Joining of tubes by gas detonation forming

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Abstract. For many applications, such as in structural components, it is required to join two tubes – sometimes with dissimilar material properties. Only few research studies have investigated the joining of tubular metallic components by means of high-velocity forming processes. In this paper, we present the novel process of joining of two tubes by a gas detonation pressure wave. In particular, the joining of a copper and a steel tube is discussed by means of a finite element study and a conducted experiment.

Keywords: high velocity forming, gas detonation forming, joining, metal forming

1. Introduction

Tubular parts find wide application as structural components due to their high stiffness to weight ratios. Often it is required to join two tubular components. Besides the predominantly used technique of welding, there exist a series of industrially applied forming technologies that are capable of joining two metallic parts such as clinching, riveting, hemming, rolling, spinning and hydroforming [1]. Some of the advantages of the use of forming technologies for joining are: Joining and shaping operations could be carried out simultaneously and therefore, the process chain could be significantly shortened; Negative effects of the local heat concentration on the microstructure, which may occur in welded joints, can be eliminated. Some material pairings with dissimilar properties that cannot be welded due to their difference in melting temperatures could be joined by forming [2]. Joining of dissimilar materials – e.g. soft versus high strength materials such as aluminium or copper joined with steel alloys – is of great interest for structural components or car frames as two conflicting properties such as structural stiffness and capability of energy absorption (relevant for the crash zone) could be integrated in one component.

In general, the joining by plastic deformation is performed by form-closed, force-closed and/ or metallurgical joints [3]. Several research works have investigated tube and cam joining operations that are based on the force-closed joint principle [4]. There exist several manufacturing techniques for the formation of a force-closed joint between two tubes. These joints can be created by rolling of the inner or outer tube. In this process, one tube is plastically deformed by a roller and pressed against the other. If the clearance between the tubes is properly selected, one tube will be solely elastically deformed as a consequence of the plastic deformation of the other joint partner [5]. After the removal of the forming stresses, the elastically deformed tube will impart pressure on the other tube and due to the friction the tubes will resist to motion as long as the forces, to which they are subjected, are smaller than the frictional forces. Moreover, tubes can also be joined by hydroforming [2]. The major advantages of hydroforming are the reduced processing times, the reduced amount of tooling due to

the absence of tools on one side and the possibility to deform cavities in hollow shaped components. Another option for joining metallic components is electromagnetic forming (EMF). EMF is a high velocity process, which forms metals with high electrical conductivity such as aluminium by a pulsed magnetic field [6]. The advantages of the high velocity forming processes compared to hydroforming and other conventional forming technologies are their reduced processing time – milliseconds in EMF and seconds in hydroforming – and the increased formability for several materials due to the extremely high strain rates [7]. A further high velocity forming process is the gas detonation forming. Kleiner et al. have used the pressure shock wave produced by the gas charge of oxygen and hydrogen to manufacture hollow shaped tubes [8]. Experimentally they have shown that the aluminium alloys AlMgSi1 and Al99.5 exhibit higher formability when deformed by gas detonation compared to conventional forming processes.

In this work, we discuss the use of gas detonation for the joining process of two tubes. Similar to EMF, extremely high strain rates can be achieved by this forming technique. Since it is aimed to create a joint of high strength, both form-closed and force-closed joints are applied. A numerical model by means of the finite element method is established to investigate the deformation process. In a numerical study, three material pairings of a material with relatively high strength (DC04 steel alloy) and a soft material (copper) are modified and tested in virtual environment. Moreover, a physical experiment of the tube joining is presented.

2. Process principle and numerical modelling

Process principle: As illustrated in Figure 1A, similar to hydroforming joining processes, an inner tube with a thin wall thickness is inserted with a small clearance-fit into an outer tube with a larger wall thickness in order to ensure that a force-closed joint is achieved after removal of the internal pressure. The inner surface of the outer tube is grooved with the purpose of creating a form-closed joint by means of the interlocked material. For maintaining a certain geometric accuracy of the outer diameter of the outer tube, a rigid die is placed around the outer tube. The inner tube has to be subjected to the pressure wave caused by gas detonation. The principle of the gas detonation is thoroughly described in [8].
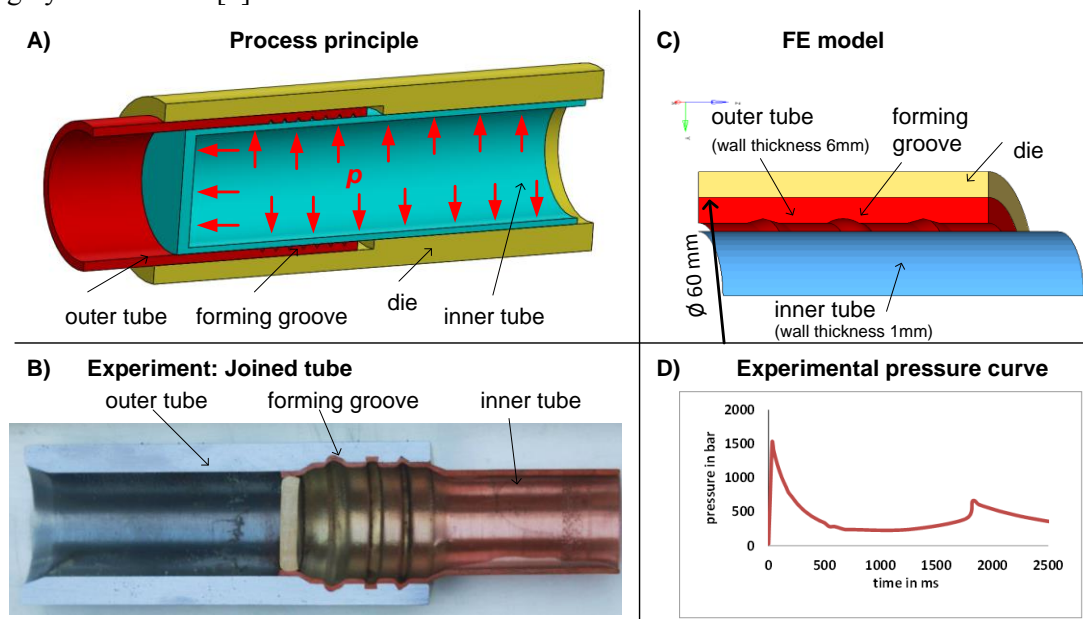

Figure 1: A) Principle of tube joining illustrated in a cross-sectional cut view. B) Cross-sectional cut of joined tubes (courtesy of SWL). C) Geometry of the finite element model. D) Plot of gas detonation pressure vs process time (courtesy of SWL).

Experimental setup: Using the described process principle, experiments with different pressure values and various groove geometries have been carried out at the Shock Wave Laboratory (SLW) of the RWTH Aachen University led by Prof Olivier. In Figure 1B a photograph of two joined tubes is shown. The inner tube is made of copper and the outer tube of steel alloy. The design of the tools is very challenging since it has to be ensured that inside the tools a technical vacuum is sustained; otherwise the metals could melt due to the extreme compression of the air. As it can be seen, the inner tube is nicely formed into the grooves of the outer tube. However, for determining the parameters required for such behaviour, a large number of trial and error experiments were required. In order to determine the appropriate parameters, the tube deformation can be modelled by means of the finite element method. For instance, appropriate pressure values need to be selected, as small pressure values may lead to partially filled grooves and high pressure values to fracture of the inner tube and excessive deformation of the outer tube. Moreover, by means of simulations the wall thickness of the tube can be predicted which strongly influences strength, durability and reliability of the components.

Finite element model: For the finite element simulation of the tube joining a quarter of the model is considered to reduce the computational cost. The outer die is modelled as rigid because of its high stiffness compared to those of the tubes. Both tubes are modelled as deformable and are assumed to be homogenous. The inner tube is modelled by 53760 Belytschko-Tsay shell elements. The outer tube is modelled by 407790 8-node linear brick elements. The outer die is fully constrained. The inner tube is subjected to pressure. The time curve of the pressure is taken from experimental data (see Figure 1D). The contacts between all components are defined by surface to surface segment based contact formulation. Because of the highly dynamic character of the process, the explicit time integration scheme of the LS-DYNA software package is used. The Johnson-Cook phenomenological material model as shown in Eq. 1 is employed in order to take into account the strain rate dependency of the used materials. The flow stress is computed as follows:

$$\sigma_y = \left(A + B \bar{\varepsilon}^{p^n} \right) \left(1 + C ln \frac{\dot{\bar{\varepsilon}}^{p^n}}{\dot{\varepsilon}_0} \right) \left(1 - \left[\frac{T - T_{room}}{T_{melt} - T_{room}} \right]^m \right) \qquad \text{Eq.1}$$

where $\bar{\varepsilon}^p$ represents the effective plastic strain, T_{room} the ambient temperature, T_{melt} the melting point, T the effective temperature, A the yield stress, B the hardening modulus, n the strain exponent, m the temperature exponent, C the strain rate factor and $\dot{\varepsilon}_0$ the strain-rate for the quasi static reference loading. The parameters and the mechanical properties of DC04 steel are taken from [7]; for copper the vales form [9] have been used. The following simulations were carried: Sim1: outer ring made of DC04 material, inner tube made of copper material; Sim2: both tubes made of DC04 material; Sim3: outer tube made of copper material and inner tube made of DC04 material.

3. Results and discussion

In Figure 2, the von Mises strain distributions of the Sim3 are depicted. It can be observed that the inner tube deforms into the grooves of the outer tube.
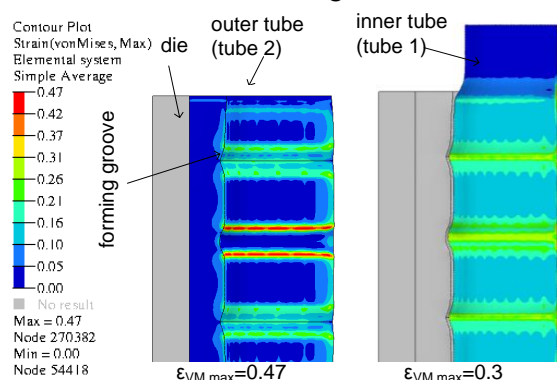

	Sim1	Sim2	Sim3
Max thickness reduction tube 1 (%)	24.8	23.3	21.8
Max. strain tube 1	0.43	0.4	0.3
Max. strain tube 2	0.33	0.31	0.47
Max deformation tube 2 (mm)	0.36	0.39	0.63

Figure 2: Exemplary simulation results of the von Mises strain distribution of Sim3 at the process time 0.5ms

Table 1: Simulation results

As expected in this case the softer outer tubes plastically deflects to a considerable amount. The maximum von Mises strain of outer tube in this case 0.47, whereas for the pairing in Sim2 (outer steel/ inner copper) the maximum value is 0.3. As expected it is not reasonable to employ a softer outer tube since its grooves even out and hence the required interlock effect is reduced.

4. Conclusion and future work

In this paper, the process of joining of two tubes by gas detonation is introduced. The feasibility of the process is shown by means of an experiment and a simulation study. In this process two joint types exist: Closed-form joint: the plastic deformation of the material of the inner tube into the grooves of the outer tube material leads to mechanical interlocking. Closed-force joint: the difference in the elastic recovery behaviour of the materials after unloading leads to a remaining pressure distribution between the tubes. As a consequence, frictional forces prevent the relative motion of the tubes.

With a FEM study, we have investigated the joining of the dissimilar metals copper and steel alloy (DC04). The study suggests that the order of the metals influences the joint strength. As expected, to place the softer material as the outer tube is not favourable since its grooves deform and flatten, and therefore the interlock effect is decreased.

The conducted experiment and our simulation study have a rather qualitative character. Therefore, there is a need for quantitative experimental and numerical studies; especially focussing on the joint strength. In particular, this requires numerical analysis of residual stresses in order to determine the joint strength resulting from force fit. Moreover, both experiments and simulations of pull-out and torsion test are suited to assess this joining technology. For determining the suited process parameters (pressure, geometric dimension of tubes and grooves, material pairing) it is also required to implement failure criteria that are capable of predicting fracture.

5. Acknowledgement

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