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Research paper

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

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ABSTRACT

This paper proposes a new joining by forming process for fixing longitudinally in position two metal sheets (or plates) perpendicular to one another, at room temperature. The proposed process employs a counterbored variant of the 'mortise-and-tenon' joint that eliminates the protrusion of the tenon beyond the mortise after mechanical locking by plastic deformation. The presentation draws from the workability limits and material stress-strain characterization to validation by joining and destructive pull-out testing. Results demonstrate the effectiveness of the new proposed process for producing flat joint surfaces, which are advantageous over typical 'mortise-and-tenon' protruded surfaces in most applications.

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. 2a) is an alternative to other joining by forming solutions in which the tenon is bent (Mraz, 2015) instead of being axially compressed (Fig. 2b). 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

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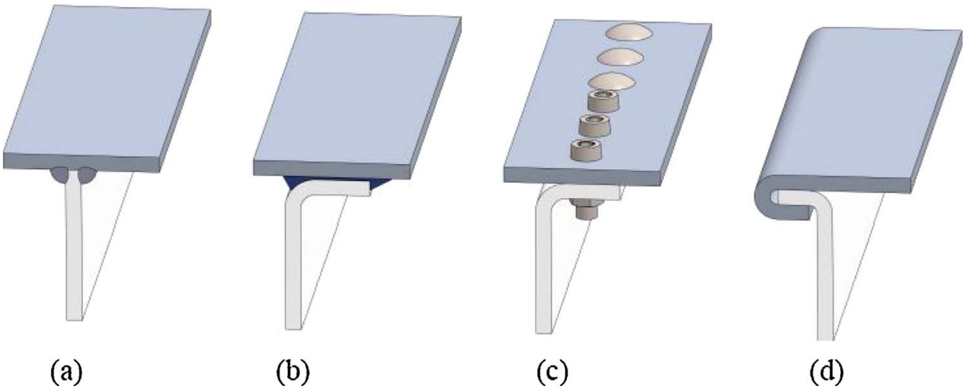

Fig. 1. Technologies for connecting two sheets (or plates) perpendicular to one other. (a) Welding; (b) Adhesive bonding; (c) Mechanical fastening and riveting; (d) Joining by forming (e.g. mechanical seaming).

Table 1
Main features of different mechanical joining processes.

	Fastening	Riveting	Seaming	Sheet-bulk forming
Mechanism	Fastening	Riveting	Joining by forming	
Type of joint	Non-permanent	Permanent	Permanent	Permanent
Shape of the joints	Lap and edge joints (other shapes with accessories)	Lap and edge joints (other shapes with accessories)	Edge joints	Lap, tee and corner joints
Working materials	Metals and polymers			
Additional materials	Yes (screws, bolts, nuts)	Yes (rivets)	No	No
Aesthetics and space availability	Low	Intermediate	Intermediate	High
Easy of disassembling	High	Intermediate	Low	Intermediate
Productivity	Low	High	Intermediate	High

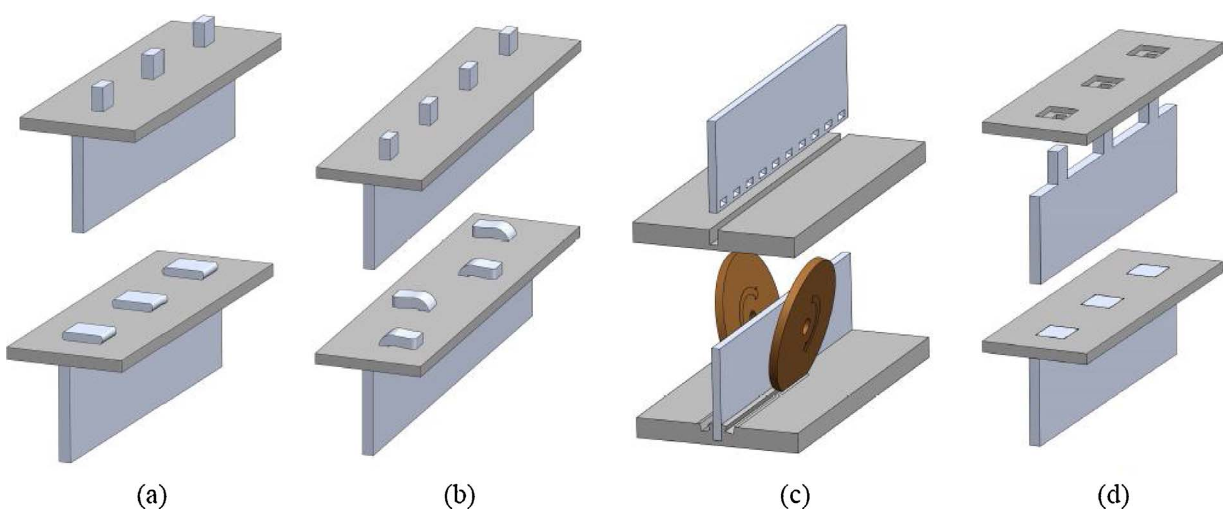

Fig. 2. Fixing longitudinally in position two sheets perpendicular to one another using different variants of the 'mortise-and-tenon' joint. (a) Joining by sheet-bulk forming; (b) Joining by bending; (c) Joining by roll-forming; (d) The new proposed two-stage joining by sheet-bulk forming.

(Fig. 2c). 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