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Sheet-bulk forming of tubes for joining applications

L.M Alves, J. Gameiro, C.M.A. Silva, P.A.F. Martins*

IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

This paper draws from the fundamentals of sheet-bulk forming of thin-walled tubes to the proposal of a new joining process for fixing tubes to sheets by means of plastic deformation at room temperature. The work on sheet-bulk forming of tubes is focused on local thickening (boss forming) by partial compression of the wall thickness along the longitudinal direction. The main goals are the understanding of the deformation mechanics of sheet-bulk forming of thin-walled tubes and the characterization of its formability limits in terms of the major process parameters. The work on joining by forming investigates how local thickening can be successfully utilized for fixing tubes to sheets by mechanical locking with a flaring die. The overall presentation is supported by finite element analysis and experimentation, and includes examples of joints made from dissimilar materials.

1. Introduction

The utilization of sheet-bulk metal forming to produce functional components with local thickening, thinning or complex functional features such as teeth, ribs and solid bosses positioned outside the surfaces of the sheets or tubes from which they are shaped is comprehensively analysed in two recent state-of-the-art reviews by Merklein et al. (2012) and by Mori and Nakano (2016).

As can be concluded from these state-of-the-art reviews, the production of sheet metal parts by sheet-bulk forming (SBF) is more widespread than the production of tubular parts by SBF. In fact, the latter is generally limited to functional tubular parts fabricated by conventional spinning or by friction spinning with self-induced heat generation (Homberg and Hornjak, 2011). Another conclusion from the state-of-the-art reviews, is that major research efforts in sheet-bulk technology have been mainly placed on the production of functional components by forming, despite its potential application in joining by forming (Mori et al., 2013).

This paper is aimed at exploring the potential application of SBF of thin-walled tubes in joining by forming and has two major broad objectives. Firstly, to extend boss forming, commonly performed by means of translational or rotational movements of tools over sheets (or plates) (Merklein et al., 2011), into the translational movement of tools along the axial (longitudinal) direction of tubes in conventional press-tool systems. In fact, and in contrast to other solutions proposed in literature, the main idea is not to increase wall thickness by rotation of forming tools around the symmetry axis of the tubes (Sieczkarek et al., 2013) but to pile-up material and obtain local thickening by partial compression of the wall thickness along the longitudinal direction in a press-tool system (Fig. 1a).

This first objective, is original and represents, as far as authors are aware, the first attempt to investigate the deformation mechanics of SBF of thin-walled tubes, as well as to identify and characterize its typical modes of deformation and to setup its formability limits as a function of the main process parameters.

The second objective of this paper, is to take advantage of localized thickening of the tube wall for subsequent joining of functional elements by forming. In particular, authors propose a new joining process for fixing tubes to sheets made from similar or dissimilar materials by mechanical locking with a flaring die, at room temperature (Fig. 1b and c).

The new proposed concept is different from previous developments in joining tubes (Alves and Martins, 2012), or joining tubes to sheets (Gonçalves et al., 2014) because instead of making use of plastic instability waves resulting from local buckling in tubes subjected to axial loading, authors are now making use of sheet-bulk forming of tubes by partial compression of the wall thickness along the longitudinal direction for fixing tubes to sheets. Finite element modelling and experimentation give support to the presentation and allow setting-up the workability limits of the process in terms

* Corresponding author.
E-mail addresses: luisalves@ist.utl.pt (L.M Alves), joao.gameiro@hotmail.com (J. Gameiro), carlos.alves.silva@ist.utl.pt (C.M.A. Silva), pmartins@ist.utl.pt (P.A.F. Martins).

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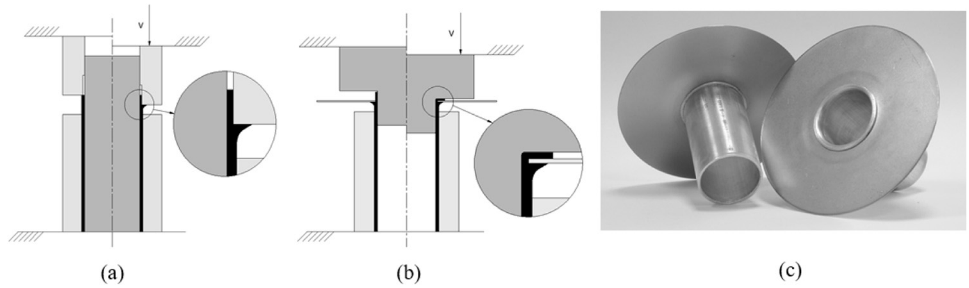

Fig. 1. Sheet-bulk forming of thin-walled tubes for joining applications. (a) Schematic representation of material pile-up and localized thickening produced by partial compression of the wall thickness along the longitudinal direction. (b) Schematic representation of the procedure for flaring out (and locking) the upper tube end inserted in the sheet hole. (c) Hollow flanged components produced by the new proposed joining process.

of the major operating parameters. Selected examples with similar and dissimilar materials are provided in the presentation.

To conclude, it is worth mentioning that the new proposed joint is particularly adequate for applications where it is needed to ensure that the inner diameter of the joint is identical to that of the supplied tube. This requirement is not easy to achieve in case of mechanical joints obtained by fasteners or by propagation of plastic instability waves and may be of great importance in applications that convey fluids from one location to another in order to prevent changes in flow and pressure drops.

2. Experimentation

2.1 Mechanical characterization of the material

The work on SBF of thin-walled tubes was performed on aluminium AA6063T6 tubes with an outer radius $r_0 = 16$ mm and a wall thickness $t_0 = 1.5$ mm.

The stress-strain curve of the material was determined by means of tensile and stack compression tests carried out at room temperature and followed a procedure similar to that utilized by the authors in a previous work on tube branching by asymmetric compression beading (Alves and Martins, 2012). The tests were performed on a hydraulic testing machine (Instron SATEC 1200 kN) with a cross-head speed equal to 10 mm/min and the resulting stress-strain curve is shown in Fig. 2a.

The critical instability force for the occurrence of local buckling was determined by compressing tubular specimens with 65 and 75 mm initial length between flat parallel platens. The tests were performed on the previously mentioned hydraulic testing machine with a cross-head speed equal to 10 mm/min and the tube ends were neither laterally supported nor otherwise constrained (free-ended boundary conditions). The resulting force-displacement evolution is shown in Fig. 2b and the critical instability force F_{cr} for triggering local buckling is equal to 25.5 kN.

2.2 Tooling and work plan

Table 1
The range of process parameters utilized in the experiments (nomenclature according to Fig. 3).

r_0 (mm)	t_0 (mm)	l_{gap}^f (mm)	t (mm)	l_{gap} (mm)
16	1.5	2	0.5–1.25	5–16

The experimental work plan was split into two parts with different aims and objectives. The first part was exclusively focused on SBF of thin-walled tubes by partial compression of the wall thickness along the longitudinal direction. Fig. 3 presents a schematic representation of the initial and final positions of the tools with a detail showing the piled-up material at the final gap length l_{gap}^f between the upper and lower dies.

The dies were made of cold working tool steel 120WV4 (WN 1.2516) hardened and tempered to a Rockwell hardness of HRC 62 and were designed and manufactured for a specific outer radius r_0 of the supplied tubes. The mandrel was made of cold working tool steel 100MnCrW4 (WN 1.2510) hardened and tempered to a Rockwell hardness of HRC 60 and was also dedicated to a specific wall thickness t_0.

The tubes were lubricated with zinc stearate.

The major process parameters were identified as the following: (i) the outer radius r_0 and wall thickness t_0 of the supplied tubes, (ii) the initial gap length l_{gap} between the upper and lower dies, (iii) the final gap length $l_{gap}^f = l_{gap} - l_f$, where l_f is the final piled-up length and (iv) the final wall thickness t resulting from the partial compression of the tube end along the longitudinal direction.

The overall range of process parameters is summarized in Table 1 and only includes variations of two main process parameters because the outer radius r_0 and the wall thickness t_0 of the supplied tubes as well as the final gap length l_{gap}^f were kept unchanged. The value of the later was not changed in order to evaluate and compare the geometry of piled-up material, namely the radius r_f of the resulting piled-up flange, for different test cases.

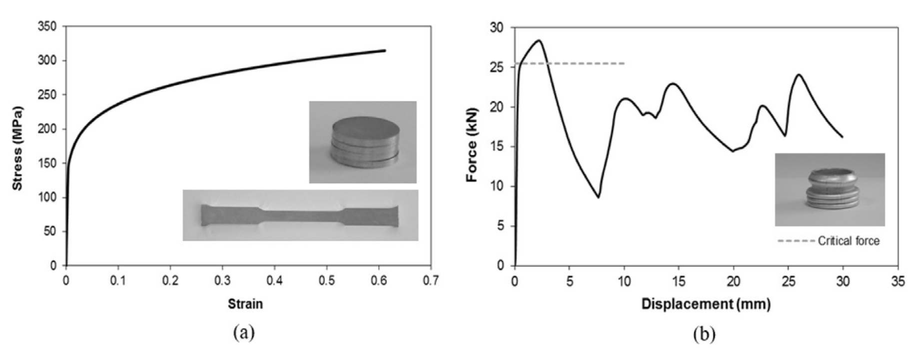

Fig. 2. Mechanical characterization of the AA6063T6 tube material. (a) Stress-strain curve obtained from tensile and stack compression tests performed in specimens cut out from the supplied tubes. (b) Force-displacement evolution and critical instability force for the axial compression of the supplied tubes between flat dies.