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Advances in Mechanical Clinching: Employment of a rotating tool

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Abstract

In the recent years, high efforts have been spent concerning the development of fast mechanical joining processes. This is due to the growing employment of materials that are difficult to weld and hybrid structures involving different materials. Mechanical clinching enables to solving the major concerns in this field. However, the formability of the materials represent a limitation to the successful employment of the process. The present research illustrates a new concept of clinching, namely friction clinching that differs from the conventional process by the employment of a rotating tool, which heats up the sheet (by friction) during the process leading to an increase in the material formability. Preliminary tests were performed to verify the feasibility of the process and determine a sound processing window. The process was applied to join thin aluminium sheets and Carbon Fibre Reinforced Plastic (CFRP) laminate. Morphological analysis and mechanical characterization of the joints was performed in order to evaluate the suitability of such the rotating tool to increase the material formability and thus the aluminium sheet integrity. According to the achieved results, the employment of the rotating tool enables to avoid crack formation in the metal sheet, improves the material flow and reduces the joining forces.

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Keywords: Mechanical fastening, joining, aluminum alloy, composite, clinching, CFRP.

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1. Introduction

In the recent years, the employment of multi-material assemblies, including materials that are difficult to weld, is widely employed in different fields including transportation industries, civil structures, medical devices, etc. metal

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sheets are combined with composite materials mainly by mechanical joining processes (involving bolts or rivets) and adhesive bonding. However, both these technologies are characterized by a series of limitations and disadvantages including pretreatment of the substrates before joining (hole drilling for mechanical joining and elimination of oil, grease before adhesive application), addition of external elements, which increase the structure weight as well as cost of joining, environmental impact (due to the employment of solvents for the surface pretreatments) and long curing time. Thus, a number of newer joining processes have been developed in the recent years to overcome the above-mentioned limitations including: friction spot joining [1-3], friction lap welding, [1, 4], ultrasonic welding [5], and laser direct joining [6]. Such processes are suitable when dealing with metals, thermoplastics and composites with thermoplastic matrices. On the other hand, other processes have been developed to join fiber reinforced thermosetting materials such as Self-Pierce Riveting SPR [7] and Mechanical Clinching MC [8, 9]. Both these processes allow to directly join the sheets by avoiding a pre-drilled hole; however, MC does not involve additional fastening elements while SPR requires relatively expensive rivets. This comes with a reduction in the structure weight and process cost. Clinched connections are formed by means of a plastic deformation produced using of a punch and a die. Thus, the main limitation is represented by the sheet material formability [10]. Because of the great advantages of MC with respect to competitive processes, its suitability has been deeply investigated on a large variety of materials other than steel alloys including aluminum [11], magnesium [12, 13], titanium [14, 15] as well as non-metals materials including polymers [16, 17] and wood [18]. In the recent years, different modifications have been proposed to the original process in order to adapt the process to the specific needs e.g. for joining materials with poor formability. To this end, two ways can be pursued: modification and optimization of the design of the clinching tools (e.g. development of flat clinching [13], optimization of the tools geometry [19]) or improving the material formability by means of external heating systems exploiting induction [13] convective [11, 20, 21], laser [22] or even flame heating [14]. Although the aforementioned methods allowed to improve the material formability, they introduced further concerns 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 safe for the operator (laser new heating system has been investigated source).

In the present investigation, a prototypal instrumented machine was developed to conduct a preliminary experimental tests by means of a rotating tool to heat up the sheets during the mechanical clinching. Some process conditions have been varied including the pre-drilled hole diameter, the depth of the anvil and the punch stroke to determine a sound processing window that enables the production of clinched joints without cracks. In addition, loads measurements were performed in order to determine the minimum requirements of a friction-clinching machine.

2. Experimental Procedure

Rolled sheets of 2.0 mm thick of AA6061 aluminum alloy were joined to thin sheets of Carbon Fiber Reinforced Polymer (CFRP) with a thickness of 1.4 mm (whose mechanical characteristics and manufacturing conditions are reported in [8]). Clinched joints were performed by means of a modification to the hole-clinching configuration reported in [23, 24] that consists in the employment of a rotating tool. In the above-mentioned researches, a pre-drilled hole was realized in the CFRP sheet and then the clinching process was performed. This process was particularly suitable to reduce the damage occurring in the CFRP sheet; however, it also came with some drawbacks including the concentricity of the hole and the punch during the MC process, and high damage that may occur in the aluminum sheet during the offsetting phase. This may result in partial cracks at the neck position (as reported in [24]) or even to the complete separation of the button (as reported in [8]). To rely the stress and strain concentration in the aluminum sheet near the punch corner, this problem was partially solved by adopting a large fillet radius (up to 3 mm). However, this came with a reduced material flow during the upsetting phase of clinching that results in the undercut reduction, as reported in [24]. To overcome such a problem, a prototypal apparatus involving a rotating tool was developed. Thus, the friction between the rotating punch and the upper (aluminium sheet) is generated to rise up the temperature of the aluminium near the joint position and thus to increase its formability. The clinched joints were made by means of an instrumented CNC drilling machine. A two-component piezo-electric cell was used to measure the plunging force and torque, while a displacement sensor was used to measure the position of the tool. The load cell was connected to a computer by means of an acquisition board. During the process, load signals were acquired and controlled by the computer by means of a feedback control system.

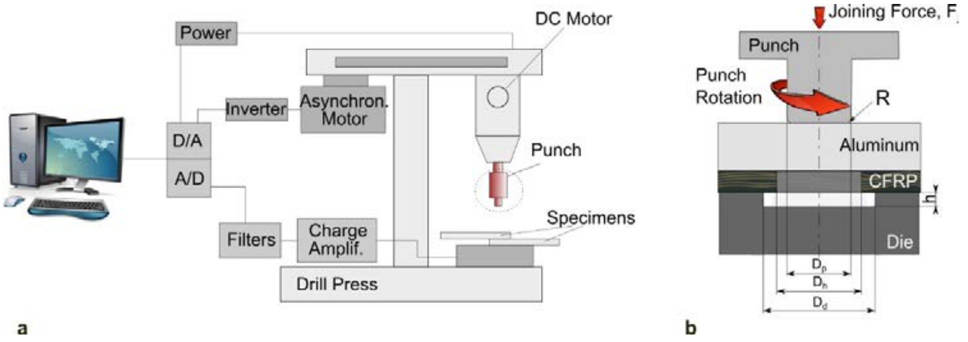

Fig. 1 Schematic representation of the prototypal apparatus developed for friction assisted clinching.

A schematic representation of the developed apparatus is reported in Fig. 1a. The main process geometrical parameters are schematically depicted in Fig. 1b: D_p, and D_d are the punch diameter and the die diameter, while h and R are the die anvil depth and the punch corner radius, respectively. A sharp tool tip was used in all the experiments (R=0 mm) in order to stress the joining process. In addition, this value enables to produce the highest material flow and consequently achieve a large undercut (as compared to tools with larger filler radii). The CFRP sheets were drilled before proceeding with clinch joining by means of precision drill with different diameters D_h. Then, since the limited plunging force available on the developed machine (as compared to that required by clinch joining without rotation) a load-control plunging program was developed in order to overcome that limit. During the experiments, the punch rotated at a given speed (n) and plunged the material (under load control) up to reaching a given depth; then, the punch was retracted up to the initial position. To understand the influence of the process parameters on the joints quality, all the joints were sectioned by means of a precision saw blade used for preparation of metallographic specimens. The cross section of the welds was analyzed by means of optical microscope with low magnification to highlight the differences in terms of dimensions and presence of defects (cracks in the aluminum neck and delamination of CFRP).

Mechanical characterization of the joints was also performed in order to determine the mechanical behavior and main failure load of the developed specimens. To this end single lap shear tests were performed on a universal testing machine model 322.31 by MTS under displacement control with a constant cross-head speed of 0.5 mm/min.

Table 1 Factors and Levels

Levels	Die Anvil Depth, h [mm]	CFRP hole diameter, D_h [mm]	Punch Stroke, P_s [mm]
I	0.7	6.5	3.4
II	1.1	7.0	3.6

3. Results and Discussion

Preliminary experiments were carried out in order to determine a suitable process window. The punch diameter D_p and the die diameter D_d were fixed at 5 mm and 9 mm, respectively. The die anvil depth (h) was varied over two levels, 0.7 mm and 1.1 mm. According to the achieved results, for D_h=6 mm excessive thinning of the aluminium neck was produced resulting in crack development, as shown in Fig. 2d. On the other hand, when a hole diameter D_h=7.5 mm was produced in the CFRP sheet, the undercut was not formed since the aluminium bulge diameter was smaller than the hole realized on the CFRP sheet, as depicted in Fig. 2c. From these results, it was evident that the clearance between the punch and the hole should range between 0.5 mm and 1 mm that is 25-50% of the initial thickness of the aluminium sheet. The other critical parameter for the achievement of a sound clinched connection was the residual thickness of the aluminium sheet at the bulge that determines the amount of material flow and consequently the formation and dimension of the undercut. Indeed, large values of h_p (given by low values of punch stroke P_s) may result in small or even no undercut formation.

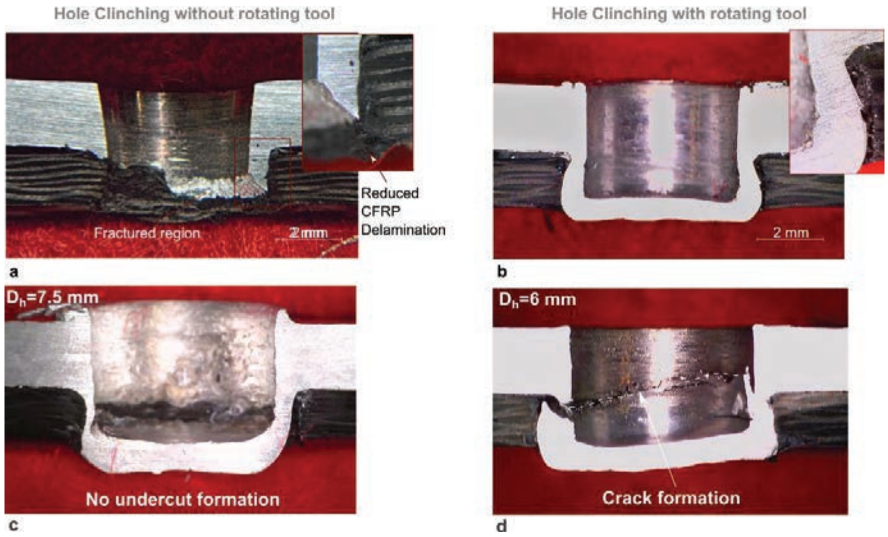

Fig. 2 Comparison of cross section of clinched joints achieved by hole-clinching with (a) common machine and with rotating tool under (b) optimized conditions (c) large hole and (d) small hole.

This is also evident from the main effects plot reported in Fig. 3a, which depicts the influence of the analysed process parameters on the joinability condition. As can be observed, the hole diameter D_h had minimum influence on the joinability, while the die anvil depth h and the punch stroke P_s had more marked influence on the joinability. Similarly, the influence of the process parameters on the shear strength is reported in Fig. 3b. As can be inferred, the process parameter has similar influence on both the joinability and the shear strength. Indeed, the increase in h reduces the shear strength since the excessive thinning of the joints neck. Increasing the punch stroke P_s had beneficial impact on both the joinability and shear strength since it allowed increasing the dimension of the undercut, while the diameter of the drilled-hole in the CFRP laminate was negligible (probably because of the relatively reduced variation of such a parameter). The typical load-displacement curve recorded during single lap shear test of the clinched connections made by rotating tool is reported in Fig. 3c. These joints failed by both pull-out and neck fracture, which are typical failure modes of clinched connections characterized by the ejection of the aluminium bulge from the CFRP hole and the fracture of the aluminium bulge ant the neck location. The shear strength of the joints produced under optimal processing conditions ranged between 0.9-1.2 kN, while the elongation at fracture was almost 2 mm before the complete separation of the sheets.

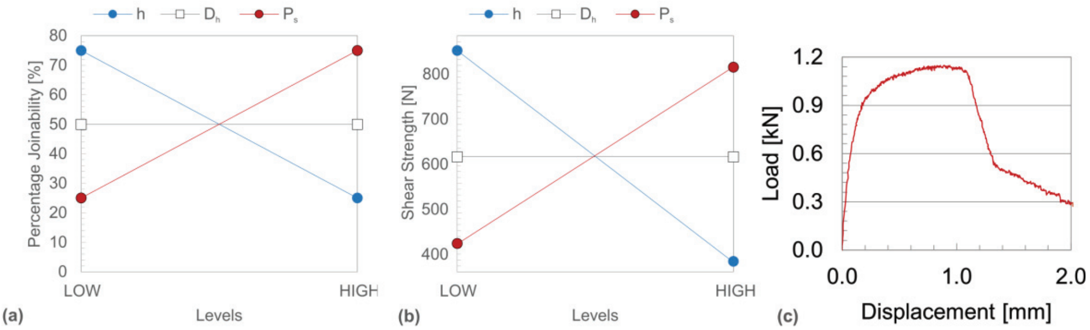

Fig. 3 Influence of the process parameters on (a) the joinability, (b) shear strength and (c) Load-displacement curve of clinched joint with rotating tool.

The employment of the rotating tool (resulting in aluminium heating) allowed to greatly increase the joinability due to the increase of process temperature. This is also evident by comparing Fig. 2a (realized without rotating tool) Fig. 2b-d (realized with the rotating tool). While in the first case the aluminum sheet fractures due to the limited formability of the base material and the absence of a vertical support during the plunging phase, the localized material heating enables to avoid or delay the onset of crack at the aluminum neck. Of course, the material heating may affect the local properties with respect to that of the base material (grains growth, thermal heat treatments leading to avoidance of precipitates in AA6xxx alloys). Thus, this aspect will be treated in detail in a further study.

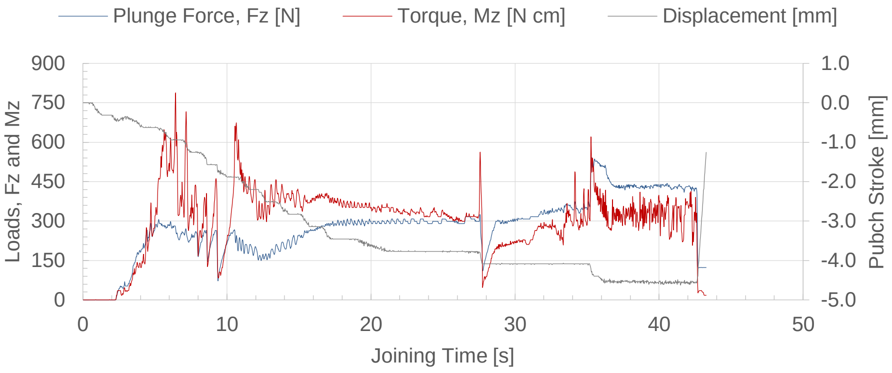

Fig. 4 Variation of plunging force, torque and vertical position of the tool during the friction-clinching process.

In order to design a dedicated machine for friction clinching, the evaluation of the loads during the process represents a fist developing step. Fig. 4 depicts the variation of the plunge force, torque and punch stroke (displacement) during the mechanical clinching using the rotating tool. As can be inferred, the peak load reached during the process is almost 500 N that is much lower than that usually involved in conventional clinching without the rotating tool. Actually, the plunging force in the latter case ranges between 20-30 kN as reported in a number of researches [25-28]; thus, friction clinching enables a reduction by 40-60 times with respect to the process performed without the rotating tool. This is allowed by the great amount of heat that is produced at the punch-upper sheet interface that reduces the yield stress of the material and thus allows such a load reduction. Considering the joining time achieved in this study, it is evident that these are very long as compared to those of conventional clinching (almost 0.5-1 s per joint). Of course such values are dictated by the limitations of the adopted equipment; thus, higher performances machines would enable to dramatically reduce also the joining time.

4. Conclusions

In the present work, a prototypal apparatus was developed to conduct preliminary friction-assisted clinching by means of a rotating tool. Although a deeper investigation is needed in order to make this process available for industrial purposes, from the results achieved in this study, the feasibility of this process was demonstrated. The main findings of the research are as follows:

- Friction-assisted clinching enabled to produce successfully hybrid aluminum/CFRP joints when using hole-clinching configuration. It enabled delaying or even avoiding the development of cracks in the aluminum alloy even when a punch with a sharp corner was utilized;
- the employment of the sharp corner has beneficial effects both from a process point of view (manufacturing, restoration) and for the mechanical behavior of the joints which are characterized by a larger undercut given by a larger material flow;
- the employment of the rotating tool that heats the upper sheet allows to dramatically reduce the plunging force (by 40-60 times with respect to standard clinching). However, despite of the other ones (flame, induction, resistance and laser heating) it can be used during the joining process and not only before the joining process. This allows to reduce the energy required since lower energy loss due to diffusion effects.

- compared to other heating systems, the employment of the rotating tool allows several advantages, e.g. it can be used on highly reflective materials (such as aluminum and copper alloys) without concerns for the safety of the operators, the heating is confined in the joint position, the heating process parameters can be easily monitored and controlled.

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