JOINING BY FORMING OF SHEETS BY SHEET-BULK FORMING

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Summary
This paper presents a new joining by forming process for fixing longitudinally in position two metal sheets (or plates) perpendicular to one another by sheet-bulk metal forming (SBMF), at room temperature. This new process is a variant of the traditional ‘mortise-and-tenon’ joint, which allows performing joints with a protrusion of the tenon beyond the mortise or flat joint surfaces employing a counterbore that eliminates the protrusion after mechanical locking by plastic deformation. The presentation draws from the workability window using an analytical model based on geometric, plastic instability and fracture workability limits, and a combined finite element analysis and experimental work to investigate the influence of the major process parameters on the overall joining feasibility. Destructive pull-out tests were carried out to demonstrate the effectiveness of the new proposed process for producing sound protruded and flat joint surfaces.

1. Introduction
Recent years saw the development of sheet-bulk metal forming (SBMF) processes (also designated as ‘plate forging processes’) for producing sheet metal parts with local thickening, thinning or functional features such as teeth, ribs and solid bosses positioned outside the plane of the sheets [1]. Moreover, joining by SBMF has been presented as an alternative to existing joining solutions based on welding, adhesive bonding, mechanical fastening and riveting and joining by forming [2], (Fig. 1).

Fig. 1 - Technologies for connecting two sheets (or plates): (a) Welding; (b) Adhesive bonding; (c) Mechanical fastening and (d) Joining by forming.

In fact, these technologies have a lot of limitations, such as distortion and residual stresses in arc welding, long cure time and surface preparation in adhesive bonding, maximum force and aesthetic requirements in fasteners and stress relaxation and elastic spring back in some joining by forming techniques.

Under these circumstances, the aim and objective of this paper is to present a simple, flexible and low-cost solution based on a variant of the traditional ‘mortise-and-tenon’ joint to connect two metal sheets (or plates) perpendicular to one another by SBMF, in order to avoid some limitations that are often negatively pointed to other joining techniques.

2. Analytical modelling
The new proposed joining by forming process involves two different plastic deformation operations (Fig. 2); (i) flat-bottomed enlargement of the mortise by partially compressing one of the sheets in the thickness direction and (ii) attachment of the two sheets by upsetting the tenon in order to completely fill the flat-bottomed enlarged cavity of the mortise.

Fig. 2 - Schematic representation of the plastic deformation operations that are utilised in the new process.

The analytical model for designing the counterbored rectangular mortises and for defining the process window of the new proposed two-stage joining process considers geometric, plastic instability and fracture workability limits. Fig. 3 presents a schematic representation of the flat-bottomed enlargement of the mortise by partial compression of the sheet across its thickness. Plastic deformation is assumed to be homogeneous and isotropic so that plane sections
of the initial rectangular through hole remain plane after compression.

Plane strain deformation assumption in the cross section detail shown in Fig. 4(a) (the material is displaced by the punch from area $A_0$ to $A_1$) allows determining the width $w_h$ of the initial rectangular through hole as a function of the required depth $h$ of the flat-bottomed enlargement of the mortise,

$$w_h = w_m + \left(\frac{w_p - w_m}{t}\right)h$$  \hspace{1cm} (1)

where $w_m$ is the width of the smaller rectangular hole of the mortise, $w_p$ is the width of the compression punch and of the larger rectangular hole of the mortise, and $t \geq h$ is the sheet thickness. The width of the smaller rectangular hole of the mortise $w_m$ is equal to the width of the cross section of the tenon $w_t = w_m$ (Fig. 5).

Equation (1) is plotted as a straight line for each pair of widths $w_p$, $w_m$ of the counterbored mortise with rectangular stepped holes (Fig. 4). The limiting condition $w_h = w_m$ corresponds to the necessity of cutting initial rectangular holes with larger widths than those of the mortises.

The value $w_{p,\text{max}}$ corresponds to the maximum acceptable width of the compression punch (and of the larger rectangular hole of the mortise). This value is obtained from experimentation in the upset compression of tenons and should correspond to the maximum width that a deformed head of a tenon with an initial cross sectional area, $w_{m,\text{max}}$, can attain without failure by cracking (Fig. 5).

Resolving volume incompressibility for the entire geometry of the counterbored mortise one obtains the following expression for determining the length $l_h$ of the initial rectangular hole,

$$l_h = \frac{w_m}{w_h}l_m + \left(\frac{w_pl_p}{w_h} - w_m\frac{l_m}{w_h}\right)h$$  \hspace{1cm} (2)

where $l_m$ is the length of the smaller rectangular hole of the mortise and $l_p$ is the length of the punch (and of the flat-bottomed enlargement of the larger rectangular hole of the mortise). Equation (2) is plotted as a non-linear relation $l_h$ vs. $h$ due to its dependency on $w_h$ (refer to Fig. 4(b)).

Once the geometry of the counterbored mortise with rectangular stepped holes is settled and it is required to identify the workability limits of the process. The condition for the plastically deformed material of the tenon to be entirely contained within the counterbored mortise with rectangular stepped holes (eliminating the protrusion of the tenon beyond the mortise after deformation), is expressed by,

$$h_t = \frac{w_pl_p}{w_t}h$$  \hspace{1cm} (3)

where, $h_t$, $w_t$ and $l_t$ are the height, width and the length of the tenon, respectively. The process window derived from equation (3) is shown in Fig. 5 due to the limiting process condition $w_pl_p > w_tl_t$ corresponding to a cross sectional area of the larger rectangular hole of the mortise to be bigger than that of the tenon.

It is worth notice that the $y$-axis in Figs. 5 along which the depth of the larger rectangular hole of the mortise $h = 0$, corresponds to joining by sheet-bulk forming without a counterbored mortise. In this case, locking is ensured only by upset compression of the tenon, creating a protrusion beyond the mortise.
Buckling of slender tenons under upset compression determines an additional limiting condition on their initial height $h_t$ ($h_t < h_t^{buckling}$), where $h_t^{buckling}$ is the minimum allowable height of a tenon with a cross sectional area $w_t l_t$ at the onset of plastic instability.

Finally, there is a process limiting condition directly related to failure by fracture during upset compression of the tenons. In fact, by assuming plane strain deformation in the longitudinal direction of the tenons $d\varepsilon_i = 0$ and considering fracture to occur for a critical amount of effective strain $\bar{\varepsilon}^f = 2\varepsilon_h^f/\sqrt{3}$ ($\varepsilon_h$ is the strain in height direction and the superscript $f$ denotes fracture) a relation between the initial height $h_t$ of the tenon and the depth $h$ of the larger hole of the mortise, is given by,

$$\bar{\varepsilon}^f = \frac{2}{\sqrt{3}} \ln \left( \frac{h_t}{h} \right) \Rightarrow h_t = \exp \left( \frac{2\bar{\varepsilon}^f}{\sqrt{3}} \right) h = Ch$$

Assuming, the critical value of effective strain at fracture $\bar{\varepsilon}^f$ to be solely dependent on the material, the above equation corresponds to the straight line bounding the process window. Merging the presented workability limits obtains the process window (Fig. 5).

3. Experimental methods and procedures

The development of the new proposed joining process was performed with aluminium alloy EN AW 5754 H111 sheets with 5 mm thickness in the ‘as-supplied’ condition. The mechanical characterization of the material was performed by means of stack compression test specimens with 10 mm diameter, resulting in the following equation $\sigma = 325 \varepsilon^{0.18}$ (MPa).

<table>
<thead>
<tr>
<th>$w_t$ (mm)</th>
<th>$l_t$ (mm)</th>
<th>$h_t/w_t$</th>
<th>$h_t/l_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5, 10, 15, 20</td>
<td>5</td>
<td>2, 3, 4</td>
<td>1, 1.5, 2</td>
</tr>
</tbody>
</table>

The work plan involved two different sets of experimental tests. The first set of tests was exclusively focused on the characterization of the failure limits of the theoretical design model that are associated to the occurrence of buckling and cracking in the upset compression of tenons (Fig. 6). The second set of tests was focused on the two-stages of the joining by sheet-bulk forming process and comprised the flat-bottomed enlargement of the mortise and the attachment of the two sheets by upsetting the tenon.

The tests were performed in a laboratory tool setup that was installed in a universal testing machine Instron Satec. The tests were carried out in ‘unit cells’ characterized by a rectangular through hole cut-out in one sheet (start of the first stage) or by a counterbored mortise and a tenon that passes entirely through the smaller rectangular hole of the mortise (start of the second stage) (Fig. 7).

4. Numerical modelling

The development of the two-stage joining by sheet bulk forming was supported by finite element modelling using the in-house computer program I-form. The numerical simulations made use of three-dimensional finite element models. The sheets were discretized by means of hexahedral elements and the tools were discretized by means of contact-friction spatial linear triangular elements (Fig. 8).

5. Results and discussion

The design conditions for joining the two sheets are taken from the process design charts that were built from the analytical model (Fig. 9).

The first operation of the joining by sheet bulk forming is the flat-bottomed enlargement of the mortise by partially compressing a sheet in the thickness direction. The width $w_h$ and length $l_h$ of the initial rectangular through holes for producing three counterbored mortises (labelled as ‘M1’, ‘M2’ and ‘M3’) with a small rectangular hole is taken equal to that of the tenon $w_t l_t = 5 \times 10 mm^2$ and the corresponding different depths $h$ were obtained from the process design charts of Fig. 9(a).

Regarding the second operation, six different sets of variables using the counterbored mortises
labelled as ‘M1’, ‘M2’ and ‘M3’ were chosen to illustrate the typical modes of deformation and to validate the process window (Fig 9(b)).

6. Destructive testing of the joints

The performance of the new joints was evaluated by means of tensile destructive tests (Fig. 11). In the case Mode II M2, the experimental setup prevents bending and the separation of the two sheets is accomplished by a ductile ‘cup-and-cone’ fracture of the tenon after necking. In contrast, for Mode II M1, the separation of the two sheets may also occur by cutting off the surface head of the tenon along the straight edges of the mortise.

7. Conclusions

A new joining by forming process utilized for fixing longitudinally in position two metal sheets (or plates) perpendicular to one another, at room temperature was presented. The process involves the enlargement of the counterbored rectangular mortise and the attachment of the two sheets by upsetting the tenon in order to completely fill the cavity of the mortise. An analytical model based on geometric, plastic instability and fracture workability limits was proved adequate for designing the joints and selecting the major operating variables. Destructive testing of a sound joint reveals that the maximum tensile load that is safely withstood by the joint is \( \approx 12 \) kN.

8. References