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Procedia Engineering 207 (2017) 968–973

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Creating load-adapted mechanical joints between tubes and sheets by controlling the material flow under plastically unstable tube upsetting

A. Sviridov[a,]*, M. Rusch[a], A. Almohallami[b], C. Bonk[b], A. Bouguecha[b], M. Bambach[a], B.-A. Behrens[b]

[a]Chair of Mechanical Design and Manufacturing, Brandenburg University of Technology Cottbus-Senftenberg, Konrad-Wachsmann-Allee 17, 03046 Cottbus, Germany
[b]Institute of Forming Technology and Machines, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

Abstract

Mechanical joining processes provide various advantages over conventional fusion welding of metallic components such as shorter cycle times, little or no heat input and reduced need for subsequent surface finishing operations. Several investigations in the past have shown that joints between tubes and sheets or plates can be manufactured by upsetting operations. Under axial compression, the tube develops a plastic instability in form of bulge. In-between two such bulges, a force and form fit to sheet material can be created. Previous work concentrated on forming fully developed bulges, i.e., at the end of the bulging process, both hinges of the bulge are in contact. This paper presents a numerical and experimental study aiming at optimizing the bulge shape to increase the bearable limit loads. Two new bulge designs are investigated, an 'arrow bulge' and a 'wave bulge'. The paper details the results of FE-simulations of the bulge shapes under bending and torsion loads. Forming tools were designed and both bulge shapes were produced experimentally. The results show that the material flow under compressive plastic instability can be controlled and that the resulting bulge shapes yield improved strength in various load cases.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: tube forming; mechanical joining; upset bulging; shape optimization

* Corresponding author. Tel.: +49-355-69-4607; fax: +49-355-69-3110.
E-mail address: sviridov@b-tu.de

1877-7058
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.860

1. Introduction

Joining by upset bulging is part of a broad range of mechanical joining processes used to manufacture innovative lightweight structures and multi-material designs, which contribute to the reduction of emissions and improve resource efficiency in industrial production. Fusion welding processes are commonly used for standard assemblies but with regard to high-strength materials and joints of different materials they are subject to limitations due to the high heat input, which causes distortion and degradation of mechanical properties. This can be avoided by mechanical joining processes which are applicable to a wide range of joints such as joining of sheet metals parts (i.e. by riveting or clinching) or joining a tube and a plate or similar flat parts (joining by upset bulging). During joining by upset bulging, a form and force fit between tube and sheet are created. First, a revolving flange is formed through axial compression of the tube by a forming tool set. A pierced sheet is then inserted, which is clamped by forming a second bulge.

Such joints can be used in various applications where they are subject to different dominant loads, e.g., torsion in the adjustment mechanism of the backrest of car seats manufactured by the company “Faurecia Autositze GmbH” or bending in the foot plate for a scaffolding (Fig. 1).

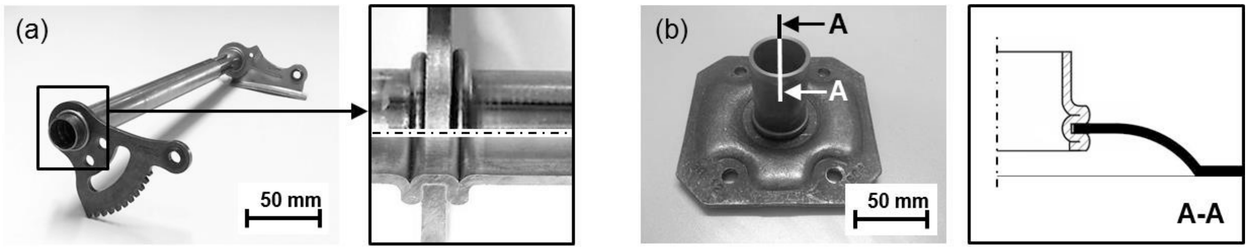

Fig. 1. (a) Backrest adjustment mechanism (source: Faurecia Autositze GmbH) and (b) foot plate for a scaffolding [1] made using joining by upset bulging.

Currently, conventional fully compressed bulges are used in these applications. The basic forming process of such bulges was described in the textbooks by Lange [2] and Spur et al. [3]. First investigations into joining by upset bulging were put forward by Viehweger [4, 5] and Grützner [1], showing the risk of crack initiation in the inner bulging radius. At the same time, Alves et al. extended the joining by upset bulging process to create, e.g., tube-to-tube connections [6]. Bambach et al. used a local heating to prevent the formation of cracks due to increased formability of the tube material [7]. The mentioned work dealt with fully compressed symmetrical bulges, which are not geometrically adapted to specific load scenarios. In this paper two new bulge shapes are investigated, an arrow bulge, aiming to increase the maximum bending load (first presented in own work [8] to reduce the crack initiation) and a wave bulge (first introduced in this study), which aims at enhancing the torsional strength.

2. Methods

2.1. Definition of bulge shapes

In conventional joining by upset bulging the hinges of the bulge are fully compressed, i.e., the tube wall is bent by 180° to produce a rotationally symmetric flange (Fig. 2a). The main geometrical parameter of this bulge is the bulging length l_k, which is described by the free length of the tube between the tools before forming and defines the material available to form the bulge. The arrow bulge (Fig. 2b) is characterized by a triangular shape and adds a further parameter, the angle ω of the bulge, but remains rotationally symmetric. The wave bulge (Fig. 2c) is also fully compressed, but not rotationally symmetric because the flange is formed with a defined local offset to create the wave shape. The wave itself can be described with three parameters: width b_W, depth e and radius r_W.

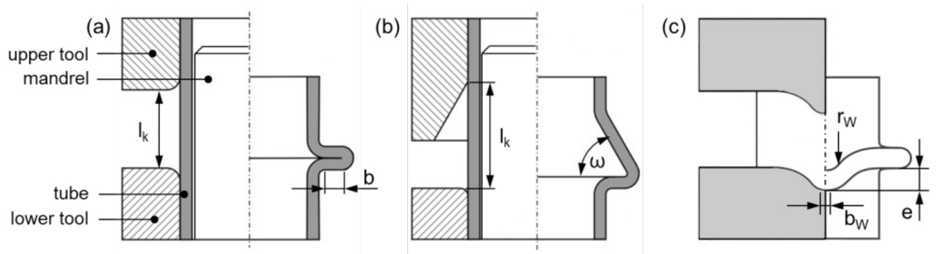

Fig. 2. Illustration of (a) conventional bulge, (b) arrow bulge and (c) wave bulge with particular geometrical parameters and specific tool setup.

The arrow bulge aims mainly at improving the bending strength compared to the conventional bulge because of the mechanical support created by the straight section of triangular flange. The wave bulge is expected to yield improved torsional strength of joints as main advantage compared to conventional joints regarding a form fit between the wave shape and the joining partner (e.g. sheet or plate). As a secondary effect, an improved tensile strength is possible with both bulge geometries.

2.2. Numerical study

The numerical study was divided into two different groups of simulations with different objectives. In the first group, the FE-simulations were carried out to investigate the bulge strength of the newly designed bulge shapes. The investigations of the second group are based upon forming simulations used to evaluate the effect of the forming process on the stresses and strains in the bulge shapes. To investigate the features of the new bulge shapes, which are relevant for their strength, several tube-cross-sections with different geometrical parameters shown in Table 1 were created as CAD-models.

Table 1. Geometrical parameters of the form-bulges used for FE-simulation of the bulges strength and the forming process.

Arrow bulge		Wave bulge					
Angle ω [°]	45, 55, 65	Depth e [mm]	2, 4, 6	Radius r_W [mm]	6, 12	Width b_W [mm]	2, 4

The simulations were performed to show the influence of the *arrow geometry* on the strength of the bulge, i.e., the load to cause plastic deformation in the bulge under *bending load* (Fig. 3a). The effect of the geometrical parameters of the *wave bulge* was examined in the simulations using *torsion loading*. To evaluate the bearable torsion load, the joint to the sheet was modelled (Fig. 3b). The loads were applied using the boundary conditions shown in Fig. 3 to the specific direction (marked by arrows) with a defined displacement of 1 mm for the bending load. The torsional loading was defined through a rotation of 5 degrees.

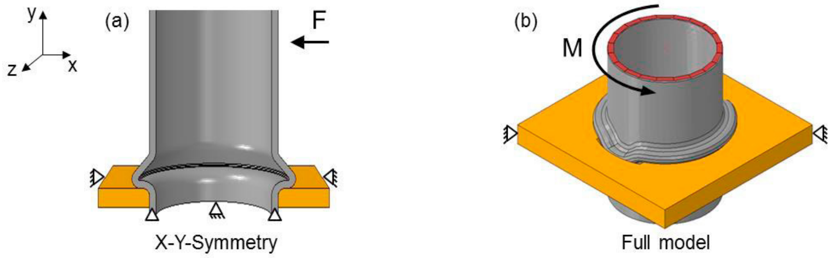

Fig. 3. The boundary conditions of FE-models: (a) arrow bulge in bending and (b) wave bulge in torsion.

The effect of the forming process on the plastic strain in the bulge shapes was evaluated in the second group of simulations. To carry out these simulations, tube upsetting using forming tools was simulated to create the appropriate geometry of the bulge shape. In both cases the forming tools were described as analytical-rigid parts and with a coulomb friction coefficient μ = 0.1. This value of the friction coefficient has shown a very good agreement to the experiments carried out by the authors in a recent investigation [9].

2.3. Experimental study

The shape of the bulges is defined by the tools, which guide the material flow during the forming process. To prevent bulging to the inside of the tube, a mandrel should be used (see also Fig. 2). For pilot forming tests of both bulge geometries, a hydraulic press with a maximum punch force of 1000 kN was used. The experimentally manufactured specimens were compared to bulges from numerical simulation regarding the reproduction of the desired geometry.

3. Results and discussion

3.1. Numerical investigation of static loads

The results of the simulations for the arrow bulge with different angles are shown in Fig. 4. The results obtained for bending show a better performance of the arrow bulges over the conventional bulge with a maximum bending moment of about 230 Nm (ω = 65°), which yields almost 40 % more performance compared to the conventional bulge. This can be explained by the supporting effect of the outer inclined flange of the arrow bulge, which creates a greater moment of inertia along the bulged area of the tube. The performance rises when the angle is increased (Fig. 4a). The bulged zone of the conventional bulge is smaller and thus leads to a reduced moment of inertia to resist bending loads. Furthermore, the simulation of the forming process (see also 3.2) has shown, that the level of strain and stress is higher during forming of the conventional bulge.

The wave bulge was compared to the conventional bulge under torsion load in a joint with a sheet. In an experimental study, the conventional bulge shows an increase of the torsion moment at the beginning, it reaches a breakaway moment of about 50 Nm and then rotates with a constant torsion moment of 40 Nm (Fig. 4b). The numerically calculated torsion moment of the joint with a wave bulge with a depth *e* of 6 mm shows a constantly increasing moment up to 65 Nm while the form fit between the bulge and the sheet is effective.

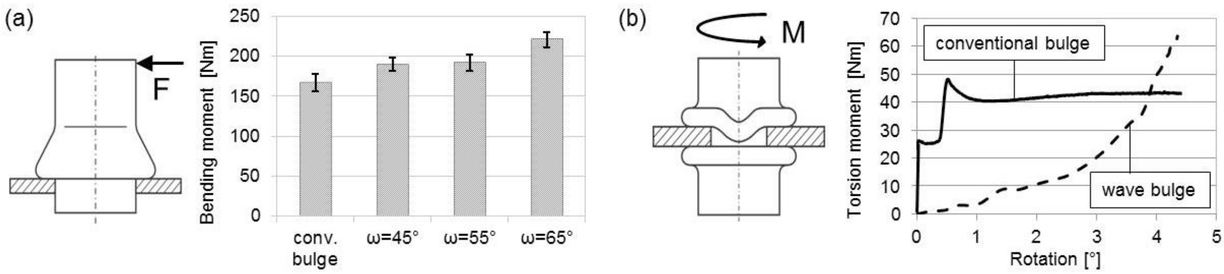

Fig. 4. (a) Comparison of strenght limits as initial loads for plastic deformation for arrow bulge under bending load; (b) comparison of torsion strength of conventional and wave bulge.

3.2. Numerical investigation of the forming process

In the simulation of the forming process for the arrow bulge, a range of angles (45°, 55°, 65°) was compared to the conventional bulge with regard to the maximum effective plastic strain reached in the inner bulging radius, which defines a critical area concerning the material damage (see also [9]). Since for the conventional bulge the tubes wall is bent by 180° to form a bulge, a higher plastic strain is reached. While the conventional bulge reaches a value of 1.93, the strain value for the arrow bulges is reduced and reaches a value of 1.13 for ω = 65° as shown in Fig. 5. The same tendency exists with regard to the residual stresses which develop during the forming.

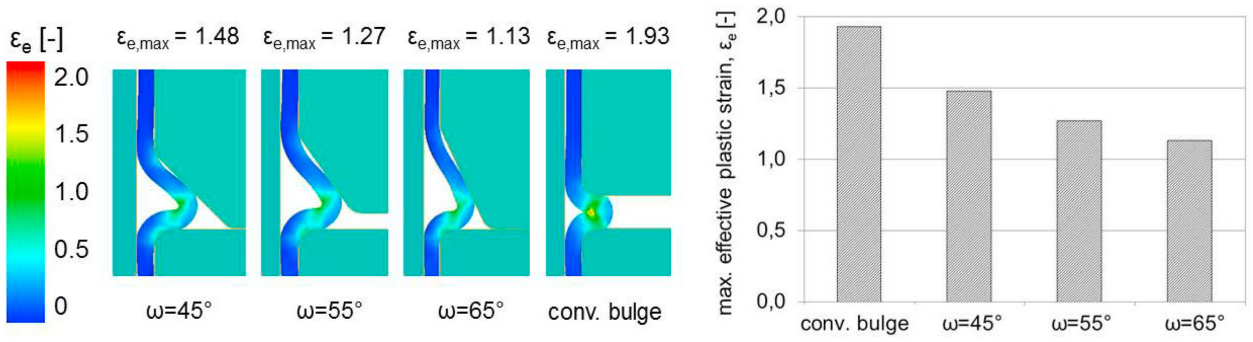

Fig. 5. Comparison of maximum effective plastic strain after the forming process for arrow bulge with different angles and conventional bulge.

The arrow bulge geometry avoids high strains and stresses by guiding the material flow into the appropriate shape with reduced risk for forming conditioned material damage. The level of plastic strain in forming the wave bulge is expected to be similar to the conventional bulge since both geometries are fully compressed but forming the offset of the flange for the wave geometry is additionally stressing the material. This effect will be investigated in future work.

3.3. Manufacturing of optimized bulge shapes

Both bulge geometries were produced in experiments with the tool setup detailed in 2.3. Seamless tubes (steel E235+N) with a diameter of 40 mm and a wall thickness of 2 mm were used. The arrow bulge was formed with an angle of ω = 55° while the wave bulge parameters were as follows: e = 4 mm, b_W = 2 mm and r_W = 6 mm. Each shape was also created using FE forming simulations. The comparison of the experimental specimens with the simulated ones showed a good agreement of the geometrical contours (Fig. 6a, b). In FE forming simulations, force-displacement-curves were analysed for the conventional bulge, the arrow bulge and the wave bulge. As seen in Fig. 6c the conventional bulge and the wave bulge have the same qualitative trend but the wave bulge requires about 10% more force in the middle of forming process due to the additional deformation in axial direction to build the wave. During the deformation of the arrow bulge the force rises abruptly when the inclined straight section of the tool comes into contact with the developing bulge. Then, the material is guided into the arrow shape with almost constant force. The tool displacement does not reach the same value as during forming of the other bulge shapes. Therefore, the forming process of the arrow bulge is shorter.

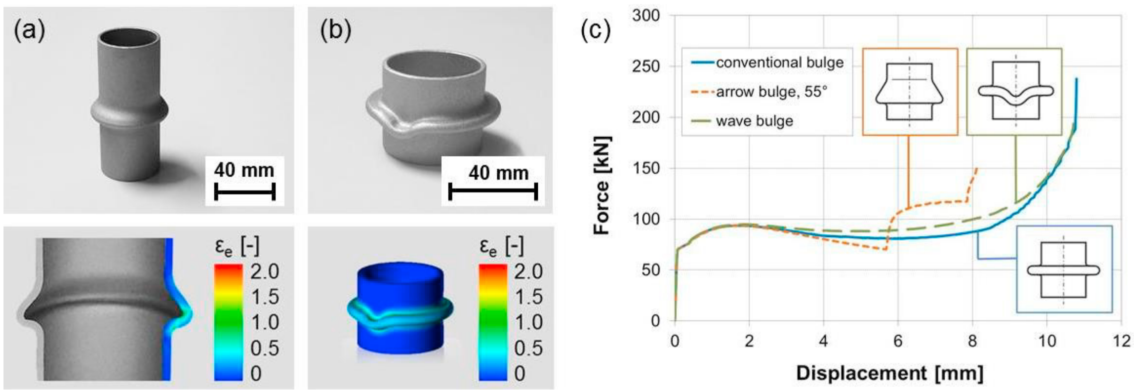

Fig. 6. Comparison of experimentally and numerically formed shapes for (a) arrow bulge and (b) wave bulge and (c) comparison of force-displacement-curves for conventional bulge, arrow bulge and wave bulge.

4. Summary and outlook

In the present paper, two new geometries for upset bulging were introduced. The arrow bulge is characterized by its triangular cross section, which is designed to create a higher resistance against bending loads while the wave bulge has a local offset in the flange to produce a form fit with the joining partner, improving torsional strength. The arrow bulge was numerically investigated concerning the influence of its geometry on bending load and regarding the forming process for different values of the angle parameter. It was compared to the conventional bulge shape showing better performance under bending because of its greater moment of inertia along the bulged zone and lower strain levels produced by forming. The wave bulge creates a form fit with the joining partner to provide improved strength under torsional loads compared to joints with the conventional bulge. While joints featuring conventional bulges bear a certain breakaway moment and then offer no further resistance to torsion, the wave bulge bears increased torsion loads compared to the conventional bulge and did not show failure under the applied loading. Further investigations will combine the simulation of forming including material damage and subsequent application of static loads for all bulge geometries and are also needed to determine the specific process limits and the performance of the joints for both bulge geometries as a function of their geometrical parameters. By combining forming process simulations, knowledge about material damage and testing of the joints under bending, tensile and torsional loading, optimized, load-adapted joints can be determined.

Acknowledgements

The project “Process extension to increase connection strength and extend the range of application” Ref.-No. AiF 18243BG is financed and supervised by the European Research Association for Sheet Metal Working (EFB). In the scope of the program to promote Industrial Collective Research it is funded by the German Federation of Industrial Research Associations (AiF) with means of the Federal Ministry of Economic Affairs and Energy (BMWi) on basis of a decision by the German Bundestag.

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