JOINING BY FORMING

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Introduction

The last years have seen a great increase in the utilization of joining by forming 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:
(a) Interfacial pressure and/or
(b) Mechanical interlocking.
Introduction

The following picture presents a selection of joining by forming processes that make use of the two above mentioned mechanisms.

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

Comparison of the main characteristics and features of the most widely used joining technologies with those of joining by forming.

<table>
<thead>
<tr>
<th></th>
<th>Welding</th>
<th>Adhesive bonding</th>
<th>Fastening/Riveting</th>
<th>Joining by Forming</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanism</strong></td>
<td>Melting with addition of filler materials</td>
<td>Physical adsorption and chemical bonding</td>
<td>Mechanically affix two or more objects with bolts, screws and rivets</td>
<td>Interfacial pressure and mechanical interlocking</td>
</tr>
<tr>
<td><strong>Shape of the connections</strong></td>
<td>Butt, lap, corner and edge joints</td>
<td>Lap and strapped joints</td>
<td>Lap and edge joints (other shapes with accessories)</td>
<td>Arbitrary</td>
</tr>
<tr>
<td><strong>Joining temperature</strong></td>
<td>Melting point</td>
<td>Room or heat (&lt;200ºC) curing temperature</td>
<td>Room temperature</td>
<td>Room temperature</td>
</tr>
<tr>
<td><strong>Heat-affected zones</strong></td>
<td>Yes (microstructure and distortion)</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Stress-affected zones</strong></td>
<td>Residual stress</td>
<td>Uniform stress distribution</td>
<td>Stress concentration in the fasteners and rivets</td>
<td>Low residual stresses</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>Similar metals</td>
<td>Dissimilar</td>
<td>Dissimilar</td>
<td>Dissimilar</td>
</tr>
<tr>
<td><strong>Coated materials</strong></td>
<td>Very difficult or impossible</td>
<td>Not recommended (compatibility and surface smoothness)</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Productivity</strong></td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>High (Labour, inspection and equipment)</td>
<td>Medium</td>
<td>Low</td>
<td>Medium/Low</td>
</tr>
<tr>
<td><strong>Environmental friendliness</strong></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
Introduction

Excellent state-of-the-art reviews on joining by forming were published by Mori et al., Groche et al. and Wang et al. The three papers address the fundamentals of the process and identify the most significant applications.

Under these circumstances,

• The main objective of my presentation is to provide an overview of a new set of joining by forming processes that have been recently developed by the authors for connecting tubes, sheets and tubes to sheets, at room temperature.

• The joining processes to be considered are mainly based on mechanical interlocking by plastic instability, bending/flaring or sheet-bulk forming.

• Both metallic and polymeric materials are considered.

• The selected processes cover applications in which the components to be joined have their axis inclined, collinear or perpendicular to each other.
Tube connections

Perpendicular or inclined tube connections
Tube connections

Perpendicular or inclined tube connections

The processes are based on controlling the development and propagation of plastic instability waves in thin walled tubes subjected to axial compression. Finite element modelling allows understanding the deformation mechanics associated with triggering and propagation of the inclined, out-of-plane, plastic instability waves.
Tube connections

Perpendicular or inclined tube connections
Experiments confirmed that deformation modes are dependent on the slenderness ratio $l_{\text{gap}}/r_0$ and on the inclination angle of the dies, among other parameters.
Perpendicular or inclined tube connections

When the slenderness ratio $\frac{\text{lgap}}{r_0}$ is very large deformation mode 3 not only produces two asymmetric instability waves that interfere destructively with each other, as the second instability wave often results incomplete due to absence of free gap opening between the upper and lower dies at the end of stroke.
Tube connections

Perpendicular or inclined tube connections

The utilization of internal mandrels is mandatory in order to ensure triggering and propagation of the sound plastic instability waves (with outward dominant plastic flow) that are needed to produce the inclined tube attachments.
Perpendicular or inclined tube connections

Load-displacement evolutions allow understanding the development of plastic instability waves.
Perpendicular or inclined tube connections

Finite element modelling allows modelling the deformation mechanics of the inclined tube joints.
Tube connections

Perpendicular or inclined tube connections
Tube connections

Connections of tubes by their ends

The process is based in mechanical interlocking 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.
Connections of tubes by their ends

Finite element modelling allowed understanding the deformation mechanics associated with the expansion, local buckling and clamping by mechanical locking that are needed for connecting the tubes by their ends.
Connections of tubes by their ends

The process is based on the development and propagation of two plastic instability waves in thin walled tubes subjected to axial compression. Experimental and finite element predicted cross sections allowed concluding that the leftmost test sample does not ensure locking between the two tubes whereas the rightmost test sample presents a joint with two compression beads instead of one.
Tube connections

Connections of tubes by their ends
Extending the connections of tubes by their ends to dissimilar materials 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.
Connections of tubes by their ends

Another example of the connection of tubes made from dissimilar materials by their ends.

The grips (purple and grey colours) are split in two halves and can be hydraulically actuated for locking and compression. The dies (black colour) are also split in two halves for allowing the two joined tubes to be easily removed.
Tube connections

Connections of tubes by their ends

Extending the connections of tubes by their ends to thermoplastic tubes made from polyvinylchloride (PVC), polyethylene (PE) and polypropylene (PP).
Sheet connections

Mortise-and-tenon joints

The new joining by forming process for connecting two metal sheets perpendicular to each other that was developed by the authors combines sheet-bulk forming with a ‘mortise-and-tenon’ joint concept.
Sheet connections

Mortise-and-tenon joints

A close observation of a typical ‘unit cell’ of the new proposed ‘mortise-and-tenon’ joint 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.
Sheet connections

Mortise-and-tenon joints

Finite elements allow understanding and defining the deformation mechanics and the workability limits of the process.
Sheet connections

Mortise-and-tenon joints

The maximum required forces are relatively small and the experimental and finite element predicted evolutions of the force with displacement for a unit cell of the new proposed ‘mortise-and-tenon’ joint disclose sensitivity to the length-to-width ratio, which is a major process parameter.
Sheet connections

Mortise-and-tenon joints

The cut surfaces and of the force-displacement evolution obtained from destructive tensile testing reveals that ‘mortise-and-tenon’ joints are detached by shearing along the contour of the mortise. The maximum tensile load that is safely withstand by the joints can be estimated by the classical analytical expression derived from conventional blanking:

$$F = C \sigma_{UTS} A_c$$
Sheet connections

Mortise-and-tenon joints

Crash boxes with ‘mortise-and-tenon’ joints can absorb the same energy and avoid problems related to the utilization of formed panels made from dissimilar materials with different thicknesses due to residual stresses induced by resistance spot-welding.
Sheet connections

Extension to metal-polymer sandwich composites

Major drawbacks on the utilization of metal-polymer sandwich composites are the costs associated with materials and processes, namely the necessity of joining parts made from sandwich composites with other adjoining components. This was the motivation to extend the application of mortise-and-tenon to metal-polymer sandwiches by means of a new, less expensive, joining by forming process.

The goal is to produce a flat-shaped head with a compression bead to increase the overall strength of the joint.
Sheet connections

Extension to metal-polymer sandwich composites

The joining by forming process cannot be performed in a classical single stage approach due to the risk of buckling.
Sheet connections

Extension to metal-polymer sandwich composites
Application of the new joining by forming process to the assembly of lightweight structural panels made from a series of representative unit cells.
Sheet connections

Lap joints
Authors developed a new joining by forming process to produce lap joints in metal sheets that combines partial cutting and bending with mechanical interlocking by sheet-bulk compression of tabs in the direction perpendicular to thickness.

(or, lancing)
Sheet connections

Lap joints

The numerical simulation of the process (bending and sheet-bulk compression) was carried out with an in-house computer program built upon the finite element flow formulation.
Sheet connections

Lap joints

Different thicknesses combinations are allowed and the design of the process is derived from an analytical model that relates the cutting length $L$ to be performed on the two sheets with their thicknesses and clearance $c$ between the bent tabs.

![Graph showing contact pressure (MPa)](attachment:image)
Sheet connections

Lap joints
The new lap joint has a dual advantage of being stronger (10.7 kN vs. 5.4 kN) and perfectly flat, with all the plastically deformed material contained within the thickness of the two sheets partially placed over one another.
Plastic instability waves in thin-walled tubes

The utilization of axisymmetric or asymmetric plastic instability waves for joining tubes to sheets makes use of compression beading and tube end flaring. Plastic instability waves are produced by means of appropriate flat or contoured dies whereas flaring is accomplished by compressing the upper tube end with an appropriate radiused punch and form a single-lap inclined flange.
Tube-sheet connections

**Plastic instability waves in thin-walled tubes**
Potential applications can be found almost elsewhere and can easily make use of dissimilar materials (e.g. polymers and metals)
Tube-sheet connections

Plastic instability waves in thin-walled tubes
An industrial application retrieved from the bottom seat frame of a passenger car.
Sheet-bulk forming and upsetting

Sheet-bulk forming of tubes involves partial compression of the tube wall thickness in order to pile-up material along its axial direction and produce a localized annular flange with rectangular cross section and tight dimensional control. Subsequent upsetting of the free tube end against a sheet ensures mechanical interlocking of the tube to the sheet.
Sheet-bulk forming and upsetting

Alternatively the upsetting of the free tube end can be performed against a sheet with a countersunk (conical) or counterbored (flat-bottomed) hole to ensure 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.
Sheet-bulk forming and upsetting

Finite element modelling allows understanding the deformation mechanics associated with the upsetting of the sheet-bulk formed tube end and allow establishing the workability limits of the joining by forming process.
Sheet-bulk forming and upsetting

The workability limits can be defined as a function of the height and width of the flat-bottomed sheet hole.
Conclusions

The new proposed joining by forming processes offer several advantages against conventional technologies because:

• They 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;
• They are simpler solutions that allow savings in raw material and eliminate addition materials, accessories and shielding gases;
• They are 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;
• They are value added solutions that are capable of connecting tubes, sheets and tubes to sheets made of dissimilar materials such as metals and polymers;
• They are cost efficient solutions that require low amount of capital investment because they can be designed to operate with existing machine-tools;
• They are environmental friendly solutions because the connections are relatively easy to disassemble, thereby allowing recyclability of the individual components at the end-of-live.
New developments in joining by forming

Bi-material collection coins with a polymer centre and a metal ring. The polymer-metal coin is fabricated by combination of coin minting and joining by forming (interfacial pressure) in a single die stroke.

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