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Joining end-to-end tubing of dissimilar materials by forming

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This paper presents a plastic deformation process for joining two tubes made from dissimilar materials by their ends. The process consists of two elementary tube forming operations that are carried out in a single stroke; expansion to produce two adjacent counterfacing surfaces and compression beading to lock the tubes together, and has potential to replace existing solutions based on the utilization of fastened, crimped, welded, brazed or adhesive bonded joints.

The investigation combines independent characterization of the materials, experimentation in a laboratory tool system and finite element modelling. Results give emphasis to the modes of deformation and failure that are used to setup the process window and demonstrate the simplicity and effectiveness of the proposed joining process for connecting carbon and stainless steel tubes by their ends. Additional results in aluminium and carbon steel tubes that were obtained by means of a two-stroke variant of the process confirm its potential for joining two tubes made from dissimilar materials with different strengths by their ends.

1. Introduction

In the state-of-the-art review on joining by forming, Mori et al. [1] concluded that application of plastic deformation is an increasingly useful solution to meet the growing demands of high productivity, low cost material versatility, high strength and environmental friendliness. Very recently, Groche et al. [2] performed a comprehensive analysis of the basic principles of joining by forming and highlighted future trends based upon ongoing research activities. They concluded that joining processes based on plastic deformation of at least one joining partner promise great potential regarding the production of multi-material joints and hybrid components consisting of dissimilar materials.

In the past months, Gonçalves et al. [3,4] developed innovative plastic deformation solutions for joining tubes to sheets and for producing tube attachments of dissimilar materials at an angle to the axis of the main tube. The solutions are based on a combination of plastic instability and locking by means of compression beading, and a patent application by a manufacturer of automotive components protects the utilization of these solutions for connecting the lever and the fulcrum of a car hand-brake system [5]. However, the challenge of joining by plastic deformation two tubes made from dissimilar materials by their ends remained up to now unsolved, despite its great relevance in industrial applications comprising pipe lines, air-conditioning, refrigeration, heat exchangers and lightweight structures, among others.

Currently available technologies for joining two tubes by their ends (or near-ends) make use of welded, brazed, adhesive bonded, fastened or crimped joints (Fig. 1) but the number of realistic options is limited when the tubes to be joined are made from dissimilar materials. In fact, joining carbon and stainless steel tubes by welding, for example, may experience bimetallic corrosion at the welds when subjected to aggressive moist environments and often requires coating the weld seam by painting so that galvanic corrosion cells cannot be setup across the joint, where there is a composition gradient. Joining steel and aluminium tubes is even more complicated due to formation of very brittle intermetallic compounds and generally require the utilization of bimetallic transition inserts at the tube ends or the coating of the steel tube end with aluminium (by hot dip aluminizing or brazing), prior to welding [6].

The difficulties of welding two tubes by their ends become even more complicated in case of applications involving thin-walled tubes of dissimilar materials, like those shown in this paper. Brazing can be a valuable alternative to welding in case of thin-

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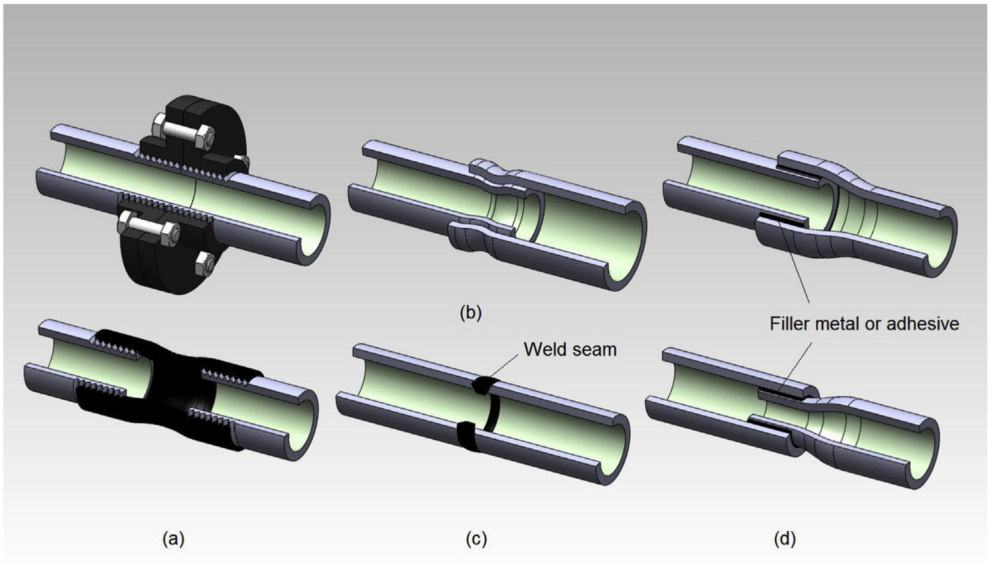

Fig. 1. Currently available technologies for joining end-to-end tubing: (a) fastened joints with flanges and bulkhead unions, (b) crimped joints, (c) welded joints and (d) brazed or adhesive bonded joints.

walled tubes made from dissimilar materials but it is not recommended for applications involving exposure to elevated service temperatures because the differences in thermal expansion rates of the tubes and fillers can give rise to thermal fatigue cracking. Brazing is also not recommended when full mechanical strength is required for the end-to-end tube joints [6].

The alternative to welding and brazing provided by adhesive bonding prevents the heating-cooling cycles but it is not a good option when high productivity is required. This is because adhesive bonding requires careful preparation with tight tolerances of the counterfacing tube surfaces and enough time for the adhesive to cure during which the joint must be kept immobilized until complete solidification. In addition, adhesive bonding may also experience decrease in performance over time under adverse environmental conditions [7].

From what was mentioned before, it may be concluded that currently available technologies for joining two tubes made from dissimilar materials by their ends are limited to mechanical fastening and crimping. Fastened joints (with flanges or bulkhead unions) make use of threads, screws and bolts, and are simple to design, easy to assemble and disassemble and available in standard sizes [8]. However, they suffer from aesthetic, geometric and dimensional limitations.

In contrast, crimped joints obtained by reduction, swaging [9] or electromagnetic forming [10] are not constrained by aesthetics or by the availability of flanges or bulkhead unions in standard sizes but are limited by the required mechanical strength and water or gas tightness. In case of crimped joints produced by electromagnetic forming there are additional demands for high electrical conductivity of the materials to be joined.

In a recent paper authors proposed a new plastic deformation process for joining two tubes by their ends and discussed its applicability to commercial carbon steel tubes [11]. The process is schematically shown in Fig. 2 and consists of two forming stages carried out in a single stroke. The first stage (hereafter referred to as 'the expansion stage') produces the adjacent counterfacing surfaces of the tubes to be joint by forcing the upper tube against the chamfered end of the lower tube in order to radially expand the initial unsupported height l_o of the upper tube. During this stage the chamfered end of the lower tube acts like a tapered punch. The second stage starts when the upper tube gets into contact with the lower die (or, alternatively, when the lower tube gets into contact with the inner surface of the upper tube) and creates the lock between the adjacent counterfacing surfaces of the two tubes by compression beading.

This paper explores the possibility of connecting two tubes of dissimilar materials by their ends using the abovementioned plastic deformation process. The motivation to take a step forward derives from the fact that previous investigation on deformation modes and process window was not influenced by differences in the plastic behaviour of the mating tubes to be joined because it was limited to commercial carbon steel tubes.

Under these circumstances, the aim and objectives of this paper are the following: (i) to revisit the previously observed modes of deformation in the light of the plastic behaviour of stainless steel tubes, (ii) to investigate the influence of the relative position between the counterfacing surfaces of carbon and stainless steel tubes on the resulting end-to-end joints, (iii) to set-up a process window for joining carbon and stainless steel tubes by their ends and (iv) to present a two stroke variant of the process for joining tubes of dissimilar materials with very different strengths (e.g. aluminium and carbon steel tubes).

The organization of the paper is the following. Section 2 summarizes the mechanical characterization of the carbon steel and stainless steel tubes, presents the fundamentals of the plastic deformation process for joining two tubes of dissimilar materials by their ends and provides information on the experimental work plan. Section 3 provides insight on the finite element simulation conditions with special emphasis on contact modelling along the counterfacing surfaces of the two tubes to be joined. Section 4 presents and discusses the results obtained, namely the modes of deformation and the influence of the major operating parameters on the process window and on the overall force requirements. Section 5 concludes.

2. Experimentation

2.1. Mechanical characterization of the material

The investigation was performed on commercial S460MC