Joining by Plastic Deformation

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**Abstract.** This paper draws from the existing processes and applications of joining by plastic deformation to a comprehensive overview of a new set of processes that have been recently developed by the authors. The presentation includes solutions for connecting tubes, sheets and tubes to sheets and provides information on the tooling systems, operating variables, deformation mechanics and workability limits. Results from analytical modelling, finite element analysis and experimentation give support to the presentation and prove the feasibility of the new joining by plastic deformation processes for connecting tubes, sheets and tubes to sheets made from dissimilar materials, at room temperature, without having to use addition materials or adhesives. The resulting joints are easy to disassembly at the end of live, thereby allowing recyclability of the individual parts.

**Introduction**

The last years have seen a great increase in the utilization of joining by plastic deformation due to numerous advantages over conventional joining technologies such as welding, adhesive bonding and mechanical fastening or riveting.

Joining by plastic deformation can be accomplished by (i) interfacial pressure and/or (ii) mechanical interlocking [1]. The first type of mechanism relies on the interference pressure acting on the contact surface between the components to be joined, after unloading. The second type of mechanism combines plastic flow of the materials with the utilization of different types of features such as, bends, curls, beads, dimples and cutouts, to shape and force a locking connection between the components to be joined (Fig. 1).

![Fig. 1. Schematic illustration of the two basic mechanisms of joining by plastic deformation.](image_url)

(a) Interfacial pressure;  
(b) Mechanical interlocking.

**Figure 2 presents a selection** of joining by plastic deformation processes that make use of the two above mentioned mechanisms.
Fig. 2. Several joining by plastic deformation processes.

(a) Joining by heating and cooling;
(b) Electromagnetic joining;
(c) Clinching;
(d) Self-pierce riveting;
(e) Hemming;
(f) Joining by press-in fasteners.

In joining by heating and cooling (Fig. 2a) one of the components (plate) is punched by a second non-heated, harder, component (rod). After cooling the first component shrinks and is fixed against the second component by interfacial pressure [2].

Electromagnetic joining (Fig. 2b) uses pulsed magnetic fields to fix components made of highly conductive materials by interfacial pressure or mechanical interlocking [3].

Clinching (Fig. 2c) is utilized to connect two or more sheets by local plastic deformation without additional materials or accessories [4]. The punch pushes the sheets into a die and forms a mechanical interlock with good static and dynamic strength.

Self-piercing riveting (Fig. 2d) is a combined cutting-riveting process for connecting two or more sheets [4]. The mechanical interlock is achieved without prior formation of holes as in case of conventional riveting.

Hemming (Fig. 2e) is also a joining process that makes use of local plastic deformation to connect two sheets. The process requires one of the sheets to be folded around the other in order to ensure a mechanical interlock between the two sheets [4].

Joining by press-in fasteners (Fig. 2f) is based on a mechanical interlock of nuts (or bolts) with a pre-punch hole in a sheet metal. The process applies a squeezing force that moves the material out of the wall of the hole into the groves of the fasteners in order to ensure a permanent connection [4].

In general, it may be concluded that joining by plastic deformation allows connecting individual components made from dissimilar materials and is free from thermal effects after welding and
curing time requirements of adhesives. The connections are relatively easy to disassemble, thereby allowing recyclability of the individual components at the end-of-life.

In addition to what was mentioned above, it is also worth noting that plastic deformation can be applied more widely and that its resulting joints are often stronger than those produced by fastening and riveting, which are limited by aesthetic and space requirements, and by the maximum force that bolts, screws and rivets can safely support. Although fastening and riveting is commonly considered the fastest and cheapest technology to mechanically connect two or more objects, joining by plastic deformation is sometimes considered the most economic and reliable alternative to produce customized multi-material products. Table 1 compares the main characteristics and features of the most widely used joining technologies with those of joining by plastic deformation.

Table 1. Summary of the main characteristics and features of the most widely used joining technologies.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Welding</th>
<th>Adhesive bonding</th>
<th>Fastening and riveting</th>
<th>Plastic deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt, lap, corner and edge joints</td>
<td>Melting point</td>
<td>Lap and strapped joints</td>
<td>Mechanical fastening with bolts, screws and rivets</td>
<td>Interfacial pressure and mechanical interlocking</td>
</tr>
<tr>
<td>Room or heat (&lt;200°C) curing temperature</td>
<td>Room temperature</td>
<td>Room temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes (microstructure and distortion)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Residual stress</td>
<td>Similar metals</td>
<td>Dissimilar</td>
<td>Dissimilar</td>
<td>Dissimilar</td>
</tr>
<tr>
<td>Stress concentration in the fasteners and rivets</td>
<td>Low residual stresses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>Coated materials</td>
<td>Not recommended (compatibility and surface smoothness)</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>Very difficult or impossible</td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy consumption</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Productivity</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>High (Labour, inspection and equipment)</td>
<td>Medium</td>
<td>Low</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Environmental friendliness</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Further information and understanding of joining by plastic deformation is available in the state-of-the-art reviews of Mori et al. [1], Groche et al. [5] and Wang et al. [6], who addressed the fundamentals of the process and identified the most significant applications. They concluded, among other things, that joining by plastic deformation offers great potential in tube, sheet and tube-sheet connections because it successfully ensures the growing demands for high productivity, low fabrication costs and environmental friendliness with high performance and material versatility.

Under these circumstances, the main objective of this paper is to present an overview of a new set of joining by plastic deformation processes that have been recently developed by the authors for connecting tubes, sheets and tubes to sheets, at room temperature. The selected processes cover applications in which the components to be joined have their axis inclined, collinear or perpendicular to each other. Both metallic and polymeric materials are considered.

The overall structure of the paper is the following. Section 2 is focused on tube connections and provides details and applications of processes built upon the development of plastic instability waves in thin-walled tubes subjected to axial compression. Section 3 is focused on sheet connections and provides details and applications of processes based on mortise-and-tenon joints produced by sheet-bulk forming. Section 4 is based on tube-sheet connections and follows the aims
and objectives of the previous two sections. The joining processes to be considered are based on mechanical interlocking based on plastic instability and sheet-bulk forming by partial compression of the tube wall thickness. Section 5 presents the conclusions.

**Tube Connections**

**Tool Systems and Process Variables.** The new set of processes for joining tubes by plastic deformation that were developed by the authors make use of axisymmetric or asymmetric plastic instability waves in thin-walled tubes subjected to axial compression. Two different situations were considered; (i) connections in which the axis of the branch tube is perpendicular or inclined to the axis of the main body tube (Fig. 3a) and (ii) connections of tubes by their ends (Fig. 3b).

In case of joining tubes in which the axis of the branch tube is perpendicular or inclined to the axis of the main body tube, the left-hand side drawings of Fig. 3a shows the upper and lower dies that are needed to trigger and propagate inclined, out-of-plane, instability waves between contoured dies at the open and closed positions \([7, 8]\).

The right-hand side drawing in Fig. 3a shows an application for producing inclined tube joints. The sectional views show the active tool components consisting of upper and lower contoured dies and internal mandrels (if present). The internal diameter of the dies is dedicated to a specific reference radius \(r_0\) of the main body tube. The radius \(R_d\) of the parting out-of-plane surface of the dies is dedicated to a specific radius of the branch tube. The difference between the radius \(R_{d+2r_0}\) and \(R_d\) of the upper and lower parting surfaces is crucial to accommodate the plastic compression bead at the end of stroke. The initial gap opening \(l_{gap}\) between the upper and lower contoured dies controls triggering and propagation of the plastic instability waves namely, the number, width and relative position of the compression beads along the axis of the main tube.

In case of joining tubes by their ends (Fig. 3b) the mechanical interlocking is accomplished by a sequence of three different plastic deformation stages that are carried out sequentially in a single stroke, at room temperature: (i) expansion, (ii) local buckling and (iii) clamping \([9]\).

Expansion is performed by forcing the upper tube against the chamfered end of the lower tube in order to enlarge the unsupported height \(l_0\) of the upper tube radially and to create adjacent counterfacing surfaces between the two tubes to be joined. During this stage the chamfered end of the lower tube acts like a tapered punch (refer to ‘first stage’ in Fig. 3b).

Once the unsupported height \(l_0\) of the upper tube reaches the lower edge of the depth of insertion \(l_{inc}\) resulting from the radial clearance between the tube and the upper end of the lower die, there is a sudden change in material flow and plastic instability waves are triggered as a result of local buckling under axial compression loading (refer to ‘second stage’ in Fig. 3b). The internal mandrel ensures that the plastic instability waves are formed exclusively outwardly so that design specifications of the inner diameter of the tube joint are met.

Finally, propagation of the plastic instability waves under continuous axial compression loading clamps the adjacent counterfacing surfaces of the two tubes by mechanical interlocking (refer to ‘third stage’ in Fig. 3b). It is worth noting that although the new proposed joining by plastic deformation process has been developed for carbon steel tubes it can also be used in tubes made from other metals or thermoplastics (refer to Fig. 6).
The main operating parameters influencing the new proposed processes for joining tubes by plastic deformation are: (i) the slenderness ratio $l_{\text{gap}}/r_0$ between the initial gap opening and the reference radius of the tube, (ii) the ratio $t_0/r_0$ between the wall thickness and the reference radius of the tube, (iii) the radius $R_{d+2t_0}$ and $R_d$ of the parting surfaces of the upper and lower dies, (iv) the mandrel (if present) and (v) the tribological conditions.

The next section addresses the deformation mechanics and the workability limits of the two joining by plastic deformation processes that are shown in Fig. 3.

**Deformation Mechanics and Workability Limits.** Fig. 4 shows the results obtained for the finite element analysis of the tube connections in which the axis of the branch tube is perpendicular or inclined to the axis of the main body tube. The simulations were carried out in the finite element computer program i-form, which is being developed by the authors since the 1980’s [10].

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**Fig. 3.** Schematic representations of the tool systems utilized for joining tubes by plastic deformation.

(a) Joining two tubes perpendicular or inclined to each other [8, 9];
(b) Joining two tubes by their ends [10].
Fig. 4. Joining tubes in cases where the axis of the branch tube is perpendicular or inclined to the axis of the main body tube.

(a) Finite element model and predicted geometries at the middle and end of stroke with photograph of an inclined connection ($\alpha = 30^\circ$) between the two tubes;

(b) Photograph and finite element predicted geometries disclosing the influence of the internal mandrel in the development of sound asymmetric, in-plane, plastic instability waves for connecting tubes;

(c) Applications with full-size and half-sectioned tubes with inclination angles of 0, 15, 30 and 45 degrees.

Fig. 4a shows the initial, intermediate and final predicted geometry of a tube attachment where the axis of the branch tube (labelled as ‘Tube B’) is inclined by 30° to the axis of the main body tube (labelled as ‘Tube A’). As seen in the figure, joining is performed by means of two inclined, out-of-plane, plastic instability waves that closely match the intersection of the two tubes. Two different types of mandrels are employed; (i) a conventional internal mandrel placed inside the main body tube (‘Mandrel A’) and (ii) a special purposed sectioned internal mandrel made of two different parts (‘Mandrel B’) placed inside the branch tube. The conventional mandrel avoids the development of unacceptable inward plastic flow during triggering and propagation of the plastic instability waves whereas the special purposed sectioned mandrel (allowing for the easy removal of mandrel in practice) prevents the compression beads to plough into the branch tube. The branch tube behaves as a sleeve during the entire joining process and its internal sectioned mandrel contributes decisively to ensure the overall success of the inclined joining process.

Fig. 4b, allows understanding the role played by the internal mandrel in preventing the development of plastic instability waves exhibiting both inward and outward plastic flow because
they would lead to the formation of non-acceptable tube joints. This justifies the reason why the utilization of internal mandrels is mandatory to ensure the required quality and tolerances for the inclined tube connections.

Fig. 4c shows applications of the joining by plastic deformation process for connecting tubes (or half-tubes) in situations where the axis of the branch tube is perpendicular or inclined to the axis of the main body tube. The test cases shown in Fig. 4c were performed with welded carbon S460MC steel tubes and seamless aluminium AA6062 tubes.

Fig. 5 shows a photograph of several tube specimens that were connected by their ends using the joining by plastic deformation process that is schematically shown in Fig. 3b. The observation of the actual and finite element predicted cross sections in Figs. 5a and 5b allows concluding that the leftmost test sample (corresponding to \( l_{gap}/r_0 = 1.9 \)) does not ensure locking between the two tubes whereas the rightmost test sample (corresponding to \( l_{gap}/r_0 = 4.4 \)) presents a joint with two compressions beads instead of one.

![Fig. 5. Joining tubes by their ends.](image)

(a) Experimental joints and cross sections;
(b) Finite element predicted geometries for joints produced with different values of the slenderness ratio \( l_{gap}/r_0 \).

In case of the leftmost test sample, the absence of connection is because the initial unsupported gap height \( l_{gap} \) is not big enough to allow compression beads to develop and lock with each other by plastic instability. In case of the rightmost test sample, the formation of two compression beads instead of one is due to the fact that high values of the initial unsupported gap height \( l_{gap} \) provide conditions for the development of multiple compression beads that will interfere and be placed on top of each other, as they are formed in-between the upper and lower dies.

Neither the operative conditions corresponding to the leftmost test sample nor those corresponding to the rightmost test sample are acceptable for connecting two tubes by their ends. The process window is therefore restricted to values of the slenderness ratio \( l_{gap}/r_0 \) in the range between the two abovementioned limits. However, as mentioned by Silva et al. [9], it is worth noticing that the process window must not be confused with the potential range of applicability because the limits on the slenderness ratio \( l_{gap}/r_0 \) only define the range of values of the unsupported heights of the upper and lower tubes that need to be utilized for successfully connecting any two tubes by their ends.

Finally, Fig. 6a shows the connection of welded carbon S460MC steel and polyvinylchloride (PVC) tubes by their ends performed by a variant of the process shown in Fig. 3b [11]. The process variant is shown in Fig. 6b and requires the metal tube to be firstly expanded with a mandrel and, subsequently, assembled and locked by compression beading with the polymer tube by means of localized plastic instability.
Fig. 6. Extending the technology of joining tubes by their ends to hybrid metal-polymer joints. (a) Photograph showing a PVC tube connected to a S460MC steel tube by their ends together with a cross section that allows visualizing the mechanical lock between the two tubes; (b) Schematic representation of the variant of the joining by forming process shown in Fig. 3 that needs to be utilized for hybrid metal-polymer joints.

Sheet Connections

**Tool Systems and Process Variables.** The new process for connecting sheets by plastic deformation that was developed by the authors combines sheet-bulk forming with a ‘mortise-and-tenon’ joint concept [12]. This type of joint is characterized by a rectangular cavity (‘mortise’) cut-out in one sheet and by a tenon cut-out in the edge of the other sheet that passes entirely through the mortise of the first sheet (Fig. 7a). The tenon is longer than wider and is compressed perpendicular to the thickness direction in order to plastically deform its free length and ensure a mechanical lock between the two sheets to be joined. Both the mortise and tenon were prepared by blanking but they could also have been obtained by laser or water jet cutting, among other processes.

Fig. 7. Joining sheets perpendicular to one other by plastic deformation. (a) The proposed ‘mortise-and-tenon’ joint with a detail showing a typical unit cell; (b) Schematic representation of the laboratory tool system for connecting a unit cell.
A close observation of a typical ‘unit cell’ of the new proposed ‘mortise-and-tenon’ joint for connecting two metal sheets perpendicular to each other (refer to the detail in Fig. 7a) allows concluding that the tenon acts like a rivet. The smooth head end of the rivet is replaced by the connection of the tenon to the surrounding material of the sheet and the opposite free end of the tenon (hereafter designated as ‘the tail’) is upset by sheet-bulk compression in order to produce a flat shaped surface head.

The major process parameters are identified as: (i) the length-to-width ratio \( l_f/w_0 \), where \( l_f \) is the free length and \( w_0 \) is the width of the tenon, (ii) the thickness-to-width ratio \( t_0/w_0 \) where \( t_0 \) is the thickness and \( w_0 \) is the width of the tenon, (iii) the mechanical strength of the two sheets to be joined and (iv) the thickness of the two sheets to be joined.

Fig. 7b, presents a schematic representation of the laboratory tool in which process development was carried out. The main active components of the tool are: (i) the compression punch, (ii) the die segments and (iii) the blank holder with suitable screws to clamp the lower sheets firmly in position during the tests. The tool was installed in an universal testing machine and the tests were performed in displacement control under a constant vertical velocity.

**Deformation Mechanics and Workability Limits.** Fig. 8 shows the experimental and finite element predicted evolutions of the force with displacement for a unit cell of the new proposed ‘mortise-and-tenon’ joint. Five different length-to-width ratios \( l_f/w_0 \) of the tenon were utilized.

Results show that when the length-to-width ratio \( l_f/w_0 < 2 \) there are no signs of out-of-plane buckling and the force-displacement evolution allow disclosing three different regions labelled as ‘A’, ‘B’ and ‘C’ (refer to \( l_f/w_0 = 1 \), in Fig. 8). Region ‘A’ corresponds to a very short initial period of time when the force experiences a steep rise and is immediately followed by region ‘B’ in which the force grows monotonically at a lower rate as the free length of the tenon is progressively upset by compression along the direction perpendicular to its thickness. Region ‘C’ corresponds to the final period of time when the free length of the tenon is folded over the upper surface of the other sheet in order to lock the two sheets together. As seen in the figure, the maximum force attained at the end of the joining process increases with the length-to-width ratio \( l_f/w_0 \) for producing final deformed flat surfaces of the tenon with equal thicknesses.

![Fig. 8](image_url)

Fig. 8. Experimental and finite element predicted evolution of the force with displacement for connecting two sheets perpendicular to one another by means of a ‘mortise-and-tenon’ joint.

Fig. 9a shows the predicted finite element cross section of a sound joint with \( l_f/w_0 = 0.5 \) at the beginning and final locking stage. Excessive force in the final locking stage may cause the upper sheets to bend, as shown in the predicted finite element cross section and photographic detail included in Fig. 9b.
Fig. 9. Joining sheets perpendicular to one another by means of a ‘mortise-and-tenon’ joint. 
(a) Finite element predicted cross section of a sound joint ($l_f / w_0 = 0.5$); 
(b) Finite element predicted cross section of an unacceptable joint ($l_f / w_0 = 1.5$) resulting from 
excessive folding and compressive loading during the final locking stage; 
(c) Unacceptable joint ($l_f / w_0 = 2.0$) resulting from out-of-plane buckling.
The type of joint shown in Fig. 9b occurs for $l_f/w_o \geq 1$ and is unacceptable for production purposes. The compression force during the final locking stage must be controlled in order to avoid excessive bending of the upper sheets.

A second group of defects involves buckling of the slender tenons (Fig. 9c). It is advisable to limit the length-to-width ratio $l_f/w_o$ to 2 in order to upset the tenons uniformly and produce symmetric ‘mortise-and-tenon’ joints.

Finally, it is important to inform that the performance of the new proposed mortise-and-tenon joints were assessed by means of destructive tests aimed at determining the tensile force to detach the two sheets. In case of a sound joint with $l_f/w_o = 0.5$ it was found that the separation of the two sheets is accomplished by cutting off the flat-shaped surface head of the tenon along the straight edges of the mortise. The mortise acts like a cutting die, and the inspection of the cut surfaces reveals a very small smooth (burnished) region and a large rough fractured region caused by cracking that are typical of cutting by shearing with small clearances. The tensile force to detach the two sheets was measured and its value is approximately equal to 14 kN [12].

**Tube-Sheet Connections**

**Tool Systems and Process Variables.** The new set of processes for joining tubes to sheets by plastic deformation that were developed by the authors make use of (i) axisymmetric or asymmetric plastic instability waves in thin-walled tubes subjected to axial compression (Fig. 10a) or (ii) sheet-bulk forming by partial compression of the tube wall thickness and upsetting (Fig. 10b).

![Diagram](image1)

(a) Joining by mechanical interlocking produced by axisymmetric or asymmetric plastic instability waves in thin-walled tubes subjected to axial compression.

(b) Joining by mechanical interlocking produced by upset compression of sheet-bulk formed tubes.

![Diagram](image2)
The utilization of axisymmetric or asymmetric plastic instability waves for joining tubes to sheets at room temperature makes use of compression beading and tube end flaring (Fig. 10a). The plastic instability waves are produced by means of appropriate flat or contoured dies whereas flaring is accomplished by compressing the upper tube end with and appropriate radiused punch in order to expand material outwards and form a single-lap inclined flange [13].

The major process parameters are the internal diameter of the dies, which is dedicated to a specific reference radius \( r_0 \) of the main body tube, the inclination \( \alpha \) of the parting out surface of the dies to the axis of the main body tube, which is dedicated to a specific instability wave and the initial gap opening \( l_{gap} \) between the upper and the lower contoured dies, which controls triggering and propagation of the plastic instability waves namely, the number, width and relative position of the compression beads along the axis of the main tube.

The process is an alternative to conventional joining processes such as welding, adhesive bonding and fastening or riveting because it requires no additional filler materials and accessories, and avoids the problems of forces being concentrated at the points of fastening or riveting. However, the resulting tube-sheet joints may show cracks in the plastically deformed beads in case of materials with low fracture toughness [14] and may also experience loosening during impact or repeated loading and unloading.

In order to overcome the above mentioned problems arising from the integrity and reliability of the compression beads produced by local plastic instability, Alves et al. [15] recently proposed the utilization of sheet-bulk forming and upsetting to produce tube-sheet connections (Fig. 10b). The sheet-bulk forming of tubes involves partial compression of the tube wall thickness in order to pile-up material along its axial (longitudinal) direction and produce a localized annular flange with rectangular cross section and tight dimensional control (Fig. 10b). The upsetting of the free tube end against a sheet with a countersunk (conical) or counterbored (flat-bottomed) hole ensures the mechanical interlocking of the tube to the sheet by means of a flat joint with no protrusion of the tube end above the sheet surface.

The major process variables of this alternative joining by plastic deformation are shown in Fig. 11a and comprise the free height \( h \) and the wall thickness \( t \) of the tube end, the inner radius \( r_0 \) of the tube, the sheet thickness \( t_s \) and the cross sectional area \( ab \) of the sheet hole (in case of a rectangular counterbored sheet hole).

Assuming the sheet to behave as a rigid object during the upsetting of the tube end, it is possible to established the following relation \( b = f(a) \) between the height \( b \) and the width \( a \) of the flat-bottomed sheet hole,

\[
b = \frac{ht(2r_0 + t)}{(a + t)(a + 2r_0 + t)}
\]

(1)

This equation corresponds to an infinite set of curved lines similar to that shown in Fig. 11b whose position varies with the selected process variables related to the free height \( h \), wall thickness \( t \) and inner radius \( r_0 \) of the tube. Each curved line provides the design guidelines to guarantee that the counterbored sheet hole is completely filled by the free tube end without a protrusion above the surface of the sheet.
Fig. 11. Joining tubes to sheets by sheet-bulk forming and upsetting.
(a) Main variables and notation associated with the new proposed type of joint;
(b) Process curve and deformation modes associated to different processing conditions labelled as ‘A’ to ‘E’;
(c) Typical joints corresponding to deformation modes I, II and III.

**Deformation Mechanics and Workability Limits.**

The inclined tube-sheet connections shown in Fig. 12a were obtained by asymmetric plastic instability waves. This applies to joints produced by means of two-stage asymmetric compression beading as well as to joints produced by asymmetric compression beading and flaring.

The figure shows metal sheets of different materials and thicknesses that were assembled to S460MC tubes at different inclination angles. Besides being successfully employed for joining sheets to tubes at different inclination angles, the proposed tube-sheet joints can also be employed for interlocking metals with polymers or sandwiches of polymers and metals, among other materials. A polycarbonate sheet connection to S460MC steel tubes is disclosed in Fig 12a.

However, the production of sound inclined joints between polymer sheets and steel tubes by means of two-stage asymmetric compression beading is limited by a more compact range of process operating conditions than those commonly used for inclined tube-sheet plastically deformed metallic joints. In fact, the highest admissible values of the slenderness ratio $l_{gap}/r_0$ ($l_{gap}/r_0 = 1.56$) for tube-sheet metallic joints gives rise to undesirable bending of the polymer sheets in case of attempting to assemble a PVC sheet to a S460MC steel tube. This is shown in the experimental and finite element predicted geometries of the tube-sheet joints that are included in Fig. 12b.

The abovementioned limitations are due to difficulties of the PVC sheets to withstand the local pressure of the compression beads without being pushed and bent away from the tube when the amount of non-symmetric plastic flow caused by the slenderness ratio is significant. Similar unsuccessful results can be obtained when the assembly of the polymer sheets to the steel tubes is performed under high values of the compressive loads.
Fig. 12. Joining tubes to sheets by plastic instability waves in thin-walled tubes subjected to axial compression.

(a) Photographs of the sheet-bulk connections between metals (S460MC steel tubes and AA5754 sheets or DC04 sheets) and metals and polymers (S460MC steel tubes and polycarbonate sheets);

(b) Finite element and experimental modelling of the connection between a metal tube (S460MC steel) and a polymer sheet (polycarbonate).

From what was mentioned in the previous section regarding the joining of tubes to sheets by sheet-bulk forming and upsetting, it is concluded that the cross sectional geometries of the counterbored sheet hole with different aspect ratios $b/a$ that are labelled as ‘A’, ‘B’ and ‘C’ and are located along the curved line $b = f(a)$ will be completely filled for identical values of the free height $h$, wall thickness $t$ and inner radius $r_o$ of the tube. The associated deformation mode is designated as ‘mode II’ (Fig. 11c).

In contrast, if the values of free height $h$, wall thickness $t$ and inner radius $r_o$ of the tube are kept constant, the cross sectional geometries labelled as ‘D’ and ‘E’ located above and below the curved line $b = f(a)$ should correspond to inadmissible joints. The geometry ‘D’ gives rise to a joint that is not completely filled due to lack of upset material from the tube end (deformation mode I) and the geometry ‘E’ gives rise to a joint with protrusions of the deformed tube end above the surface of the sheet due to excess of upset material (deformation mode III).

The dashed grey horizontal line of Fig. 11b is related to geometry constraints and corresponds to the limiting workability condition of the height $b$ of the counterbored sheet hole being equal to the sheet thickness $t_s$. 
\[ b = t_s \]  \hspace{1cm} (2)

The dashed grey vertical line of Fig. 11b derives from the workability limit caused by cracking during the upsetting of the free tube end,

\[ a = a_c \]  \hspace{1cm} (3)

The limiting condition \( a_c \) corresponds to a critical width \( a \) above which the upper tube end will fail by cracking during upsetting, before finish filling out the counterbored sheet hole. In case the cross sectional geometry ‘C’ is located to the right of the limiting condition \( a = a_c \) a new deformation mode IV will be observed as a result of crack opening in the outer surface of the plastically deformed free tube end. The occurrence of this deformation mode is directly dependent on the aspect ratio \( b/a \) of the joint and on the fracture toughness of the tube material.

Figs. 13a and 13b shows the experimental and finite element predicted modes of deformation for a joint made from aluminum AA6063-T6 tubes with an inner radius \( r_0 = 14.5 \text{ mm} \) and a wall thickness \( t_0 = 1.5 \text{ mm} \) and aluminum AA7178-T6 sheets with a thickness \( t_s = 4 \text{ mm} \). The overall agreement is very good and sound joints are easy to fabricate under deformation mode II (Fig. 13c)

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Fig. 13. Joining tubes to sheets by sheet-bulk forming and upsetting.
(a) Finite element predicted cross sections of the joints corresponding to deformation modes I, II and III (cases ‘D’, ‘A’ and ‘E’ of Fig. 11b);
(b) Photographs of the cross sections of the mechanical joints corresponding to (a);
(c) Photographs of the sheet-bulk formed tubes and of the resulting tube-sheet connection.
Conclusions

The new joining by plastic deformation processes for connecting tubes, sheets and tubes to sheets offer several advantages as compared with conventional technologies based on welding, adhesive bonding and mechanical fastening or riveting. This is because the new joining by plastic deformation processes are:

- flexible solutions that are capable of handling small, medium or large batch sizes with different geometries and high levels of repeatability in production line;
- simpler solutions that allow savings in raw material and eliminate addition materials, accessories and shielding gases;
- energy saving solutions that eliminate heat-cooling cycles as well as heat affected zones in the regions of the tubes and sheets to be joined;
- value added solutions that are capable of connecting tubes, sheets and tubes to sheets made of dissimilar materials such as metals and polymers;
- cost efficient solutions that require low amount of capital investment because they can be designed to operate with existing machine-tools;
- environmental friendly solutions because the connections are relatively easy to disassemble, thereby allowing recyclability of the individual components at the end-of-live.

Because the new joining by plastic deformation processes can be successfully employed in fixture conditions that are difficult and costly to ensure by means of conventional joining technologies they can also foster innovative ideas in product development.

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