Research paper

Two-stage joining of sheets perpendicular to one another by sheet-bulk forming

C.M.A. Silva, I.M.F. Bragança, L.M. Alves, P.A.F. Martins

1. Introduction

Fixing two metal sheets (or plates) perpendicular to one another is commonly performed by welding, adhesive bonding, mechanical fastening or riveting and joining by forming (Fig. 1).

Welding (Fig. 1a) is the fastest joining technology but its utilization is limited by distortion and residual stresses arising from the expansion and contraction of the weld and adjacent base metals during the heating-cooling cycles. Clamps, jigs and fixtures that lock and hold the sheets in position during welding are commonly utilised to eliminate (or partially eliminate) distortion. Other reasons for not welding are the difficulty in joining dissimilar materials and the cost and time of the inspection of defects that is more significant than with any other technology.

Adhesive bonding (Fig. 1b) circumvents the above mentioned difficulties in joining dissimilar materials but its utilization is limited by environmental working conditions related to service temperature and moisture, among others. Clamps, jigs and fixtures are also needed for ensuring a uniform pressure across the adhesive bonded area during curing time.

Mechanical fastening and riveting (Fig. 1c) is the simplest and cheapest available technology for producing non-permanent (fastened) or permanent (riveted) joints. The fastened and riveted joints can be used for metallic and non-metallic materials (such as, polymers) and are free from thermal after effects and curing time requirements. Moreover, they can also be assembled and disassembled without damaging the sheets. However, the utilization of fasteners and rivets is limited by the maximum load they can safely support, by aesthetic requirements and by working conditions in corrosive environments.

Mechanical seaming (Fig. 1d) is a joining by forming process (Mori et al., 2013) that requires no additional filler materials and accessories and avoids the problems of loading being concentrated at the points of fastening or riveting. However, the mechanical seamed joints are not hermetic and, therefore, its use is limited by the intrusion of moisture, water and other fluids between the two sheets upon loading (due to the open nature of the joint). Moreover, this type of joint can also experience loosening during impact or material stress relaxation.

In a previous paper, authors reported the development of an innovative joining by forming process that circumvents the above-mentioned difficulties of mechanical seaming (Bragança et al., 2017a,b). The process employs sheet-bulk forming (Merklein et al., 2012) with a ‘mortise-and-tenon’ joint and its main features are briefly compared with those of conventional mechanical joining processes in Table 1.

Joining by sheet-bulk forming using a ‘mortise-and-tenon’ joint for fixing longitudinally in position two sheets perpendicular to one another (Fig. 1d) is an alternative to other joining by forming solutions in which the tenon is bent (Mraz, 2015) instead of being axially compressed (Fig. 1b). In fact, not only the resulting sheet-bulk formed joints are stronger as they are not influenced by springback after bending.

Joining by sheet-bulk forming may also be seen as an alternative to joining by roll forming (Niemeier, 2013) in applications where a continuous longitudinal connection between the two sheets is not needed.
Joining by roll forming is a multi-stage process that involves milling, embossing and locking of the two sheets by roll forming, which was originally developed to produce long profiles such as I-beams and T-beams. However, and in contrast to joining by sheet-bulk forming, the process is limited by the minimum allowed thickness of the sheet in which the groove needs to be milled.

Despite the effectiveness of joining by sheet-bulk forming for fixing metal sheets (Bragança et al., 2017a,b), polymer sheets and metal to polymer sheets (Bragança et al., 2017a,b), the resulting joint surfaces are not flat due to protrusions of the tenons beyond the mortises, after plastic deformation. This gives rise to aesthetic, dimensional and space availability problems similar to those that are often negatively pointed to fasteners and rivets.

Under these circumstances, the purpose of this paper is to present a new two-stage joining by sheet-bulk forming process that eliminates the protrusion of the tenon beyond the mortise after plastic deformation (Fig. 2d). As seen in the figure, the resulting joint surface is flat with the plastically deformed tenon contained within a counterbored mortise with rectangular stepped holes. Potential applications include ship decks, floors of train carriages, automotive crash boxes, structural frames and customized T-shaped profiles made from different materials, among others.

The paper is organized in five different sections. Section 2 presents an analytical model for designing the joints built upon the major variables and workability limits of the new two-stage joining by sheet-bulk forming process. Section 3 is focused on experimentation and provides information on the determination of the stress-strain curve of the sheet metal and on the work plan that was carried out for validating the new proposed joining process. Section 4 presents a brief overview of the finite element modelling work that was carried out in the
development of the new joining process. Finally, Section 5 presents and discusses the results. Special emphasis is placed on the observed modes of deformation, on the required forming forces and on the determination of the maximum force that the new joints are capable to withstand before cracking.

2. Theoretical model

The new proposed joining process involves two different plastic deformation operations (Fig. 3); (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 the direction perpendicular to its thickness in order to completely fill the flat-bottomed enlarged cavity of the mortise.

This section of the paper presents an analytical model for designing the counterbored rectangular mortises and for defining the process window of the new proposed two-stage joining process based on geometric, plastic instability and fracture workability limits.

2.1. Counterbored mortise with rectangular stepped holes

Fig. 4 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. The cross-section detail of the initial and final counterbored mortise with rectangular stepped holes shows the punch and the material being displaced from area ‘A0’ to ‘A1’.

Plane strain deformation assumption in the cross section detail shown in Fig. 4 allows determining the width \( w_0 \) of the initial rectangular through hole as a function of the required depth \( h \) of the flat-bottomed enlargement of the mortise, by the following expression,

\[
w_0 = w_{mlm} + \left( \frac{w_h - w_{mlm}}{t} \right) h
\]

In the equation above, \( w_{mlm} \) is the width of the smaller rectangular hole of the mortise, \( w_h \) 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 \( w_{mlm} \) is equal to the width of the cross section of the tenon \( w_t = w_{mlm} \) (refer to Fig. 6a).

Eq. (1) is plotted as a straight line for each pair of widths \( w_h, w_{mlm} \) of the counterbored mortise with rectangular stepped holes (Fig. 5a). The limiting condition \( w_h = w_{mlm} \) corresponds to the necessity of cutting initial rectangular holes with larger widths than those of the mortises.

The value \( w_{h \text{ max}} \) included in Fig. 5a 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 (refer to Section 3.2) and should correspond to the maximum width that a deformed head of a tenon with an initial cross sectional area \( A_{0 \text{pp}} \) can attain without failure by cracking.

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 through hole,

\[
l_h = \frac{w_{mlm} l_m}{w_h} + \left( \frac{w_h l_p - w_{mlm} l_m}{w_h t} \right) h
\]

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). Eq. (2) is plotted as a non-linear relation \( l_h \) vs. \( h \) due to its dependency on \( w_h \) (refer to Fig. 5b).

Main variables and workability limits of the new two-stage joining process

Once the geometry of the counterbored mortise with rectangular stepped holes is settled it is necessary to identify the workability limits of the new proposed two-stage joining by sheet-bulk forming. The methodology followed by the authors considers the upset compression of the tenon to be homogeneous and isotropic so that plane sections remain plane after deformation. Buckling due to plastic instability and material failure by cracking are introduced as limiting conditions, where appropriate.

Under these circumstances, the condition for the plastically deformed material of the tenon to be entirely contained within the counterbored mortise with rectangular stepped holes and, therefore, for eliminating the protrusion of the tenon beyond the mortise after deformation, is expressed by,

\[
l_t = \frac{w_t l_h}{w_{mlm} l_m}
\]

Fig. 4. Schematic representation with notation of the flat-bottomed enlargement of the mortise by partial compression of the sheet across its thickness. The cross section includes a detail of the punch and of the material being displaced.
where, \( h_t \), \( w_t \) and \( l_t \) are the height, width and the length of the tenon, respectively. The process window derived from Eq. (3) is shown in Fig. 6a due to the limiting process condition \( w_{plp} > w_{lt} \) 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 Fig. 6a to e 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 that was previously proposed by the authors (Bragança et al., 2017a,b) (refer to the leftmost schematic drawing in Fig. 2a).
Conversely, the maximum allowable depth of the larger rectangular hole of the mortise $h$ along the $x$-axis needs to be smaller than the sheet thickness $t$,

$$h < t$$

because in case $h = t$ it corresponds to a situation where the rectangular stepped holes degenerate into a single rectangular through hole with a volume equal to $w_d t$ (Fig. 6b).

Buckling of slender tenons under upset compression determines an additional limiting condition on their initial height $h_i$ given by,

$$h_i < h_{b,\text{buckling}}$$

where $h_{b,\text{buckling}}$ is the minimum allowable height of a tenon with a cross sectional area $w_d l$ at the onset of plastic instability. The process window derived from Eq. (5) is schematically plotted in Fig. 6c.

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 $\Delta h = 0$ and considering fracture to occur for a critical amount of effective strain $\varepsilon_f = 2\varepsilon_h / \sqrt{3}$, where $\varepsilon_h$ is the strain in height direction and the superscript $f$ denotes fracture, it follows,

$$\varepsilon_f = \frac{2}{\sqrt{3}} \ln \left( \frac{h_i}{h} \right)$$

The equation above can be rewritten in order to provide a relation between the initial height $h_i$ of the tenon and the depth $h$ of the larger hole of the mortise, as follows,

$$h_i = \exp \left( \frac{\sqrt{3}}{2} \varepsilon_f \right) \times h = C h$$

Assuming, the critical value of effective strain at fracture $\varepsilon_f$ to be solely dependent on the material, the above equation corresponds to the straight line bounding the process window depicted in Fig. 6d.

In conclusion, by merging the workability limits resulting from Eqs. (3) to (7) one obtains the process window of the two-stage joining of sheets perpendicular to one another by sheet-bulk forming that is schematically plotted in Fig. 6e. The accuracy and reliability of this process window will be validated by means of numerical and experimental work to be presented in the following sections of the paper.

3. Experimentation

3.1. Material

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 standard tensile and stack compression tests. The tensile test specimens were cut out from the supplied sheets at 0, 45, and 90° with respect to the rolling direction and the stack compression test specimens were assembled by piling up three discs with 10 mm diameter that were also cut out from the supplied sheets.

The average stress-strain curve resulting from the entire set of experiments was approximated by the following Ludwik–Hollomon’s equation,

$$\sigma = 325\varepsilon^{0.18}$$

Further information on the procedure utilized for determining the stress-strain curve of the material is available in Bragança et al. (2017a,b).

3.2. Work plan, methods and procedures

The work plan involved three different sets of experimental tests. The first set of tests was exclusively focused on the characterization and quantification of the failure limits of the theoretical design model presented in Section 2 that are associated to the occurrence of buckling and cracking in the upset compression of tenons. This was carried out by confining one end of the tenon in a die and applying pressure to the other end in order to force the material to plastically deform in a similar way to that observed in the mechanical locking of the mortise-and-tenon joints (refer to the schematic drawing included in Table 2). The experimental tests were performed for different values of the free height-to-width ratio $h_i/w_t$ and of the free height-to-length ratio $h_i/l$, (Table 2).

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 by partially compressing one of the sheets in the thickness direction and the attachment of the two sheets by upsetting the tenon in the direction perpendicular to its thickness in order to completely fill the flat-bottomed enlarged cavity of the mortise.

The tests were performed in a modified version of a laboratory tool setup originally developed by the authors (Bragança et al., 2017a,b) that was installed in the universal testing machine where material characterization had been performed (Fig. 7). 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).
Table 3 summarizes the test cases that were selected for investigating the influence of the main operating variables and to validate the process workability limits (refer to Fig. 6e). A detailed discussion on the selected values for some of these variables will be performed later in Section 5.

The third set of tests consisted of tensile pull-out experiments for determining the maximum force that the new proposed joint is capable to withstand without failure.

4. Finite element modelling

The development of the two-stage joining by sheet bulk forming was supported by finite element modelling with the in-house computer program I-form. The program was developed by the authors and is based on the irreducible finite element flow formulation which is built upon the following variational statement,

\[
\Pi = \int \int \int (\sigma : \varepsilon - \frac{1}{2} K \dot{\varepsilon} : \dot{\varepsilon} - \int_T T_{ij} u_{ij} dS + \int_{\partial \Omega} \pi_{ij} \tau_{ij} dS) dV
\]

where the symbol \(\sigma\) denotes the effective stress, \(\varepsilon\) is the effective strain rate, \(\dot{\varepsilon}\) is the volumetric strain rate, \(K\) is a large positive constant imposing the incompressibility of volume \(V\), \(T_{ij}\) and \(u_{ij}\) are the surface tractions and velocities on surface \(S_T\), \(\tau_{ij}\) and \(u_r\) are the friction shear stress and the relative velocity on the contact interface \(S_f\) between the material and tooling. Further details on the computer implementation of the finite element flow formulation with special emphasis to contact and frictional sliding between rigid and deformable objects is provided by Nielsen et al. (2013).

The numerical simulations made use of three-dimensional finite element models. The schematic drawing in Fig. 8 shows the physical models that simplify the actual two-stage joining by sheet bulk forming process and enable calculations by means of finite elements. As seen, both models are limited to the vicinity of the plastically deforming regions with the remaining volumes of the sheet and tenon being replaced by a fixed value displacement boundary condition.

This observation of the plastically deforming regions also allows concluding that a spacing between two consecutive joints equal to the width \(w_p\) of the compression punch of the larger rectangular hole of the mortise is adequate for design purposes.

The sheets were discretized by means of hexahedral elements and the tools were discretized by means of contact-friction spatial linear triangular elements. Several remeshings were needed to carry out the numerical simulation of the first stage but no remeshings were needed for the numerical simulation of the second stage. The bottom part of Fig. 8 shows the initial and final computed meshes (with distribution of effective strain) for each stage of the new proposed joining by sheet-bulk forming process.

### Table 3

Summary of the experimental work plan for investigating the two-stage joining of sheets perpendicular to one another by sheet-bulk forming.

<table>
<thead>
<tr>
<th>Test case</th>
<th>Rectangular through hole</th>
<th>Counterbored mortise with rectangular stepped holes</th>
<th>Tenon</th>
</tr>
</thead>
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<tr>
<td></td>
<td>(w_p) (mm)</td>
<td>(l_p) (mm)</td>
<td>(h) (mm)</td>
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<td>6</td>
<td>7.4</td>
<td>11.7</td>
<td>4</td>
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5. Results and discussion

5.1. Failure of the tenons by buckling and cracking

Table 4 provides the results of the experimental tests that were performed with the objective of characterizing and quantifying the failure limits associated to the occurrence of buckling and cracking in the upset compression of tenons. One end of the tenon was fixed in a die and the other end, where pressure was applied, was free in order to upset the material in a similar way to that experienced in the mechanical locking of the new proposed joining process (refer to schematic drawing included in Table 2).

As shown in Table 4, the tenons with \( h_t = 5, 10 \) and 15 mm do not buckle during upset compression. Their formability is limited by the occurrence of shear cracks in the plastically formed heads as a result of exceeding the admissible level of deformation. The values of \( \Delta h_t \) included in Table 4 provide the vertical displacement that each tenon can successfully withstand without cracking.

The slender tenon with \( h_t = 20 \) mm fails by buckling and allows setting-up the minimum allowable height \( h_{buckling} = 15 \) mm for a tenon with an initial cross sectional area \( w_d = 5 \times 10 \) mm² at the onset of plastic instability.

Fig. 9 shows the finite element distribution of effective strain \( \varepsilon \) in the head of the tenons with \( h_t = 5, 10 \) and 15 mm for an amount of displacement \( \Delta h_t \) corresponding to the onset of failure by cracking listed in Table 4. As shown, the average value of the effective strain at fracture \( \varepsilon_f \) for the three tenons is within 1.9 to 2.7. This range of values is compatible with the plane strain estimate \( \varepsilon_f = 2.2 \) obtained by applying Eq. (6) with the experimental values of \( \Delta h_t \) included in Table 3.

The results obtained by this first set of tests allows determining the formability limits by buckling and cracking of the analytical model described in Section 2 (refer to Fig. 6c and d) that will be utilized for designing the new proposed two-stage joining by sheet-bulk forming.

5.1. Two-stage joining by sheet-bulk forming

5.1.1. Forming the counterbored mortise with rectangular stepped holes

The first operation of the two-stage 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 with a small rectangular hole \( w_d = w_{small} = 5 \times 10 \) mm² and the corresponding different depths \( h \), were obtained from the process design charts of Fig. 10a. These charts were built from the analytical model described in Section 2 and the working areas correspond to those shown in Fig. 5.

The process design conditions that are labelled as ‘M1’, ‘M2’ and ‘M3’ in Fig. 10a correspond to the three different mortises shown in Fig. 10b. Major deviation between the ideal and actual shape of the mortises is minimum and found at the corners. However, they cause no problems to the overall joining concept.

Fig. 10c shows the finite element predicted cross section of a counterbored mortise with a rectangular stepped hole resulting obtained from the flat-bottomed enlargement of a mortise by partial
compression of a sheet in the thickness direction.

As shown in the experimental evolution of the force with punch displacement depicted in Fig. 11, the maximum compression force to produce a typical counterbored mortise from an initial rectangular hole by partial compression of the sheet in the thickness direction is approximately equal to 25 kN.

The agreement between the numerical and experimental evolution of the force with displacement is generally good and the slight overestimation provided by finite elements is attributed to the fact that the physical model is slightly stiffer than the actual process as a result of a

<table>
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<th>$h$ (mm)</th>
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<table>
<thead>
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<tbody>
<tr>
<td>$\varepsilon f$</td>
<td>2.25</td>
<td>2.13</td>
<td>2.15</td>
</tr>
</tbody>
</table>

Fig. 9. (a) Finite element model showing the initial and final computed meshes and computed distribution of effective strain for the tenons with (b) $h = 5$ mm, (c) $h = 10$ mm and (d) $h = 15$ mm.
significant amount of volume being replaced by fixed value displacement boundary conditions.

5.1.2. Attaching the two sheets by sheet-bulk forming of the tenon

The design conditions for joining the two sheets by upsetting the tenon in the direction perpendicular to its thickness are taken from the process design charts that are included in Fig. 12a. These charts were built from the analytical model described in Section 2 and the working areas correspond to those shown in Fig. 6.

Six different sets of variables corresponding to Cases 1 to 6 of Table 3 and to the utilization of the counterbored mortises labelled as ‘M1’, ‘M2’ and ‘M3’ were chosen to illustrate the typical modes of deformation and to validate the process window that was previously considered in Section 2.

The sound mortise-and-tenon joint that is associated to deformation mode II is obtained by choosing tenons with free-heights compatible with the depths h of the larger rectangular holes of the mortises. This means that flat joint surfaces with the plastically deformed tenons contained within the counterbored mortises with rectangular stepped holes requires choosing values of ht and h along the inclined line corresponding to fixed cross sectional areas of the tenon wmlm = wtlt and of the larger rectangular hole wplp.

In contrast to what was said above, inadmissible mortise-and-tenon joints corresponding to deformation modes I, III and IV are obtained for process conditions below and above the inclined line of Fig. 12a. For example, by selecting the mortise M2 with a free-height ht of the tenon below what is needed it is not possible to completely fill its volume due to lack of material. This mode of deformation is designated as mode I and a picture of the resulting joint is shown in Fig. 12b (refer to the side gaps inside the white ellipse of the leftmost specimen).

Deformation mode III is associated to situations where a protusion of the tenon beyond the mortise is observed as a result of using a tenon with a free-height ht above what is needed. A picture of the resulting joint is also shown in Fig. 12b (refer to the third specimen).

Deformation mode IV is associated to the utilization of very slender tenons that fail by buckling. In fact, when the free-height of a tenon...
it does not matter if its volume is appropriate or in-appropriate to completely fill the mortise and avoid the protrusion of the tenon because it will always fail by buckling. A picture of such a joint is shown in the rightmost specimen of Fig. 12b.

In addition, Fig. 12c shows three sound mortise-and-tenon joints associated to deformation mode II that were produced using the three different mortises ‘M1’, ‘M2’ and ‘M3’. The process conditions lie on top of the inclined dashed grey line of Fig. 12a and prove the adequacy of the analytical model for designing the joints that was presented in Section 2.

In what regards the quality of surface finish, average roughnesses $R_a = 0.233 \mu m$ and $R_a = 0.254 \mu m$ were measured for the plastically deformed tenon and sheet surfaces, respectively. These values are influenced by the surface quality of the upset compression tools and supplied sheets.

Finally, Fig. 13 shows the experimental and finite element evolution of the force with the displacement for a unit cell of the new proposed two-stage joint produced by sheet-bulk forming. Three different zones labelled as ‘A’, ‘B’ and ‘C’ are observed. Region A is characterized by 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 mechanical lock during which the tenon completely fills the flat-bottomed rectangular large hole of the mortise. The maximum required force is approximately equal to 40 kN.

The reason why the finite element prediction overestimates the actual evolution of the force with displacement is once again attributed to the fixed value displacement boundary conditions that slightly over stiff the resulting physical model.

The test case 3 of Table 3 included in Fig. 13 corresponds to a tenon with a free height $h_t = 4.8$ mm and the reason why it deforms homogeneously instead of non-homogeneously (buckling) is because the critical instability force $F_{cr}$ derived from the theory of elastic stability ($E$ is the elasticity modulus),

$$F_{cr} = \frac{\pi^2 EI}{4ht^3} \quad I = \frac{l_i w_h^3}{12}$$

is equal to $F_{cr} \approx 780$ kN. This value of the critical instability force $F_{cr}$ is much higher than the compression forces that are needed for the upsetting of the tenon during the second stage of the joining by forming process (refer to Fig. 13) and is compatible with the experimental observations included in Table 4. In fact, tenons with a free height $h_t \leq 15$ mm are energetically more favourable to be upset homogeneously than non-homogeneously under buckling.

5.2. Destructive testing of the joints

The performance of the new joints for fixing longitudinally in position two metal sheets (or plates) perpendicular to one another, at room temperature was evaluated by means of tensile destructive tests. Fig. 14a shows a schematic representation of the experimental setup and Fig. 14b shows the evolution of the engineering stress with displacement for two destructive tests of a unit cell corresponding to cases 1 and 3 of Table 3. The engineering stress was obtained dividing the applied tensile force by the initial cross sectional area of the tenon.

As seen in the photograph corresponding to case 3 of Table 3 (Mode II, M2), the experimental setup prevents bending during the application of tensile forces and the separation of the two sheets is accomplished by a ductile ‘cup-and-cone’ fracture of the tenon after necking (and reduction of its cross sectional area). The required stress to separate the two metal sheets is equal to 244 MPa and corresponds to a tensile force of approximately 12 kN.

In contrast, the photograph corresponding to case 1 of Table 3 (Mode II, M1) shows that separation of the two sheets may also occur by cutting off the surface head of the tenon along the straight edges of the mortise. In this case, the mortise acts like a cutting die and the required engineering stress to separate the two metal sheets is approximately equal to 110 MPa, which corresponds to a force of approximately 5.5 kN. This value is much smaller than that obtained for the mortise M2 and justifies the reason why the depth $h$ of the larger rectangular hole of the mortise should not be taken much smaller than the sheet thickness.

The performance of the new joints for fixing longitudinally in position two metal sheets (or plates) perpendicular to one another, at room temperature could also have been evaluated by means of shear destructive tests. In this case, the maximum admissible force $F_{adm}$ is determined in a similar way to that of riveted joints under shear loading,

$$F_{adm} = \tau_s A_t$$

In the equation above, $A_t = w_h l_i$ is the cross-sectional area of the tenon to be sheared off and $\tau_s$ is the allowable shear stress, which is assumed to be equal to $\sigma_{UTS}/\sqrt{3}$ and uniformly distributed over the cross sectional area $A_t$.

Under these circumstances, by considering the ultimate tensile strength of aluminium AA5754-H111 equal to $\sigma_{UTS} = 220$ MPa, the maximum admissible force $F_{adm}$ of a tenon with a cross sectional area $A_t = 50$ mm$^2$ is equal to,

$$F_{adm} = \frac{\sigma_{UTS}}{\sqrt{3}} A_t = 0.577 \times 220 \times 50 = 6347 \text{ N}$$
This value is 47% smaller than that obtained in the tensile pull-out tests.

6. Conclusions

The protrusion of the tenon beyond the mortise in joints utilized for fixing longitudinally in position two metal sheets (or plates) perpendicular to one another, at room temperature is eliminated by employing a new joining by forming process that involves two different plastic deformation operations; (i) flat-bottomed enlargement of the counterbored rectangular mortise by partially compressing one of the sheets in the thickness direction and (ii) attachment of the two sheets by upsetting the tenon in the direction perpendicular to its thickness in order to completely fill the flat-bottomed enlarged cavity of the mortise.

An analytical model based on geometric, plastic instability and fracture workability limits proved adequate for designing the joints and selecting the major operating variables. The model was successfully validated against experimental and finite element simulation data and revealed that the production of sound joints is limited to geometrical features within a compact range. Outside this range, the joints are characterized by incomplete fill of the counterbored rectangular mortise due to lack of material, by protrusion of the tenon beyond the
mortise due to excess of material or by buckling due to the utilization of very slender tenons.

Destructive testing of a sound joint reveals that the maximum tensile force that is safely withstood by the joint is 12 kN when the separation of the two sheets is performed by a ductile ‘cup-and-cone’ fracture of the tenon after necking. The maximum destructive shear force is estimated to be 47% smaller than that obtained in the tensile pull-out tests. This weaker performance in shear may limit the range of applications of the new proposed joint.

Acknowledgments

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References


Fig. 13. Experimental and finite element predicted evolution of the force with displacement for the new proposed two-stage joining by sheet-bulk forming (case 3 of Table 3).

Fig. 14. Tensile destructive test of the new proposed joint. (a) Schematic representation of the experimental setup with a picture of the joint after being tested; (b) Experimental evolution of the force with displacement for two sound joints corresponding to deformation mode II (cases 1 (mortise M1) and 3 (mortise M2) of Table 1).