Rotary swaging forming process of tube workpieces

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Abstract

With the fast development of manufacturing industry, rotary swaging technology is applied more and more widely in automobile, aviation and aerospace industries, due to its advantages such as saving materials, reducing lead time and improving product quality. Rotary swaging technology is mainly used to fabricate tubes, rods or act as preprocessing of other process. For instance, it can conduct necking of the tube ends before tube hydroforming process and internal gear machining process. In this paper, finite-element simulations using Forge 2011 3D has been carried out to investigate the rotary swaging process of tubes. According to the swaging method and presence of mandrel, rotary swaging process of tubes includes four categories, infeed method without mandrel, infeed method with mandrel, recess method without mandrel and recess method with mandrel. Metal flow and stress state of those four kinds of method are investigated. For the infeed method without mandrel, the metal mainly flows radially at the sinking zone. At the sizing zone, the metal flows axially with small velocity. When a mandrel is used, the axial flow velocity at the sizing zone gets larger. For the recess method, the main deformation area is the forging zone. The metal mainly flows radially at the forging zone with large velocity. Experiments have been carried out. Discrepancy of the tube thickness between the experiments and simulations for the infeed swaging without mandrel is less than 1.1%.

1. Introduction

Rotary swaging technology is an incremental forming method for reducing cross sections of metal rods, tubes or...
wires. It belongs to the open die forging processes and net-shape-forming processes according to DIN 8583. With the development of manufacturing industry, metal rods and tubes are used more and more widely in automobile, aviation and aerospace fields. Rotary swaging technology, as a special type of the radial forging (Altan et al., 1983), becomes a competitive plastic forming technology in manufacturing metal rods and tubes, due to its advantages such as saving materials, reducing lead time and improving product quality. Recently some researchers have carried out significant works to investigate the rotary swaging process.

Ghaei et al. (2008) developed a finite element model to assess some problems existing in radial forging of tubes without mandrel such as the axial tensile stresses, the axial feed and the possibility of crack initiation. Ghaei et al. (2006) also presented a new upper bound solution considering three distinct regions of deformation in radial forging of the tubes. Sanjari et al. (2012) used finite element method and microhardness test to determine the strain field and heterogeneity of the tube in radial forging process. Abdulstaar et al. (2013) investigated the microstructure evolution and change in mechanical properties of commercially pure aluminium (Al 1050) during severe plastic deformation by rotary swaging at the ambient temperature and found that rotary swaging led to a marked decrease in grain size. Yong et al. (2013) presented a simulation and experimental study on the formation characteristics of sinking thin-walled copper tube with axially inner micro grooves through radial forging. Piwek et al. (2010) presented the production-orientated capabilities of light weight design of rotary swaged components such as hollow shaft drives and they also developed an innovative high dynamic feed system to increase the productivity and quality of the workpiece. Kuhfuss et al. (2008) conducted experimental investigations on micro components that were made by rotary swaging and they showed the change in microstructure after rotary swaging such as the distortion structures and the residual stress.

However, the current research on the mechanism of rotary swaging of tubes is not comprehensive. This study aims at making a contribution for better understanding of rotary swaging of tubes. In this paper, finite-element simulation using Forge 2011 3D has been carried out to investigate the rotary swaging process of tubes. Some specific experiments have been conducted and the experimental results and the simulated ones are in good agreement.

2. Rotary swaging process of tubes

2.1. The principle of rotary swaging of tubes

Rotary swaging process usually utilizes three, four or eight dies arranged uniformly in the circumference of the workpiece. The swaging dies revolve around the workpiece and perform high-frequency radial movement with short strokes, simultaneously. Therefore, local uniform necking occurs on the tube or bar material owing to the multidirectional forging and high-frequency loading method.

As shown in Fig. 1, rotary swaging can be divided into two categories, the infeed swaging process and the recess swaging process. The main distinction between these two variations is that the workpiece is gradually fed into the swaging dies axially from the entrance of the dies during the infeed swaging while it is positioned in the open swaging dies during the recess swaging process. Therefore, the infeed swaging process is often utilized at the occasion where the workpiece is necked from one end. The recess swaging process is often used to reduce diameter at a certain position of the workpiece or form a concave profile.

![Fig.1. Two variations of rotary swaging: (a) infeed swaging and (b) recess swaging.](image-url)
2.2. Finite-element model

To investigate the metal flow of rotary swaging process of tubes, metal forming simulation software Transvalor Forge 2011 3D was used to simulate the process. Considering that rotary swaging is cold forming process, the following assumptions were made to analyze the process: (a) the material is isotropic and uniform, (b) the thermal exchange at the interface of the dies and the workpiece is ignored, and (c) the gravity and inertial force are left out of account.

According to the two variations of rotary swaging process and taking the presence of the mandrel into account, FE model of the rotary swaging of tubes is divided into four types, (a) infeed method without mandrel, (b) infeed method with mandrel, (c) recess method without mandrel and (d) recess method with mandrel. Elastic-plastic material model was used to establish the tube workpiece and the hammer die and mandrel models were meshed with rigid elements. The material of the tube was copper AISI C11000 with an equivalent stress-strain relationship of $\sigma = 360 \times e^{0.15}$ at room temperature. The friction condition in the die-workpiece interface was modelled by the combined friction law. It was assumed that the limiting shear stress was obtained by $\mu \sigma_y / \sqrt{3}$, where $\sigma_y$ was the flow stress and $\mu = 0.15$ was the friction coefficient commonly used for cold forging conditions (Ghaei et al., 2008). The swaging dies moved radially toward the tube and achieved swaging to the tube. The length of the tube was 80mm, the outer diameter was 27 mm, and inner diameter was 17.5 mm. Table 1 shows some parameters of the four FE model.

| Element number of the tube | (a) | (b) | (c) | (d) |
|----------------------------|-----|-----|-----|-----|
| Axial feeding amount       | 1mm/blow | 1mm/blow | 0   | 0   |
| Radial forging amount      | 1.5mm/blow | 1.5mm/blow | 0.3mm/blow | 0.3mm/blow |
| Axial rotation angle       | 15°/blow | 15°/blow | 15°/blow | 15°/blow |

2.3. Numerical results and analysis

Fig.2 shows the velocity distribution of the four types of rotary swaging process of tubes and the arrows indicate the metal flow direction. For infeed swaging method without mandrel (Fig.2 (a)), it can be seen that the velocity at the sinking zone reaches to the largest, indicating that the metal mainly flows radially at the zone. At the sizing zone, the metal flows forward along the axial, but the flow velocity is small. When a mandrel is used (Fig.2 (b)), the axial flow velocity at the sizing zone gets larger, which indicates that the axial flow gets more severely. For the recess method (Fig.2 (c) and Fig.2 (d)), the main deformation area is the forging zone. As can be seen from the figures, the metal mainly flows radially at the forging zone with large velocity. The metal flows to both sides along the axial from the forging zone to other zone. Similarly, the axial flow velocity is small and it is more severe when the mandrel is used.

Fig.3 shows the stress state of the tube workpiece after extracting the 1st, 2nd and 3rd principal stress data. The 1st, 2nd and 3rd principal stress representative the axial, radial and circumference stress, respectively. The stress state of the tube is investigated at the outside, middle and inside position along the wall direction. For the infeed swaging method, the stress state is the same at the sinking zone no matter whether the mandrel exists. The middle of the material is in the two-direction compressive stress, which may cause increasing of the wall thickness. At the sizing zone, the middle of the material suffers circumference compressive stress when the mandrel is not used (Fig. 3(a)) and the material may flow along both the axial and radial directions. When the mandrel is used (Fig. 3(b)), the material suffers the radial compressive stress additionally and this may increase the tendency of the axial flow significantly. For the recess method without mandrel (Fig. 3(c)), the middle of the material suffers radial and circumference compressive stress and this may cause increasing of the wall thickness. When the mandrel exists (Fig. 3(d)), the material is in the state of triaxial compressive stress, which may increase the wall thickness of the tube. However, the wall thickness may also decrease when the striking displacement is big and at this condition, the material flows to both sides along the axial direction sharply.
Fig. 2. Velocity distribution of four types of rotary swaging process of tubes: (a) infeed method without mandrel, (b) infeed method with mandrel, (c) recess method without mandrel and (d) recess method with mandrel.

Fig. 3. Stress state of tube workpiece during the four types of rotary swaging process: (a) infeed method without mandrel, (b) infeed method with mandrel, (c) recess method without mandrel and (d) recess method with mandrel.

Fig. 4 shows the stress state of a point at the middle along wall thickness of the tube for the four types of rotary swaging process. It can be clearly seen that the tube suffers triaxial stress. The stress gets bigger suddenly when the dies strike on the tube. For the infeed swaging method, the point experiences sending zone, sinking zone, sizing zone and discharging zone. The compressive stress at the sinking zone is the largest, indicating that this is the main deformation zone. The stress at the discharging zone is the residual stress and the residual stress is larger when the mandrel is used. The maximum residual is along the circumference direction. It is about 50% of the yield stress when the mandrel is not used and is about 75% when the mandrel is used. For the recess method, the point always locates at the forging zone. Thus the stress only changes with the strike of the dies. The residual stress is quite small comparing with the infeed method. The maximum residual is just about 10% of the yield stress.
Fig. 4. Principal stress of point at middle of wall thickness of tube workpiece: (a) infeed method without mandrel, (b) infeed method with mandrel, (c) recess method without mandrel and (d) recess method with mandrel.

2.4. Experiments of rotary swaging

To verify the accuracy of the FE model, experiments of infeed swaging without mandrel of tubes were conducted. The experiments were carried out on the rotary swaging machine as shown in Fig. 5. The material of the tubes was the same with the simulation, copper AISI C11000. There were four types of tubes with the same length 80mm and inner diameter 17.5 mm, of which the outer diameters were 26, 26.5, 27 and 28 mm, respectively. Fig. 6 shows the tube wall thickness of the experimental and simulated results. It can be seen that the discrepancy of the wall thickness between the experiment and simulation is small and the largest gap is less than 1.1%.

Experiments of recess swaging without mandrel were also conducted. Fig. 7 shows tube/tube parts joined by recess rotary swaging without mandrel process. The appearance of the experimental and simulated results of the tubes is consistent. The wall thickness of the experimental tubes was measured. Compared with the simulated wall
thickness as shown in the figure, the error is very small and the biggest discrepancy is within 10μm.

![Image](image.png)

Fig.7. Joined tubes by recess swaging.

3. Conclusions

In this study, four types of rotary swaging process, infeed method without mandrel, infeed method with mandrel, recess method without mandrel and recess method with mandrel are introduced. Following conclusions can be drawn:

1. For the infeed method, the metal mainly flows radially at the sinking zone and the metal flows forward along the axial at the sizing zone. The axial flow is small and it is larger when the mandrel is used. For the recess method, the forging zone is the main deformation area and the metal mainly flows radially at the zone. The metal flows axially to both sides from the forging zone to other zone.

2. The tube suffers triaxial stress during rotary swaging process. The maximum residual stress is along the circumference. It is 50% of yield stress for the infeed method without mandrel and 75% of yield stress for the infeed method with mandrel. The maximum residual stress is only 10% for the recess method.

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