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Friction-assisted clinching of Aluminum and CFRP sheets

Francesco Lambiase [a,b,*], Alfonso Paoletti [a,b]

[a] Dept. of Industrial and Information Engineering and Economics, University of L'Aquila, via G. Gronchi 18, Zona Industriale di Pile, 67100 (AQ), Italy
[b] University of Naples Federico II, CIRTIBS Research Centre, P.le Tecchio 80, 80125 Naples, Italy

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ABSTRACT

The employment of a rotating tool when joining thin aluminum sheets with Carbon Fiber Reinforced Polymer (CFRP) laminates by means of clinching is investigated. This new process, named friction-assisted clinching, was aimed at increasing the aluminum formability and at the same time reducing the joining forces. An instrumented servo-drilled machine was employed to measure the plunging force and torque during the joining process. The influence of the main process parameters (hole diameter in the CFRP sheet, die anvil depth, tool fillet radius and residual sheet thickness) on quality of the joints and strength was determined. Morphological analysis and mechanical characterization based on single lap shear tests were performed to evaluate the difference among the joints. According to the achieved results, the employment of friction clinching allowed increasing dramatically the material formability and enabled the production of joints without fractures even with sharp pin tools. The advantages of this advanced joining process can be potentially applied to conventional clinching of materials with poor ductility either friction clinching allows increasing the undercut dimension by using sharper tools, which produces higher material flow and leads to an increase in the joint strength.

1. Introduction

Multi-material assemblies and joining processes of such hybrid structures are gaining increasing interest due to the growing employment in different fields including automotive and aircraft industries, civil structures, medical devices, etc. In these assemblies, the characteristics of the materials, differing by physical, mechanical, and technological behavior are exploited to improve the overall performance. These structure often involve metals, polymers and composite materials (with both thermosetting either thermoplastic materials). Because of the great difference among these materials, welding processes, which require that the materials show similar chemical structure and thermal properties (such as the melting points), are not generally suitable for theis purpose.

Adhesive bonding and mechanical joining processes are often involved for this scope. Mechanical joints are characterized by high static and dynamic load capacity and do not require extensive surface preparation with exception of preliminary drilling of both the sheets. The drilling process and the adoption of external fastening element (such as screws or rivets) involve time-consuming and costly preliminary work, require additional material (the connecting element), and increase the structure weight. In addition, hole-drilling may come with damage of the composite material, fiber interruption, and stress concentration. Despite of mechanical joining processes, in adhesive bonds the load is distributed over the entire overlapping area [1–3]; in addition, the absence of holes lead to lower stress concentration. Nevertheless, adhesive bonds are often characterized by a reduced elongation at break, usually smaller than 10% [4–6] and catastrophic failure. In addition, the long curing time and surface preparation (including etching, grinding, and degreasing), result in long processing time, high environmental impact and low standardization of the mechanical behavior. To overcome the above-mentioned limitations, the industrial research is focusing on the development of new joining processes to ensure high repeatability, automatization and productivity. This represents the key step to allow the wider diffusion of such high-performing hybrid structures. To this end, three categories of new joining methods were developed namely, heat-assisted joining, thermoforming and fast mechanical joining processes. In heat-assisted joining processes, such as friction spot joining [7–9], friction lap welding [7,10], ultrasonic welding [11], and laser-assisted joining [12,13], the adhesion between the components is produced by melting the thermoplastic matrix of the composite on the metal substrate. On the other hand, thermoforming joining processes e.g. friction-based stacking [14,15], infrared stacking [16,17], friction riveting [18,19], injection joining

* Corresponding author at: Monteluco di Roio, 67040 (AQ), Italy.
E-mail address: francesco.lambiase@univaq.it (F. Lambiase).

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[20] and flow drilling [21] produce a mechanical interlock between the components. Recent developments have been also reported when laser texturing is produced as pre-treatment of the metal part. Thus, micro teeth are produced on the metal substrate that are forced against the softened thermoplastic polymer to produce distributed micro interlocks as reported for Laser Assisted Joining [22–24] and Friction Assisted Joining [25]. However, the aforementioned processes involve great amount of heat being generated near the joining area; thus, they are not suitable while joining composite having thermosetting matrix (to avoid thermal degradation of the polymer). In this case, fast mechanical joining processes such as Self-Pierce Riveting SPR [26] and Mechanical Clinching MC [27,28] represent valid alternatives to conventional mechanical and adhesive bonding processes. Both these processes do not require a drilled hole with evident simplification and cost reduction. Despite SPR, MC does not require external fastening elements. This leads to reduction in the structure weight and cost. The great advantages allowed by clinching process has attracted the attention of many researchers. Thus, the process, that was originally developed to join steel structures [29,30] has been extended for joining more performing materials including: aluminum [31], magnesium [32,33], titanium [34,35] as well as non-metals materials including polymers [36] and wood [37]. In clinched connections, the joint is produced by high plastic deformation of the sheets (at least the punch-sided one). If the clinching tools are not designed properly, during the clinch joining, damage can occur in different locations, typically at the upper sheet neck and at the lower sheet bulge [38]. During the first phase of clinching (offsetting), the upper sheet undergoes severe thinning because it is drawn between the punch and the lower sheet. An excessively long offsetting phase (e.g. use of deep die-anvils) may lead the upper sheet fracture resulting in unsuccessful clinching. This becomes even more critical in hole-clinching process. In this process, that was originally developed to join metal sheets with composite laminates [39–41], the laminate is previously drilled to reduce delamination of the composite [27,28,42]. Thus, the upper sheet is not supported during the offsetting phase resulting in lower compressive hydrostatic stress and consequently higher material damage [38,43]. In order to rely the stress acting on the upper sheet, smoother punches are adopted (the fillet radius, that in clinching is generally in the range 0.2–0.4 mm, in hole clinching ranges between 2 and 3 mm). The increase in the punch fillet radius comes with a lower material flow (during the upsetting and flow pressing phases) that limits the dimension of the undercut leading to weaker joints.

To extend the suitability of MC to materials with low ductility, several modifications to the original clinching scheme have been proposed. However, to overcome some of the aforementioned formability issues, a spring die has been recently proposed in [44]. Other studies investigated heat assisted clinging with the aim at increasing the ductility of metal sheets; to this end, different heating systems based on induction [33] convective [31], laser [45] or even flame heating [34] have been involved before or during clinch joining. Nevertheless, despite of the increase in the material ductility, the adoption of such heating systems introduced further issues including efficiency of energy consumption (convective heating), difficulty to integrate the system directly on the clinching press (flame heating), production of thermal distortions (as expected by flame heating), relatively high cost of the heating system (laser and induction systems) and safety for the operator (laser source). In a recent investigation [46], the authors developed a modified clinching process, namely Friction Assisted Clinching, which involved a rotating tool was used instead of a fixed tool. This enabled to produce a localized heating of the upper sheet with significant improvement of the material formability. However, only preliminary results were reported as the study was at a beginning stage and the work was mainly aimed at demonstrating the feasibility of the process and identify the potential advantages.

In the present investigation, a more comprehensive analysis of this process is performed. The process was tested during hole-clinching of an aluminum alloy AA6061 and CFRP sheet with epoxy matrix. The influence of the main process parameters, including hole diameter in the CFRP sheet, die anvil depth, tool fillet radius and residual sheet thickness) on quality of the joints and strength was determined. To this end, single lap shear tests, morphological analysis and micro-hardness distribution were carried out. In addition, the thermal history and temperature distribution, as well as the main forces acting during the process were monitored during the joining process.

2. Materials and methods

2.1. Materials

Thin rolled sheets of 2.0 mm thick AA6061 aluminum alloy were used in this study. This kind of alloy is a precipitation hardenable alloy with Si and Mg as main alloying elements. The aluminum sheet was coupled to thin sheets of Carbon Fiber Reinforced Polymer (CFRP) with a thickness of 2.0 mm. these are 50% thicker than those utilized in [46] to further test and stress the aluminum formability.

The CFRP laminates were manufactured using plain weave (SK Chemicals, UGN200). The carbon fiber prepregs (0/90°, 50% in the warp and weft directions, MRC Pyrofil, TR30S) and a thermosetting epoxy resin (bisphenol-A type epoxy + phenol novolac type epoxy) were cured by hot pressing for 2 h at 130 °C and 5 MPa. The final fiber content was estimated to be about 47% in weight.

Mechanical characterization of the materials was performed according to ASTM standards; particularly, tensile tests of the aluminum alloy and CFRP were conducted according to ASTM E8M [47] and ASTMD3039 [48] respectively, while the bearing strength of the CFRP material was conducted according to ASTM D5961-04. The mechanical characteristics of the adopted materials are summarized in Table 1.

2.2. Friction-assisted clinching

During clinching process, the upper sheet undergoes severe tensile and shear stresses which can lead to sheet failure [38]. The amount of stress and eventually damage on the sheets being joined depend on several process parameters including punch-die clearance, die anvil depth, punch corner radius, as well as sheets thickness and material ductility. In the case of hole-clinching, the punch-sided sheet is not supported due to the hole performed in the die-sided sheet leading to higher damage [27]. Thus, Friction Assisted Clinching was tested using a hole clinching configuration, in order to stress the process and verify whether under such extreme conditions, the adoption of a rotating tool enables to reduce the damage of the punch-sided sheet.

Table 1
Mechanical characteristics of the materials.

Material	Elastic Modulus [GPa]	Tensile Strength [MPa]	Elongation at rupture [%]	Flow Stress [MPa]
AA6061	68.9	125	23	
CFRP	175	962.7	0.55	$\bar{\sigma} = 533\,\bar{\varepsilon}^{0.172}$