CIRP Annals - Manufacturing Technology 62 (2013) 299–302

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Fundamentals for controlling thickness and surface quality during dieless necking-in of tubes by spinning

L. Kwiatkowski, A.E. Tekkaya (1)*, M. Kleiner (1)

Institute of Forming Technology and Lightweight Construction (IUL), Technische Universität Dortmund, 44227 Dortmund, Germany

ARTICLE INFO

Keywords:
Forming
Toolpath
Tube spinning

ABSTRACT

Dieless necking-in by spinning is a highly flexible process to manufacture tubular parts with variable cross-sections and nearly arbitrary contours. However, the thickness distribution of such products is influenced primarily by the toolpath. Based on analytical models this study introduces the fundamentals to control the tube thickness. Two principal tool movements are identified causing different deformation modes: shear-necking, which leads to thickening, and stretch-necking, which leads to thinning. Based on an additional model for the surface quality general criteria are derived to setup basic process parameters. The developed approach is validated by various experiments.

1. Introduction

Hydroforming or crimping have their undisputed relevance in tube forming for large batches [1]. But these processes are not flexible enough to be cost-efficient procedures for small batch sizes since they use specific tools dedicated to each individual part geometry. Additionally, the challenge with lightweight products often requires the integration of several functions in one single product, which frequently leads to complex part geometries and high local strains that cannot be achieved by hydroforming or crimping.

Promising processes to meet these requirements are spinning or flow forming [2]. A demonstration of the flexibility of spinning is presented in [3] and of flow forming in [4]. Nevertheless, in most cases an individually shaped mandrel is necessary. Additionally, dissembling of the mandrel after forming might be critical for products with undercuts. These two limitations can be overcome using necking-in by dieless spinning (Fig. 1).

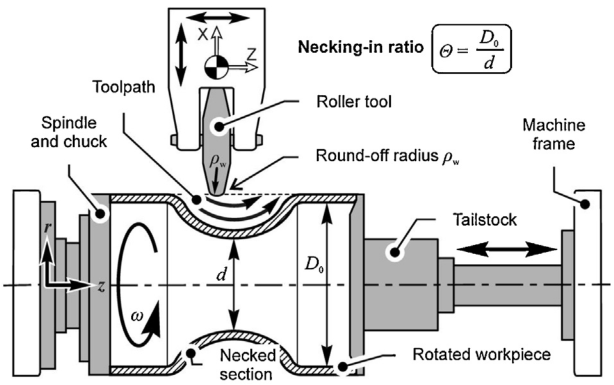

Fig. 1. Necking-in of thin-walled tubes by dieless spinning.

* Corresponding author.
E-mail addresses: erman.tekkaya@iul.tu-dortmund.de, erman.tekkaya@udo.edu (A.E. Tekkaya).

0007-8506/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirp.2013.03.054

In this process a tube is clamped in a chuck and rotated by the main spindle. For shaping, a roller penetrates into the part along a toolpath, which is controlled by CNC. The workpiece can be supported by a tailstock. The basic parameter characterising the process is the necking-in ratio Θ, that is the ratio of the initial diameter D_0 and the final diameter of the tube d. Compared to flow forming, the flexibility and the freedom of part design are increased significantly by this dieless process.

The process flexibility of dieless necking-in by spinning is demonstrated in [5] by an evaluation of the process shape family. Obviously, nearly arbitrary shapes even with several undercuts can be manufactured in series in one part. This method was applied in [6] (Fig. 2).

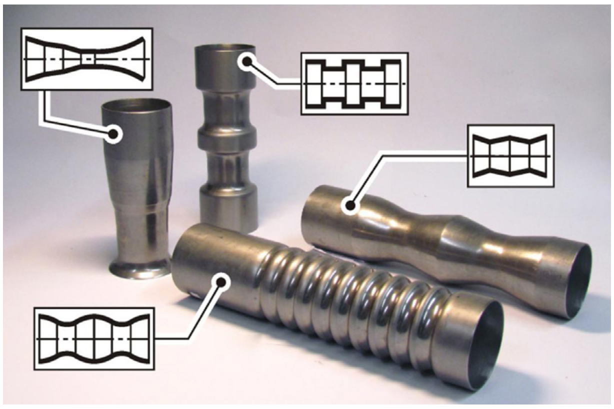

Fig. 2. Parts made by dieless necking-in by spinning [6].

Dieless necking-in by spinning is known for a long time [7]. As a result of the flexibility, there are many parameters that influence the process [8]. In order to manufacture precise parts, statistical optimisation methods were applied in [9]. But up to now no feasible theoretical models are available to allow a deterministic process setup [10]. Consequently, parameter adjustment and toolpath design are done by a cost-intensive trial-and-error approach and require highly skilled workers [11].

In this paper, analytical models will be used to derive general design rules for the toolpath and process setup. The models will be verified by various experiments.

2. Analytical modelling of thickness strains

The most challenging aspect during dieless necking-in by spinning is the prediction of the final thickness and its distribution. An analysis of the geometry is conducted applying the principle of volume constancy. The models are developed for global and local deformations.

2.1. Global analysis

Within this first method the local deformation in the forming zone under the roller is neglected. The thickness is calculated for an infinitesimal element with a length *dl*, Fig. 3(a). It is assumed that the tailstock is in use so that the workpiece cannot change its overall length. Furthermore, it is assumed that all infinitesimal

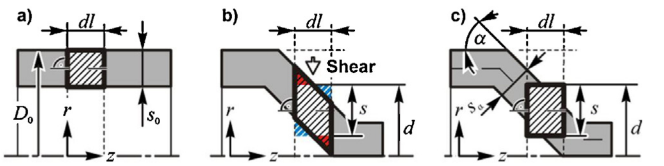

Fig. 3. Model for thickness calculation (a) semi-finished part, (b) shear-necking and (c) simplified analysis.

elements remain normal to the rotation axis of the workpiece. By these constraints, a shear deformation mode has to be assumed to achieve the desired diameter reduction, Fig. 3(b). Consequently, this deformation mode is named "shear-necking".

To calculate the thickness *s* of the sheared element, a rectangular geometry is used, Fig. 3(c). Compared to the trapezoidal geometry in Fig. 3(b), this is a simplified state because the highlighted areas of the cross section have different diameters and, consequently, different volumes. This is neglected because of the small value of the length *dl*. The local normal thickness s_α can be calculated by (Fig. 3c)

$$s_\alpha(z) = \frac{D_0}{d(z)} \cdot s_0 \cdot \cos\alpha = \Theta(z) \cdot s_0 \cdot \cos\alpha. \qquad (1)$$

The model shows that the thickness s_α has to increase during the diameter reduction since $\Theta(z) > 1$. Furthermore, the thickness will decrease when the angle of the inclination α is increased. The model is comparable to the sine-law, which is known from conventional shear forming [12] or incremental forming of sheets [13], but is extended by the necking-in ratio Θ.

Fig. 4(a) illustrates the workpiece geometry which was used for experimental model verification. The geometry is characterised by an undercut and two conical transition zones. The corresponding toolpath is illustrated in Fig. 4(b). The final shape was achieved by applying multiple forming stages. According to the results in [8,13] for incremental sheet forming, only a bi-directional toolpath was considered because a uni-directional toolpath leads to a non-symmetrical thickness distribution with respect to the centre-plane of the tube. A typical experimental result is shown in

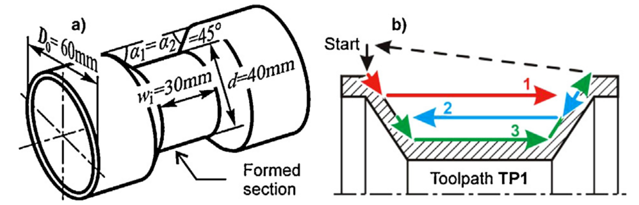

Fig. 4. (a) Used part geometry and (b) applied toolpath TP 1.

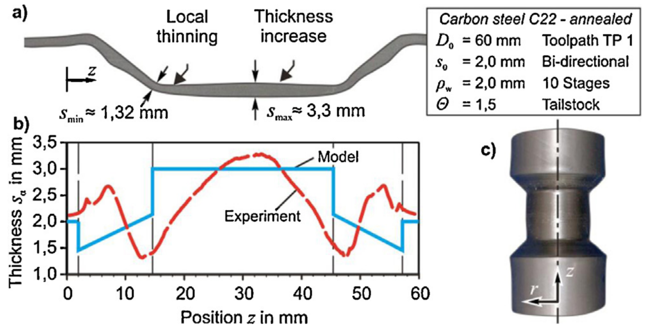

Fig. 5. (a) Cross-section of necked workpiece, (b) thickness distribution and (c) real workpiece.

Fig. 5(a). The process parameters were selected by the recommendations given in the literature [8,10]. The achieved thickness distribution is symmetrical, but not homogeneous. While the thickness is increased at the centre, a local thinning is observed at the transitions between cylindrical and conical part sections. The experimental result is compared to the analytical model in Fig. 5(b). For simplicity, the thickness was calculated in sections assuming an idealised contour. This means that the transitions between cylindrical and conical zones are discontinuous. Alternatively the round-off radius of the tool ρ_w can be used in the transition regions delivering a continuous thickness distribution.

The results show that the developed model is satisfactory to evaluate the effect of the parameters Θ and α, on the one hand. This was also verified for different materials in [6]. On the other hand, local effects cannot be explained by this model. Particularly the observed thinning at the transitions characterises the weakest positions of the part, which are critical for fracture and have to be avoided anyway. To consider this, an analysis of the local strains at the contact area between tool and workpiece is necessary, as given in the next section.

2.2. Local analysis

As illustrated in Fig. 4(b), the given workpiece was formed using multiple intermediate forming stages. This leads to three different contact conditions during the forming operation:

During forming of the conical section, Fig. 6(a), the tool is only in contact with its rear part. This deformation corresponds to the presented shear-necking mode, given by Eq. (1). Once the tool reaches the cylindrical workpiece section obtained during the previous forming stage, the contact area increases, Fig. 6(b). While the toolpath is directed radially, the tool is in full contact with the workpiece in the rear and additionally in the front. Finally, the toolpath direction changes, Fig. 6(c). Now the tool is penetrated only at the front. The shear forming model can be used again assuming $\alpha = 0$. The contact condition in Fig. 6(b) leads to the

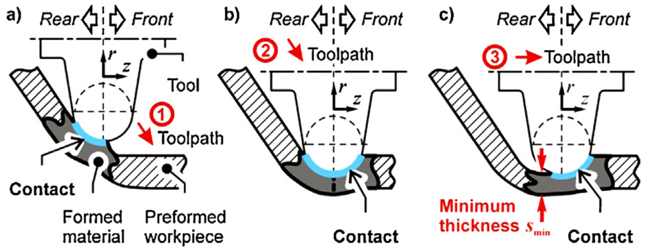

Fig. 6. Change of contact during the toolpath TP 1 (a) rear contact, (b) full contact and (c) front contact.

locally reduced thickness s_{min} observed in the experimental study reflected in Fig. 5(b).

To isolate this effect, the workpiece was shaped only by a radial toolpath in further experiments. A circumferential groove is formed consequently. The ratio between the radial indentation *i* and the round-off radius of the tool ρ_w is specified by the