tools after single lap shear tests. As above-mentioned, these type of joints failed by pull-out of the metal bulge from the PC sheet. Actually, in such type of joints, a large bearing was observed before the separation of the sheets, except in those produced with flat die and joining force F_j = 18 kN which remained almost undeformed. Such different behaviour owns to the small interlock t_s and reduced joint bulge height H_R, which results in an early pull-out of the metal bulge from the polymer sheet.

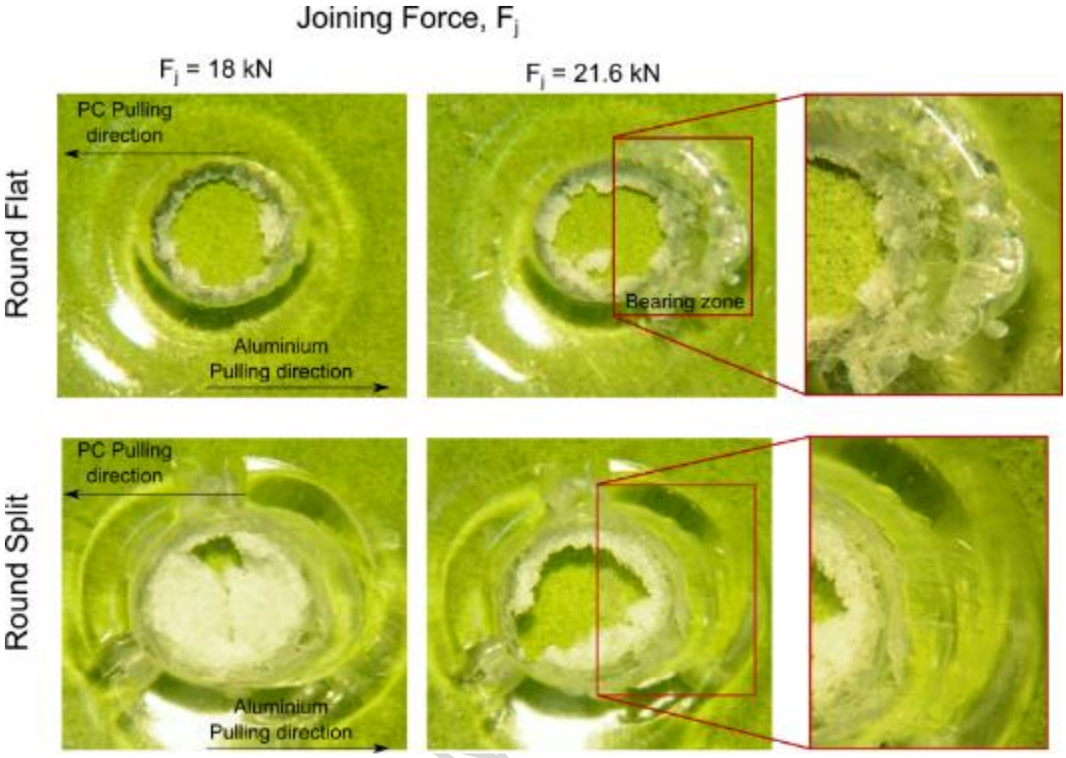


Fig. 17 Macrograph of clinched connection performed with round tools after the single lap shear test.

Fig. 18a shows the force-displacement curve recorded during shear tests of clinched connections performed with rectangular clinching tools. The joint produced with the lower joining force (F_j = 7.2 kN) behaves differently from the others. Actually, for F_j = 7.2 kN, the force reduces smoothly after reaching a peak value owing to a prolonged sliding (pull-out) effect; then, the load steeply decreases with the separation of the two sheets. On the other hand, the joints produced with higher joining forces ($F_j \geq 10.8$ kN) are characterized by a steeper reduction of the load after the peak owing to a higher fastening effect resulting from the presence of the side protrusions. Under such condition, the aluminium sheet bulge is more constrained by the PC sheet leading to a lower sliding. Further increase in the joining force results in larger interlock between the sheets and consequently joint produced with the highest joining force (F_j = 21.6 kN) is characterized by the highest strength of 0.82 kN.

Fig. 18b depicts the force-displacement curves of joints produced with round (flat and split) dies. As can be noted, the trends of the joints produced by split die (Split18 and Split21.6) and that produced by flat die with the maximum joining force Flat21.6 are qualitatively similar. First, there is a steep increase in the force up to the onset of a knee at approximately 1.1 kN (onset of bearing effect in the polymeric sheet); such a value is slightly higher than that calculated by means of eq. 2 by assuming a compression yield stress of the PC of 80 MPa [40]. However, the joints Split18, Split21.6 and Flat 21.6 are characterized by similar values of the maximum bearing load MBL (880 N, 856 N and 864 N, respectively) as experienced during the experimental tests. As the tests proceeds, the force continues to increase but with lower slope (since the polymer bearing comes with large displacements) and reaches a peak (shear strength). It follows the pull-out of the metal bulge from the joint with the reduction in the holding force. The onset of polymer bearing in these joints suggests the high performances of hybrid polymer-metal clinched joints since the failure mainly occurs on one of the materials rather than in the joint. On the other hand, the joint Flat18 failed by pull-out with negligible bearing since the much smaller dimensions of interlock and bulge depth.

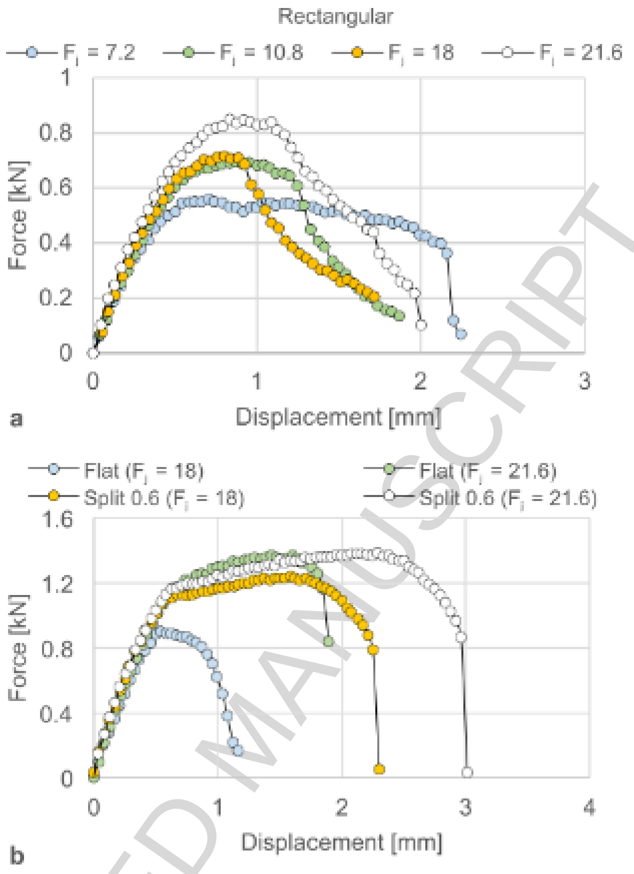


Fig. 18 Force-Displacement curve of clinched connections produced with different types of dies and Joining forces (F_j).

The shear strengths of the joints produced with different clinching tools and joining forces are compared in Fig. 19. Here, the toughness is calculated as the area underlying the force-displacement curve, while the shear strength is the maximum value of the force. As expected, since the joints produced with round tools failed by pull-out, the increase in the joining force resulted in larger interlocks and bulge depth and then in higher performances (shear strength and toughness). For joints produced with rectangular tools, the influence of the joining force is different. Indeed, the increase in the joining force from the threshold value (F_j = 7.2 kN) up to 18 kN produced a negligible difference in the shear strength F_{max}, which increased from 0.7 to 0.73 kN; on the other hand, further increase in the joining force (F_j = 21.6 kN) resulted in an increase of 18% in the shear strength F_{max} = 0.85 kN owing to the contribute of the side protrusions. The employment of the round and flat die allowed producing the strongest joints since the absence of fracture on the aluminium neck. Here, the increase in the joining force resulted in larger interlocks, deeper bulge and consequently higher shear strength and toughness (since the joints failed by pull-out). Nevertheless, the joints produced with round split dies were characterized by the higher toughness and elongation-at-break owing to the larger interlock and height of bilge which postponed the onset of pull-out. As can be inferred, the joints produced by the rectangular tool showed the weakest performances as compared to those produced with round tools since the presence of the fracture on one arm which caused the whole external load being supported by the other arm.

Fig. 19 Variation of shear strength and toughness of clinched connections (produced with different dies) with Joining force achieved in single lap shear tests.

3.3.2 Peeling test

Common failure modes developing during tensile [25] and peeling tests of clinched connections are referred as neck fracture and button pull-out [31]. The former failure mode is characterized by the progressive thinning of the punch-sided sheet wall at the joint neck, while the latter consists in the spreading of the die-sided sheet housing at the joint and the subsequent pull-out of inner bulge. The onset of one or the other failure mechanisms depends on the geometrical characteristics of the joints other than the strength of the base materials. The performed aluminum-polycarbonate clinched connections never failed by neck fracture since the large neck thicknesses and the higher fracture stress of the aluminum material as compared to the polymer. Fig. 20 depicts the forces acting on a clinched connection during peeling tests. The tests consist in applying a vertical displacement on the left edge of the aluminum (punch-sided) sheet, while the polycarbonate is constrained, as shown in Fig. 20. The external peeling force F_p is exerted to overcome the contact force P and the friction τ acting on the contact region. The above-mentioned displacement is produced by deforming the contact region and spreading the PC housing (the inner diameter of the PC housing D_i increases). Thus, since the conical shape of the aluminum bulge, the external force increases during the test up to reaching a maximum F_{max} (to which corresponds the maximum spreading of the PC housing) and then drops abruptly. The strength and toughness of mechanical behavior of aluminum-polycarbonate clinched joints undergoing peeling load thus increase with the magnitude of interlock and α-angle.

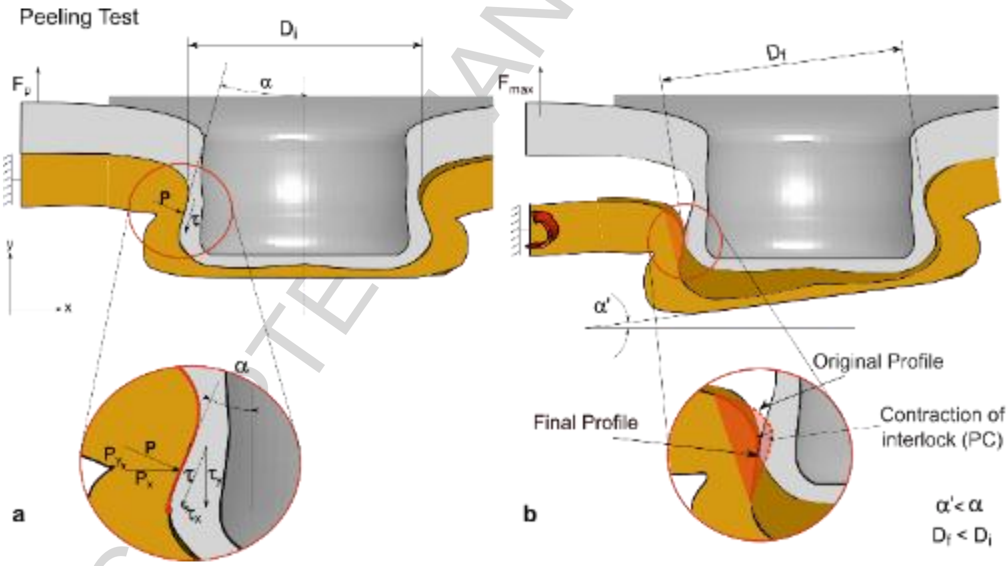


Fig. 20 Main forces acting on a clinched connection performed with round tools during peeling test.

Fig. 21 depicts the force-displacement curves of joints during peeling tests. The values of the forces are much smaller compared to those observed in the shear tests (almost 1/5). As can be seen, in all the specimens, except those produced by flat dies, the polymer sheet undergoes a large displacement before the joint failure. On the other hand, the joints produced with the flat die were characterized by the weakest performances (peeling strength, toughness and elongation at break) since the limited amount of interlock and α-angle.

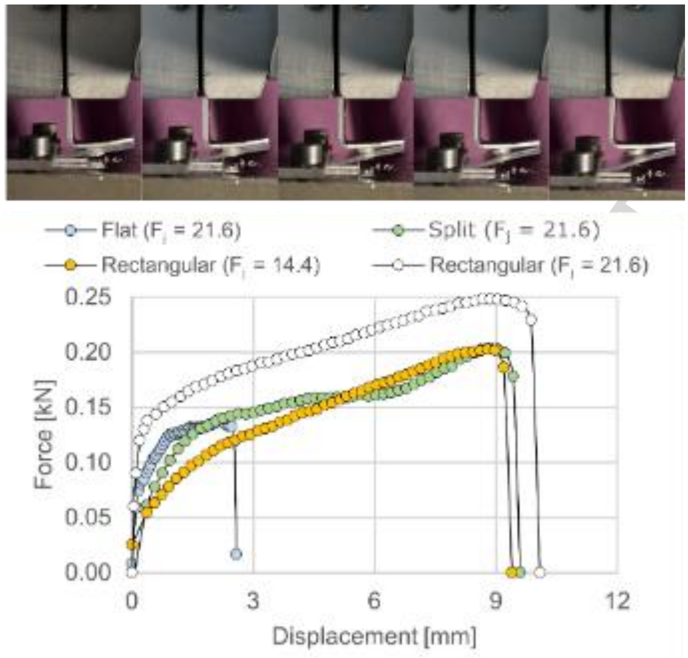


Fig. 21 Force – displacement curves recorded in peeling tests using different dies.

Fig. 22 compares the mechanical behaviour of clinched connections during the peeling tests. The joints performed with rectangular tool and joining force of 14.4 kN and those performed with the split die (F_j = 21.6 kN) were characterized by similar values of toughness and shear strength. Actually, these joints showed similar amounts of interlock t_s = 0.27 mm and t_s = 0.25 mm as well as interlock length l = 11 mm and l = 12.5 mm, respectively. On the other hand, the joint produced with the rectangular tools and maximum joining force (F_j = 21.6 kN) where characterized by higher mechanical performances since the larger interlock.

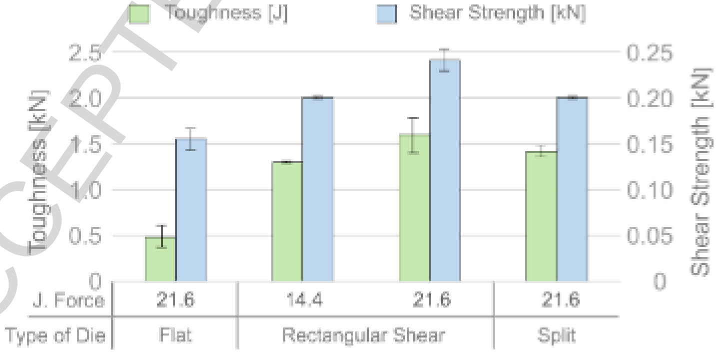


Fig. 22 Variation of shear strength and toughness of clinched connections (produced with different dies) with Joining force achieved in peeling tests.

3.4 Comparison with recently developed joining processes of different materials

The growing employment of hybrid structures has driven towards the development of new joining processes for connecting different materials. Although it is not easy to relate the results from researches performed on different materials and thicknesses, a preliminary comparison is attempted in this section. The main limitation of clinching process concerns the sheet material formability. Nevertheless, such limitation is less restrictive as compared to metal-metal clinch joining. Indeed, since the difference of yield strength between the metal and the polymer, a lower neck thinning effect is produced on the punch-sided (metal) sheet relieving the stress concentration acting on the metal sheet which is the principal cause of fractures development on the bulge (metal) neck. The formability of the polymer is even less restrictive since a number of thermoplastics including polycarbonate, polypropylene, high density polyetilene etc. show a high elongation at room temperature (higher than 50%). The suitability of clinching to produce hybrid metal-thermoplastic joints could be extended to brittle (at room temperature) thermoplastics (e.g. Poly(methyl methacrylate), polystyrene, filled and unfilled Poly(EtherEtherKetone), etc.) using an external heat source, as described in [37].

From a mechanical point of view, the achieved results show that hybrid polymer-metal clinched connections have similar shear strength to joints produced by Friction spot joining [14, 15, 41], friction riveting [8] and injection clinching [16]. Nevertheless, from a production point of view, the clinching process offers several advantages over the above-mentioned ones. Actually, the processing time of clinching is much shorter (almost 0.5-1 s per joint), while the other processes last from 5-20 s for friction spot joining [42] and almost 15 s in friction riveting [9]. Although the processing time of injection clinching was not reported in [16], it is presumable that it is comparable to Friction Spot Stir Welding of polymer, and thus it ranges from 20-40 s [43]. In addition, since these are thermo-mechanical processes, a cooling phase is required to let the polymer consolidate. Such a phase is often carried out under pressure in order to reduce the thermal relaxation of the polymer and improve its consolidation [16] which further complicate the process control and the machine equipment. Clinching machines are also simpler and smaller (often portable) since the process involves only one phase (plunging the punch against the sheets) and thus a simple hydro-pneumatic actuator is often adopted. On the contrary, injection clinching involves pre-heating phase, plunging and cooling phase which imply the employment of more complex control systems. Even worse, more complex displacement-controlled machines are required for friction spot joining (the process involved different phases and different actuators for moving the pin and the sleeve independently) and friction riveting (the process develops in two phases, namely friction and plunging). Further advantages of clinching lie in the absence of external joining elements (such as those involved in friction riveting) either no surface preparation (as that used in friction spot joining for increasing the roughness of the sheets by sandblasting).

4. Conclusions

Hybrid joints were performed on aluminium and polycarbonate sheets by means of mechanical clinching. Different clinching dies were tested including rectangular and round tools. According to the above-mentioned results, the joint shape plays a crucial rule for determining the mechanical behaviours of the joints. The main results are reported as follows:

- round grooved dies are not suitable to join aluminium and PC sheets since the bulge was torn out from the rest of the (polymeric) sheet after joining. On the other hand, round split tools with deeper die anvil i.e., h = 0.8 mm and 1.1 mm, failed to join the sheets owing to the shearing effect in the metal button since the low ductility of the aluminium alloy;
- rectangular tools allowed to join the analysed sheets with the lowest joining force (F_j = 7.2 kN). This was ascribed to the shearing effect that resulted in the reduction in the hydrostatic stress. On the other hand, round tools required much higher joining force (F_j = 18 kN).
- Clinched connections performed on aluminium-polycarbonate sheets by means of round tools were characterized by large neck thickness since the difference in yield stress of the two materials, which relied the thinning effect on the aluminium neck during the joining operation.
- During single lap shear tests of hybrid polymer-metal clinched connections, the high difference in yield stress of the two materials introduces another failure mode that consists in the bearing on the polymer sheet. In order to improve the mechanical behaviour of such joints undergoing shearing loads, the joint bulge height should be increased in order to reduce the bearing stress.
- In clinched connections undergoing shear loads the main quality parameters are the neck thickness, the undercut and the height of the joint bulge. Clinched connections undergoing peeling loads, the dimensions of undercut and neck thickness represent the key geometrical parameters that determine the mechanical behaviour of the joint. In polymer-meatal joints, the former is predominant on the latter since the high difference in the yield strength of the polymer and the aluminium other than the thick aluminium necks.
- Clinched connections performed by flat die were characterized by large neck thicknesses, large height of the bulge but small interlocks; therefore, they showed good performances when undergoing shearing loads but weak behaviour when subjected to peeling loads. Joints performed by rectangular tools were characterized by the presence of the fracture on one arm (owing to the poor ductility of the base material) that compromised the shear strength; on the other hand, these joints showed the highest strength and toughness when

undergoing to peeling tests since the large interlocks. The joints performed with split tools showed the highest performances in shear tests since the high values of the interlock, neck thickness and height of the joint bulge and good performances in peeling tests.

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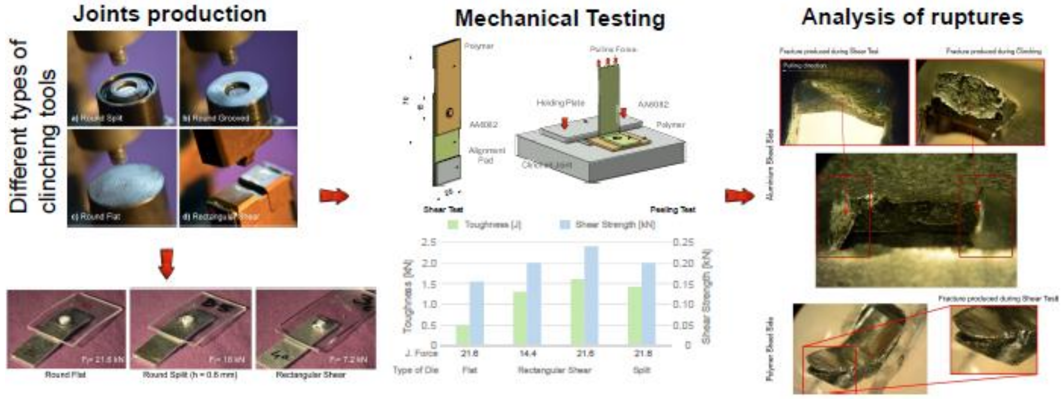

Graphical abstract

Highlight

- Hybrid polymer metal clinched connections were performed using different tools
- Rectangular joints showed weak shearing resistance and the highest peeling strength
- Flat joints were characterized by high shearing strength but weak peeling strength
- Split joints showed the highest shearing strength and also high peeling strength