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A self-clinching fastener for hidden lap joints

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ABSTRACT

This paper presents a new self-clinching fastener to connect two sheets (or plates), made from similar or dissimilar materials, placed over one another by means of a mechanical form-closed joint that is hidden inside the sheets. The development of the fastener, the definition of its main design variables and the identification of its workability limits are carried out by means of a combined experimental and numerical simulation work based on finite elements. It is shown that self-clinching by pressing the two overlapped sheets against each other to displace material around the annular groove of the fastener shank and create undercuts in both sheets requires an appropriate choice of the design variables. Wrong values of the design variables resulting in lack or excess of material displaced by plastic flow gives rise to inappropriate lap joints that cannot be used in production. The new proposed fastener allows, for the first time ever, joining by forming with the use of auxiliary elements that are harder than the sheet materials to fabricate invisible joints with no material protrusions in applications requiring minimum installation space.

Introduction

Lap joints are used to connect metal sheets (or plates) that are placed over one another and are commonly manufactured by welding, adhesive bonding, and mechanical joining. Arc welding, resistance spot welding and friction stir welding are among the most used welding processes but are limited by distortion and residual stresses induced from the heating-cooling cycles, and by weldability problems when the sheets are made from dissimilar materials with different thermomechanical properties [1]. The use of adhesive bonding makes it possible to overcome the above-mentioned difficulties of welding, but its use for mass production is constrained by surface preparation, temperature, durability, crashworthiness, and environmental compliance derived from the use of epoxy or solvent-based agents [2]. The use of clamps, jigs and fixtures is required for applying a uniform pressure on the adhesives during the curing time.

The term 'mechanical joining' applies to a broad range of processes that can be grouped into two main categories: (i) thread fastening and (ii) joining by forming. Thread fastening [3] makes use of auxiliary elements (e.g. bolts and nuts) to produce lap joints that are easy to assemble and disassemble and free from the above-mentioned problems related to thermal cycles, curing time and dissimilar material sheets. However, its utilization is often limited by the existence of material protrusions (bolt head and nut) above and below the sheet surfaces, by the development of non-uniform contact pressures and by the risk of unintentional self-loosening.

Joining by forming [4] combines plastic material flow with at least one of the following three fundamental joining mechanisms: (i) form-closed, (ii) force-closed and (iii) material-closed. Form-closed joints use different types of features such as bends, curls, beads, and undercuts to create mechanical interlockings. Force-closed joints rely on the development of residual normal stresses (pressures) after elastic unloading. Material-closed joints are built upon interatomic and intermolecular forces at the contact interface between the joining elements.

A possible way of classifying the joining by forming processes applicable to lap joints is based on the distinction between those that use or do not use auxiliary elements. Then, in case of the former, it is possible to distinguish between those in which plastic deformation is mainly performed on the sheets, on the auxiliary elements or on both. Fig. 1 resumes this classification and identifies the most well-known joining by forming processes belonging to each specific category.

In the last years, much attention has been paid to clinching (Fig. 1) [5], hemming [6], and self-pierce riveting (Fig. 1) [7] due to their increasing use in the automotive industry [8]. However, other joining by forming processes with auxiliary elements that have received less attention from the research community such as, for

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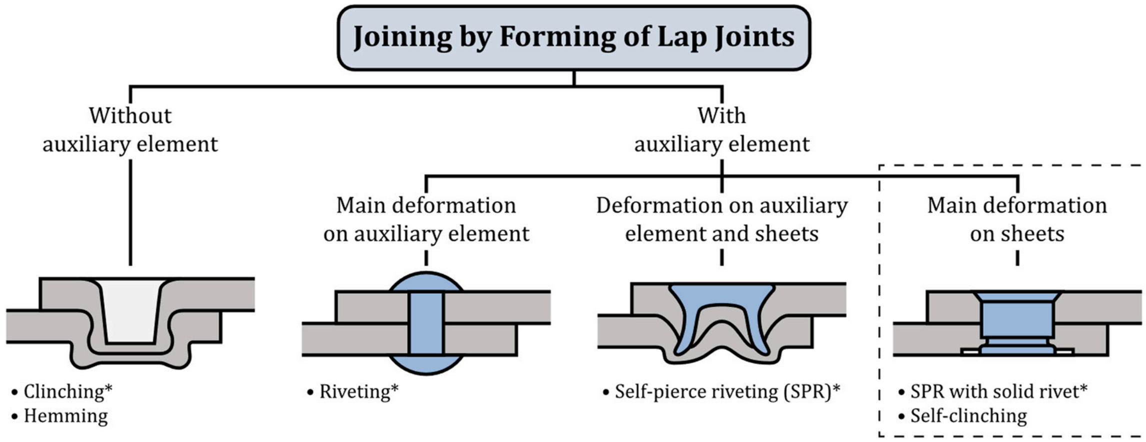


Fig. 1. Classification of the joining by forming processes to connect overlapped metal sheets with identification of the most well-known processes belonging to each category. The asterisk indicates the process shown in the schematic drawing.

example, self-pierce riveting with solid rivets and self-clinching with special designed fasteners (also known as 'self-clinching fastening') are paving the way for becoming increasingly used in automotive and other industries.

Self-pierce riveting with solid rivets (Fig. 1) [9], like conventional self-pierce riveting, does not require holes to be drilled or punched in the overlapped sheets. The holes are created as the rivet is pierced through the sheets, and once the force applied on the conical rivet head starts to plastically deform the upper sheet, which must always be softer than the rivet. Sheet material is then forced to plastically flow into a specially designed annular groove of the rivet shank to create an undercut and a permanent form-closed joint.

Unlike self-pierce riveting, self-clinching (Fig. 2b and 2c) [10] requires holes with properly sized dimensions to be drilled or punched in the overlapped sheets before applying a squeezing force to the fasteners. The applied force causes the sheet material around the fastener to plastically flow into a specially designed annular groove of the shank to create an undercut and a permanent form-closed joint.

Self-clinching fasteners are available in many different shapes [11], like those shown in Fig. 2b–2d, and are an effective and easy-to-install alternative to conventional thread fasteners (Fig. 2a). They have different designations (e.g. 'self-clinching nuts' in case of Fig. 2b and 'self-clinching blind nuts' in case of Fig. 2c), and some of the shapes are protected by industrial patents. However, the original idea of creating fasteners that become an integral part of sheets is due to Swanstrom [12], who patented the concept of 'lock nuts designed to be secured to sheet metal or similar structures' in 1936.

Fig. 2d, shows the ultimate alternative to the use of conventional thread fasteners (Fig. 2a) in which self-clinching makes use of a special designed fastener with two separate grooves in the shank. This other type of fastener is also squeezed into the drilled or punched hole and the applied pressure causes the material from both sheets to plastically flow into the corresponding grooves of the fastener shank to create an undercut (and a form-closed joint) in each sheet.

The self-clinching fastener shown in Fig. 2d is named as 'double-flush' because it prevents protrusions above and below the lap joints by giving rise to upper and lower flush (or sub-flush) surfaces.

Despite the advantages of self-clinching double-flush fasteners in preventing material protrusions and producing smooth sheet surfaces with minimum space requirements, the resulting joints are visible and allow distinguishing the fasteners from the sheets. Because this visibility can be undesirable for aesthetic and safety reasons, one may question if there are self-clinching fasteners to produce invisible lap joints in metal sheets, without having the need to perform post-joining operations of painting or coating to hide the joints.

As far as the authors are aware, no self-clinching fasteners have ever been developed to render lap joints between metal sheets invisible. The closest attempt was recently made by the authors, who developed a special joining by forming process to connect two overlapped metal-polymer sandwich composite sheets [13]. The process involves drilling a blind hole in each sandwich composite sheet for removing the polymer core layer and one metal skin, and fixing the sheets together by compressing an auxiliary flanged ring (or cylindrical) element placed in-between. The auxiliary element must be softer than the metal skins of the sandwich composite sheets and the mechanical interlocking is obtained by forcing material of the auxiliary element to plastically flow into the regions of the sandwich composite sheets that were originally occupied by the polymer.

From all that has been said above it may be concluded that the process for connecting two overlapped metal-polymer sandwich composite sheets cannot be used in metal sheets.

Therefore, the main objective of this paper is to present a new self-clinching fastener that allows producing hidden lap joints in metal sheets made from similar or dissimilar materials. In contrast to the auxiliary elements used in [13], the new self-clinching fastener needs to be harder than the sheets to be joined and its geometry must be designed to permit undercuts and permanent form-closed joints to be formed in both sheets.

Moreover, in contrast to self-pierce riveting with solid rivets (Fig. 1) [9] that are squeezed directly into the sheets, and to existing self-clinching fastening that require drilling through holes in both sheets (Fig. 2) [11], the new self-clinching fastening process involves drilling a blind hole in each sheet and positioning a special designed fastener made from a stronger material in-between them. The sheets are then pressed against each other to displace material around the fastener into the annular grooves of the fastener shank to create undercuts and produce a hidden lap joint.

As in all papers presenting a new manufacturing process, it is the authors' intention to focus on the working principle of the hidden self-clinching fastening process, to identify its design variables and workability limits, and to determine the required joining forces. The work combines experimentation and numerical simulation with finite elements, and shear destructive tests allow evaluating the performance of new joints.

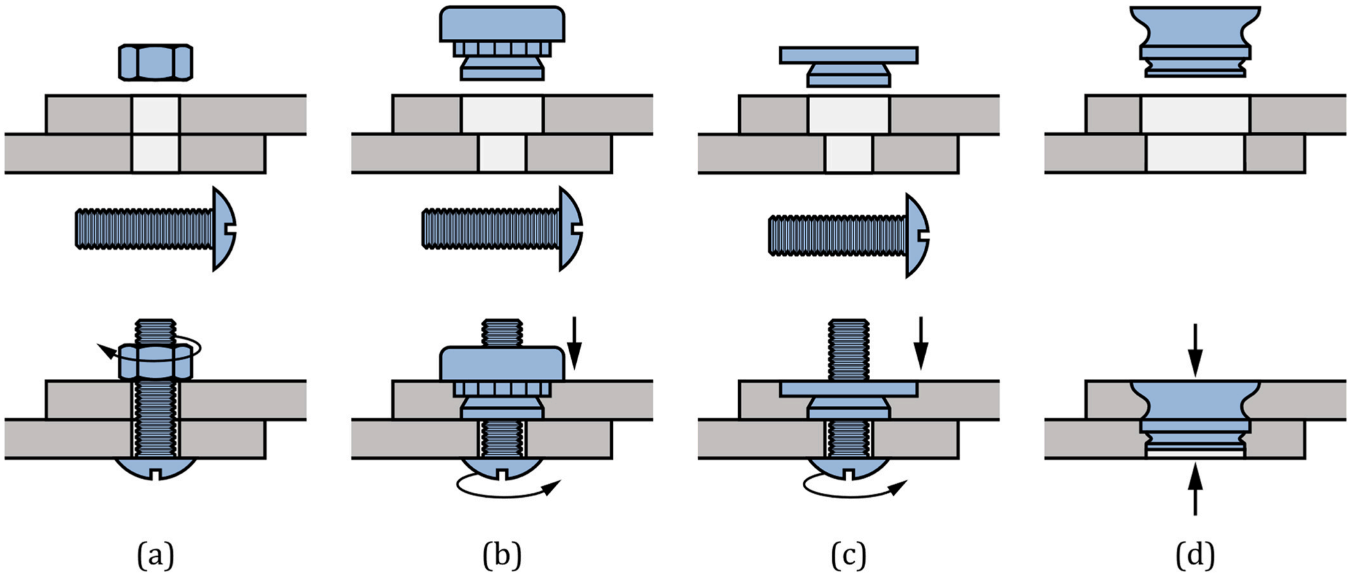


Fig. 2. Thread fastening vs. self-clinching fastening before and after joining. (a)Conventional thread fastening using a bolt and a nut, (b)Self-clinching nuts, (c)Self-clinching blind nuts, (d)Self-clinching double-flush fasteners.

Materials and methods

Material flow curves

The materials utilized in the experiments were AA5754 H111 aluminum sheets with 5 mm thickness and AISI 316 L stainless-steel rods with 15 mm diameter, from which the new self-clinching fasteners were machined.

The flow curve of the aluminum sheets was determined by means of stack compression tests performed on multi-layer cylinder specimens that were assembled by pilling up 3 circular disks with 15 mm of diameter cut out from the sheets [14]. The flow curve of the stainless-steel rods was determined by means of compression tests performed on solid cylinder specimens with 12 mm diameter and 12 mm height that were machined out from the rods.

The multi-layer and solid cylinder specimens were compressed between two flat polished, well-lubricated, parallel platens in a Instron SATEC 1200 kN hydraulic testing machine, with a crosshead speed equal to 10 mm/min and the average material flow curves from these tests are shown in Fig. 3.

The flow curves of the AA5754 H111 aluminum sheets and of the AISI 316 L stainless-steel rods were utilized in finite element modelling of the new self-clinching process.

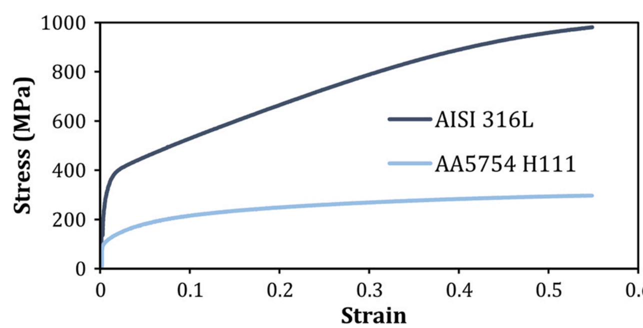


Fig. 3. Flow curves (true stress–true strain curves) for the AA5754 H111 aluminum sheets and the AISI 316 L stainless steel rods at ambient temperature.

Self-clinching experiments

The work was carried out in unit cells that are representative of the new type of hidden lap joints. Their geometry and dimensions (150 mm length, 50 mm width, and 50 mm overlap length) were based in the ISO 14273:2016(E) standard [15] that is commonly used in shear destructive tests of joints produced by resistance welding due to absence of standards for the new type of joints.

The new self-clinching process for producing hidden lap joints is schematically disclosed in Fig. 4a. The process requires pre-drilling a flat-bottom hole in each sheet and positioning a special designed fastener made from a stronger material in-between the two sheets. Then, the sheets are pressed against each other by means of flat parallel platens causing material around the fastener to plastically flow towards its upper and lower heads and into the shank annular grooves. The latter are needed to create undercuts in both sheets and to obtain a permanent form-closed hidden joint that holds the two sheets tightly together.

Fig. 4b shows the geometry of the self-clinching fasteners with identification of its main design variables. Details of the cross-section AA' and of the grooves located in the fastener shank (refer to detail B) are also disclosed. The main design variables of the fasteners include: (i) the outer diameter D, (ii) the total height H, (iii) the upper and lower head diameters d, (iv) the flange height h, and (v) the fillet radius r (vi) the depth a and (vii) the inclination θ of the fastener annular grooves.

To focus the experiments on the deformation mechanics and workability limits of the new self-clinching process, and to limit the total number of tests, authors decided to keep the upper and lower head diameters d and the fillet radius r and inclination θ of the annular grooves of the fasteners with constant values. The total height H, flange height h and depth a of the annular grooves were subjected to variations within the range of values that are listed in Table 1. The outer diameter D was not pre-established because its value is a direct consequence of the values chosen for the other design variables.

The holes in each sheet were made with a depth equal to half of the total height H of the fastener to be used.

The self-clinching experiments were carried out at ambient temperature in the same hydraulic testing machine that was used to obtain the material flow curves. A crosshead speed of 5 mm/min

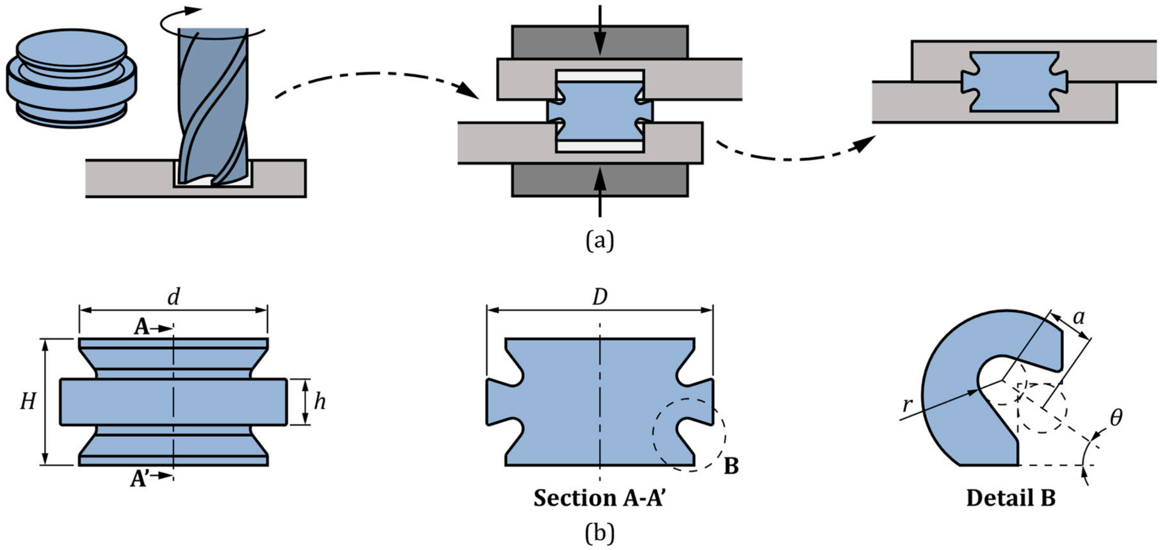


Fig. 4. Self-clinching of hidden lap joints. (a)Schematic representation of the procedure to fabricate the joints, (b)Geometry and design variables of the new self-clinching fastener.

(quasi-static loading conditions) was utilized and at least three samples were prepared for each combination of parameters.

After fabricating the hidden lap joints, some specimens were halved lengthwise to reveal its cross-section and others were subjected to shear destructive tests to determine the maximum force that the new joints can withstand.

Table 1
Summary of the design variables of the self-clinching fasteners utilized in the experiments. Notation according to Fig. 4b.

D (mm)	***H*** (mm)	***d*** (mm)	***h*** (mm)	***r*** (mm)	***a*** (mm)	θ (°)
10–19	4.5–7.5	10	1.5–3	0.5	0.5–1.5	35

Numerical simulation

Self-clinching of hidden lap joints was numerically simulated with the in-house computer program i- form [16]. The program is built upon the finite element flow formulation and allows the sheets and fasteners to be modelled as deformable, isotropic, rotationally symmetric objects. The local compression platens are modelled as rigid objects.

The initial cross sections of the sheets and fasteners were discretized by means of quadrilateral elements with the mesh of the sheets being refined in the regions that are subjected to large plastic deformations and to contact between the deformable objects. The local compression platens were included in the model through the discretization of their contour by means of linear contact-friction elements. Fig. 5 show a typical finite element model with approximately 6000 quadrilateral elements that was utilized in the numerical simulative work at the beginning and end of the self-clinching process.

Friction between the sheets and the compression platens was included in the finite element model by means of the law of constant friction $\tau_f = mk$, where k is the shear flow stress and m is the friction factor. A value of m equal to 0.1 was employed after checking the finite element predicted self-clinching forces that best matched the experimental values.

Results and discussion

Deformation mechanics and workability limits

The working principle of self-clinching of hidden lap joints consists in pressing two overlapped ductile sheets against each other, so that material around the fastener is displaced and plastically flows into specially designed annular grooves of the fastener shank. This creates an undercut and a form-closed joint in each sheet and the fastener eventually becomes an integral part of both sheets.

However, the deformation mechanics of self-clinching of hidden lap joints is dependent on the geometry of the fastener because situations may arise in which the fastener will not work properly and, therefore, no adequate joint will be made. Fig. 6 shows three different experimental and finite element predicted cross-sections corresponding to three different modes of deformation that were obtained from distinct combinations of the design variable values utilized to define the geometry of the fasteners (Table 1).

The first deformation mode shown in Fig. 6a, corresponds to a situation where plastic deformation of the sheet material around the fastener is not sufficient to fill the annular grooves of the fastener shank. As a result of this, the undercut is almost inexistent, and no acceptable form-closed joint is obtained between the two overlapped sheets. Hereafter, we will refer to this deformation mode as 'mode 1 – inadequate joint due to lack of material'.

The second deformation mode shown in Fig. 6b, corresponds to a combination of design variables that is capable of simultaneously ensuring complete filling of the annular grooves and good contact with absence of empty spaces along the interface between the two overlapped sheets. This deformation mode is named as 'mode 2 – adequate (or sound) joint'.

The third deformation mode shown in Fig. 6c, corresponds to a situation of excessive material displaced by plastic deformation. Interfacial contact is affected by the amount of displaced material and empty spaces are triggered between the two overlapped sheets. This deformation mode will be hereafter referred to as 'mode 3 – inadequate joint due to excessive material'.

Now, by extending the experimental and numerical simulative work to other combination values of Table 1, it is possible to obtain a much broader characterization of the deformation modes and to define the workability limits of self-clinching as a function of the fastener's main design variables. The result is shown in Table 2, and it is worth mentioning that the positions occupied by the so-called mode 4 do not correspond to real deformation modes of self-clinching. In fact, the term 'mode 4′ is utilized to identify the combination values of design variables that do not allow the fasteners to

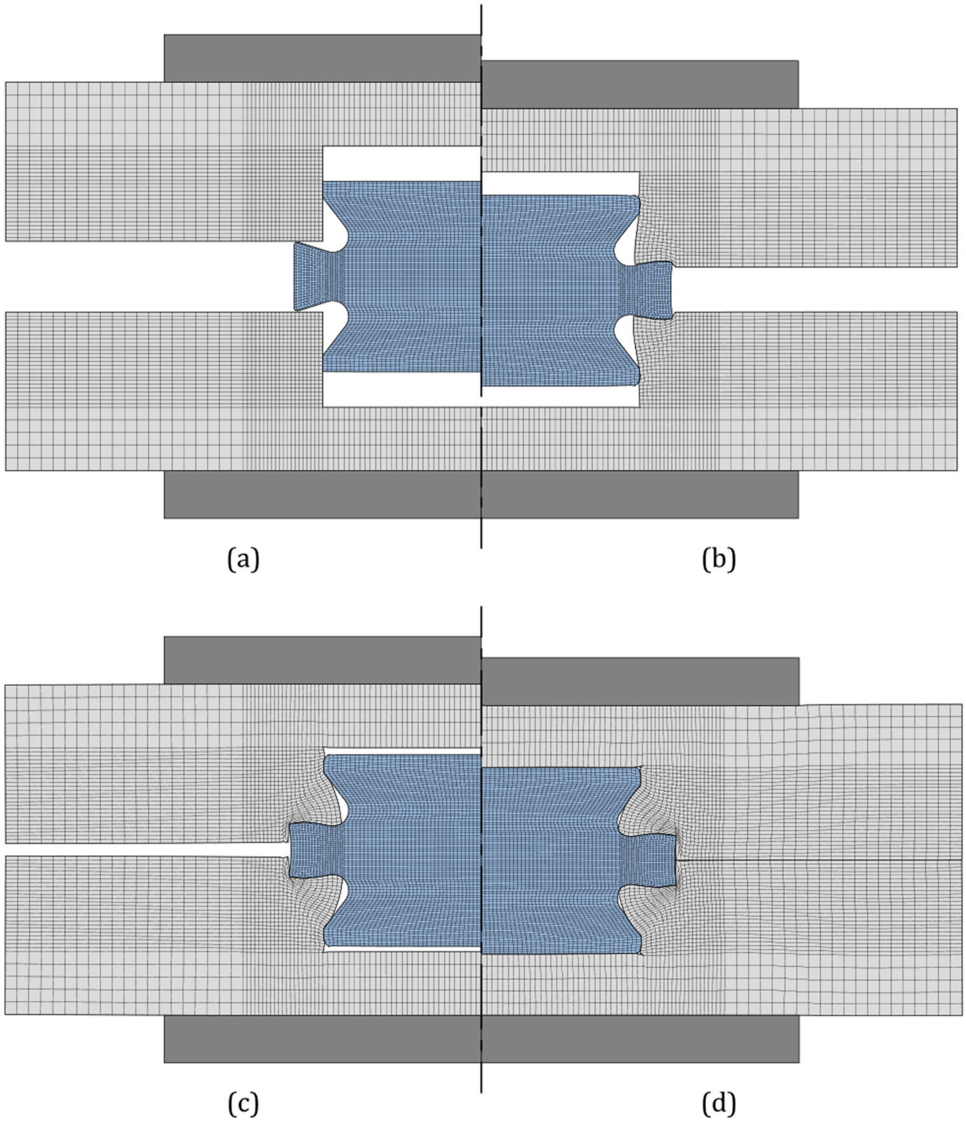


Fig. 5. Finite element model of the self-clinching of hidden lap joints showing (a) the initial mesh, (b) the intermediate mesh after 33% of total vertical displacement, (c) the intermediate mesh after 66% of total vertical displacement, and (d) the final mesh at the end of the process.

be fabricated. In practical terms mode 4 corresponds to fasteners that cannot be used in self-clinching of hidden lap joints due to absence (or very small) flange heights *h*.

The results included in Table 2 show that for each value of the total height *H* of the fasteners, there will always be a combination of values for the remaining design variables to fabricate an adequate hidden lap joint (mode 2). The depth of the annular groove *a*, for example, must increase with *H* because of the greater amount of material being displaced around the fastener by plastic deformation. The increase of the flange height *h* with *H* is also a consequence of

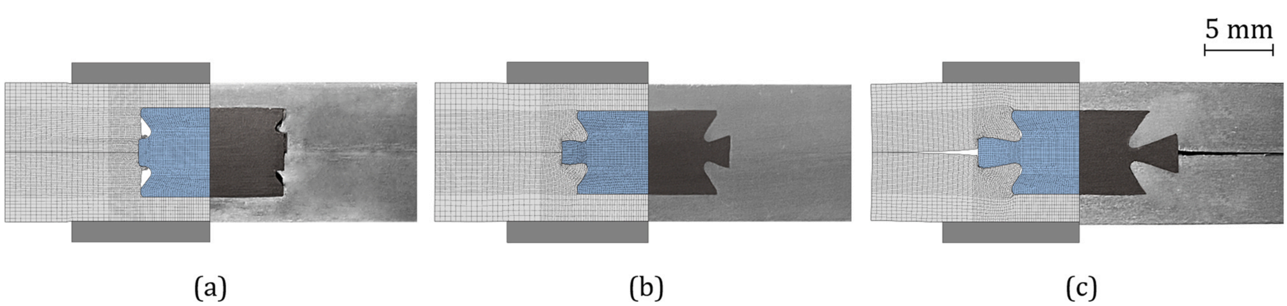
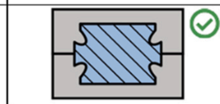
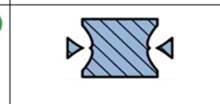
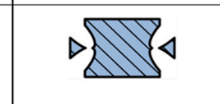
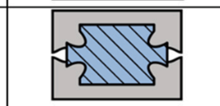
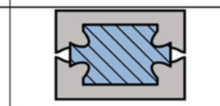
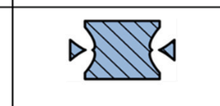
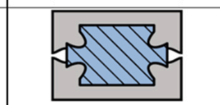
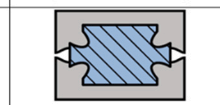
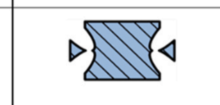
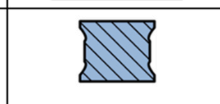
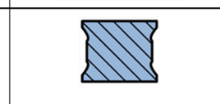
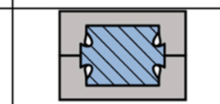
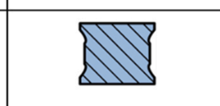
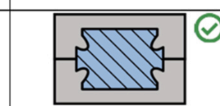
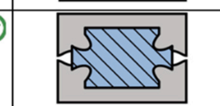
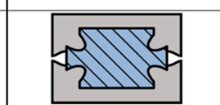
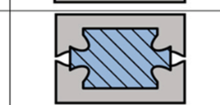
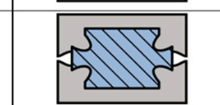
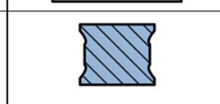
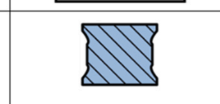
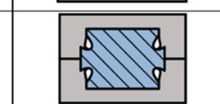
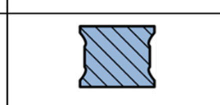
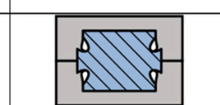
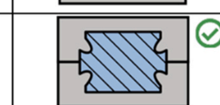
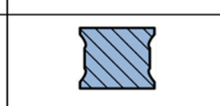
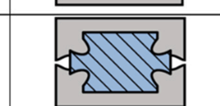
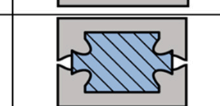
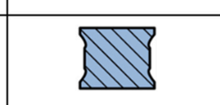
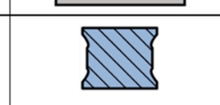
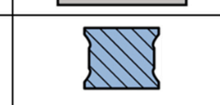
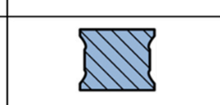
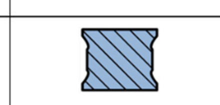
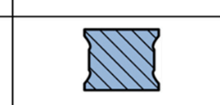
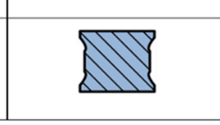
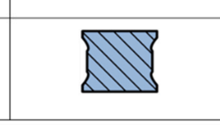
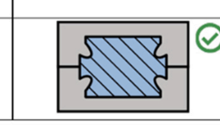
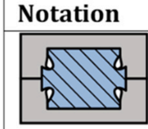
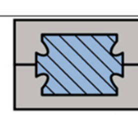
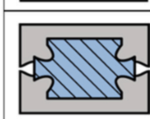
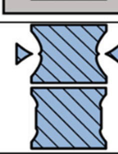


Fig. 6. Finite element predicted cross-sections and photographs of three different modes of deformation that may arise in self-clinching of hidden lap joints. (a) Mode 1 - lack of material (H = 6.5 mm, h = 2.25 mm and a = 1mm), (b) Mode 2 – adequate joint (H = 6 mm, h = 2.25 mm and a = 1mm), (c) Mode 3 - excess of material (H = 6 mm, h = 3 mm and a = 1mm).

Table 2
Workability limits of self-clinching of hidden lap joints distinguishing between adequate (mode 2) and inadequate (modes 1 and 3) modes of deformation, and fasteners not possible to be fabricated (mode 4).

		a **(mm)**		
H **(mm)**	***h*** **(mm)**	0.5	1	1.5
4.5	1.5			
	2.25			
	3			
6	1.5			
	2.25			
	3			
6.5	1.5			
	2.25			
	3			
7.5	1.5			
	2.25			
	3			

Notation

	**Mode 1**		**Mode 2**
	**Mode 3**		**Mode 4**

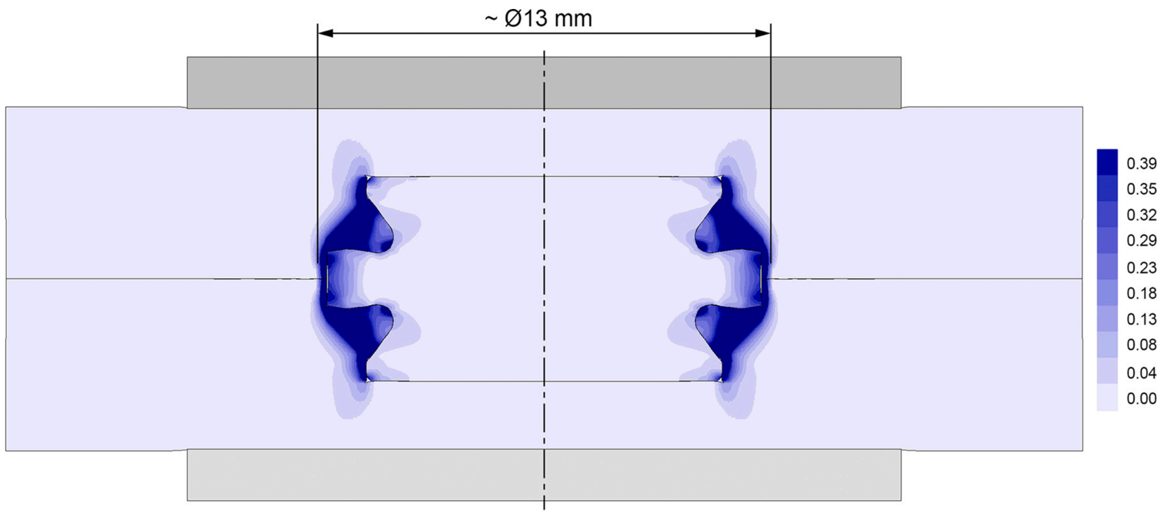


Fig. 7. Finite element computed distribution of effective strain for a self-clinching hidden lap joint corresponding to H = 6 mm, h = 2.25 mm and a = 1mm.

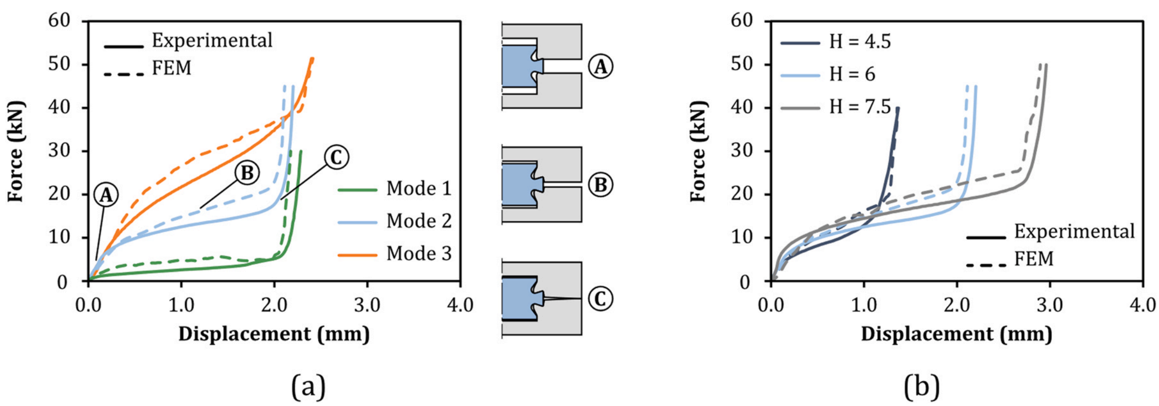


Fig. 8. Experimental and finite element predicted evolution of the self-clinching force with displacement of the local compression platen for two different sets of tests. (a) Modes 1, 2 and 3 corresponding to the combinations of design variables of Fig. 6 where ‘A′, ‘B′ and ‘C′ correspond to 0.2 mm, 1.2 mm, and 2.0 mm of displacement, respectively, (b) Mode 2 joints produced with self-clinching fasteners having different total height values (H = 4.5 mm with h = 1.5 mm and a = 0.5 mm, H = 6 mm with h = 2.25 mm and a = 1 mm, and H = 7.5 mm with h = 3 mm and a = 1.5 mm, refer to Table 2).

what was mentioned before because h is directly related to the depth a of the annular grooves when the values of the fillet radius r and of the inclination θ are kept constant (refer also to Fig. 3b and Table 1).

A topic that arises directly from the sheet material being displaced around the fasteners by plastic deformation is the minimum allowable distance between two successive joints. Fig. 7 shows the finite element predicted distribution of effective strain for a sound hidden lap joint (mode 2), which allows concluding that plastic deformation is limited to a small region around the fastener. Beyond a diameter of approximately 13 mm, for the test case included in Fig. 7, the effective strain drops to near zero, allowing fasteners to be placed very closed to each other.

Joining and shear destructive forces

Fig. 8 shows the experimental and finite element predicted evolution of the self-clinching force with displacement for two different sets of test cases. The test cases that are included in Fig. 8a correspond to modes 1, 2 and 3 of Fig. 6. As seen, when the amount of displaced material around the fasteners is less than (mode 1) or equal to (mode 2) that needed to fill the annular grooves, the force grows very little with displacement (refer to instant ‘B′ in Fig. 8a) and only presents a steep increase at the end of the process when the two overlapped sheets get into contact with each other (refer to ‘C′). A self-clinching force of approximately 20 kN corresponding to the beginning of contact between the two overlapped sheets (refer to ‘C′ once again) was calculated and measured for the fastener design variables of mode 2.

In contrast, when the displaced material around the fastener is greater than necessary, there is a monotonic increase of the force with displacement caused by the excessive amount of material subjected to plastic deformation and the progressive contact between the two overlapped sheets along their contact interfaces.

The selected test cases included in Fig. 8b correspond to adequate (sound) joints (mode 2) produced with values of the design variables retrieved from Table 2. As seen, the evolution trend of the self-clinching force with displacement is similar and differences are mainly related to the total amount of displacement and maximum force required by each test case. The longest fastener H=7.5 mm with the deepest annular groove a = 1.5 mm presents the highest displacement and force values whereas the shortest fastener H=4.5 mm with the shallowest annular groove a = 0.5 mm presents the smallest displacement and force values. The use of self-clinching forces beyond the equivalent to instant ‘C′ of mode 2 increases the risk of damaging the sheets by excessive plastic deformation of the material around the fasteners.

The performance of the new hidden lap joints was evaluated by means of destructive shear tests carried out in an Instron 4507

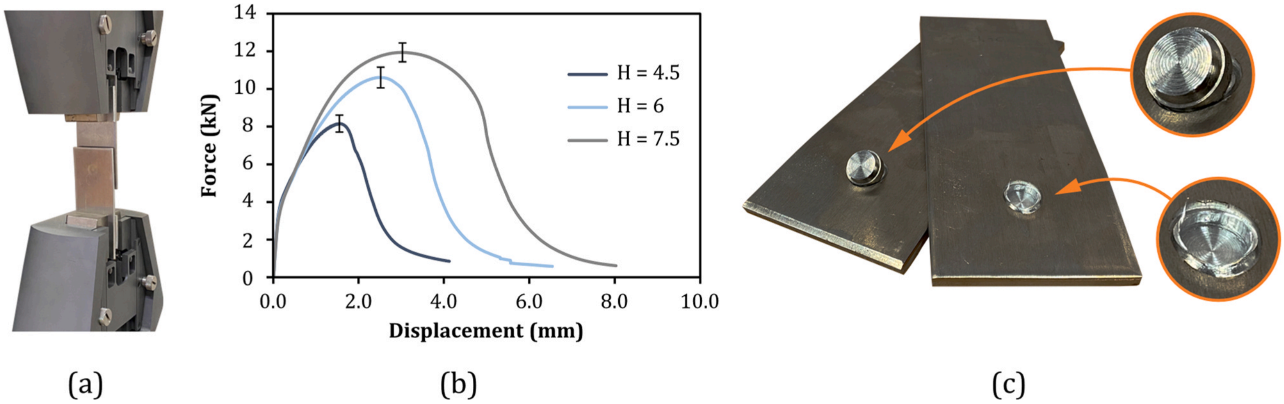


Fig. 9. Destructive shear testing of the self-clinching hidden joints. (a) Photograph of the shear testing apparatus, (b) Evolution of the destructive force with the crosshead displacement of the testing machine for self-clinching fasteners under deformation mode 2 (H = 4.5 mm with h = 1.5 mm and a = 0.5 mm, H = 6 mm with h = 2.25 mm and a = 1 mm, and H = 7.5 mm with h = 3 mm and a = 1.5 mm, refer to Table 2). (c) Photograph of a test specimen after separation with details of the fastener and hole.

Fig. 10. Application of the self-clinching fastener to hidden lap joints made from dissimilar materials (C11000 copper and AA5754 H111 aluminum sheets).

universal testing machine (Fig. 9a). Fig. 9b shows the evolution of the separation force with displacement for the three adequate (sound) joints corresponding to the test cases of Fig. 8b. As seen, the fasteners are detached from the sheets by pull-out (Fig. 9c) and the required separation forces to destroy the joints (corresponding to the peak forces in Fig. 9b) are smaller for the shortest fastener due to its smaller undercut value. Error bars at the peak values allow observing the variations in results that were obtained for the three samples utilized for each testing condition.

The photograph and details included in Fig. 9c combined with the slow drop in the force vs. displacement evolutions after reaching the peak forces allows concluding that full separation occurs with significant amount of plastic deformation.

Hidden lap joints made from dissimilar materials

The last section of this paper shows an example of application of the new proposed self-clinching fastener to produce hidden joints between Copper C11000 and AA5754 H111 aluminum overlapped sheets with 5 mm thickness (Fig. 10). The selected example was chosen from current research trends in electric vehicles, electric substations, and industrial installations, to replace monolithic busbars made from copper by hybrid busbars made from copper and aluminum due to their potential of combining the excellent electrical conductivity of copper with the low density and cost of aluminum.

In contrast to thread fastening solutions based on the use of bolts and nuts, the new self-clinching fastener installs without material protrusions above and below the sheet surfaces and does not suffer from self-loosening problems caused by mechanical and/or thermal loading during service life [15].

Conclusions

A self-clinching process that makes use of a new type of fastener and presses the sheets against each other instead of squeezing the fastener directly into the sheets was successfully utilized to fabricate invisible lap joints. The fastener must be harder than the sheets and include two annular grooves to allow undercuts to be formed and permanent form-closed joints to be created inside the two overlapped sheets.

A workability lobe summarizing different combinations of the fastener design variables related to the total height H, flange height h and depth a of the annular grooves allows concluding that non-acceptable joints result from lack or excess of plastically displaced material and from a physical impossibility of appropriate fasteners being fabricated.

The observation and analysis of the force evolution in self-clinching and destructive testing allows concluding that the steep rise in force at the end of joining needs to be closely monitored to prevent the risk of damaging the sheets by plastic deformation and that failure by separation of the two sheets occurs by pull-out after extensive plastic deformation.

An application of the new self-clinching fastener to hybrid busbars made from copper and aluminum sheets demonstrates its potential to be used in modern distribution of electric power trends.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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