Axial and Radial Material Flow Analysis in Infeed Rotary Swaging of Tubes

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Abstract. In rotary swaging – an incremental cold forming production technique to reduce the diameter of axisymmetric parts – the material flow can be assumed to be predominantly axial and radial. The actual ratio of this axial and radial flow influences the mechanical properties and especially in tube forming the final geometry. It is known that during mandrel free infeed rotary swaging of tubes the wall thickness changes. The change is depending on the process parameters like incremental and cumulated strain. Hence, the ratio of axial and radial material flow changes. Consequently, the analysis of the wall thickness of rotary swaged tubes enables fundamental insight how to control the material flow direction. In this study, the infeed rotary swaging process of steel tubes with different wall thicknesses from 3 mm to 7 mm and rods were investigated with FEM under two feeding velocities. The axial and radial material flow and the resulting geometry were studied by the relative wall thickness. It could be seen that the relative wall thickness was affected by the feeding velocity as well as the initial wall thickness. The findings of the simulation were validated by rotary swaging experiments.

Keywords: Metal forming, Cold forming, Modeling

Nomenclature		
d_0	initial diameter	mm
d_1	final diameter	mm
f_{st}	stroke frequency	Hz
h_T	stroke height	mm
l_0	initial length	mm
l_1	final length	mm
l_h	drilling length	mm
R_n	radial neutral boundary	-
R_{nr}	position of R_n	mm
R_{np}	radial relative position of R_{nr}	%
s_0	initial wall thickness	mm
s_1	final wall thickness	mm
s_{1-fem}	final wall thickness of FE model	mm
s_{1-exp}	final wall thickness of experiment	mm
s_n	wall thickness that enables $\Delta s_p = 0$	mm
v_f	feeding velocity	mm/min
y_0	original mesh height	mm
y_1	final mesh height	mm
z_0	original mesh length	mm
z_1	final mesh length	mm
I	reduction zone	-
II	calibration zone	-
III	exit zone	-
α	die angle	°

Δs_p	change of wall thickness	%
Δy_p	change of mesh height	%
Δz_p	change of mesh length	%
δ	relative error of FE model	%
μ	friction coefficient	-

1 Introduction

Rotary swaging is an incremental cold forging process. Usually it is used for reducing the cross section of rods and tubular workpieces, or for achieving certain wall thicknesses of tubes [1]. This technology can improve the material strength as well as the surface condition with reduced roughness values. In addition, this process can produce advantageous inner profiles for tubes [3]. Nowadays, rotary swaging is widely used in automobile and textile industry [4]. The main part of a rotary swaging machine is the swaging head, wherein two or more dies are concentrically arranged. During the process, the dies rotate with the driving shaft. Simultaneously, the dies strike repeatedly towards the workpiece in the center. The forming is achieved either by axially feeding of the workpiece into the swaging

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head (infeed rotary swaging) or by radially feeding of the dies (plunge rotary swaging).

The principle of mandrel free infeed rotary swaging is shown in Figure 1. According to the geometry, the die is distinguished into three main zones: reduction zone (I), calibration zone (II) and exit zone (III). During the process, the plastic deformation of the workpiece appears mainly in the reduction zone, which features the die angle α . The main material flow is initiated in this zone. In the calibration zone and exit zone the geometry of the workpiece is predominantly maintained. The main parameters of the process are feeding velocity (v_f), striking frequency (f_{st}) and stroke height (h_T). The geometry of the tubes is given by the initial diameter (d_0) and the initial wall thickness (s_0). After the deformation a final diameter (d_1) and final wall thickness (s_1) are achieved. When the calibration zone is fully filled during the process, a quasi-constant condition is established. Thus, the same amount of material is deformed with the same conditions with every further stroke. In this situation, a stable phase is assumed [5].

Fig. 1. Principle of mandrel free tube infeed rotary swaging.

In former research, rotary swaging has been widely investigated by Finite Element Method (FEM) and experiments. Rong et al. [6] studied the radial material flow in pure magnesium rods with simulations. They found that the radial strain distribution was not notably affected by different values of v_f . Moumi et al. [7] studied the material flow by 2D axisymmetric simulations and the means of the axial neutral plane –the zone where the actual axial velocity equals Zero. They identified that the neutral plane was changing in shape and position during one stroke. Gan et al. [8] and Abdulstaar et al. [9] investigated the microstructures and tensile properties of commercial pure magnesium and pure aluminum in rotary swaging experiments. They found that both materials were gradually refined and the tensile yield strength was increased due to material flow. Ishkina et al. realized asymmetric strokes and used flat dies to change the radial material flow. They produced hexagonal wires and found that the shear strain distribution could be affected by these measures. In

consequence, the formability of AISI304 in subsequent cold extrusion operations was improved [2, 10].

According to former research [11], tubes with $d_0 = 8$ mm and $s_0 = 0.4$ mm developed a thicker s_1 after forming. For tubes with s_0 higher than a half of d_1 , s_1 must become definitely smaller than s_0 . Hence, the radial material flow must change significantly depending on the initial wall thickness s_0 . Due to the constancy of material volume, when the cross section of the workpiece is reduced in the process, the material flows both in axial and radial directions. Additionally, the reducing of the cross section of the workpiece is finished with many increments. That makes the material flow complex, because the same part of the workpiece experiences different load conditions in different zones of the dies. Beneath the final geometry of the product the material flow also changes mechanical properties. Consequently, a profound knowledge of the material and its dependency on processing parameters is needed for improved controllability and further optimization.

In this paper, mandrel free infeed rotary swaging process of steel alloy (1.0308) tubes was studied with varying wall thickness and feeding velocity values by simulations and experiments. The data from simulation and experiment were represented as “fem” and “exp” for short.

2 Methods

In FE model, the process was realized in the general finite element software ABAQUS (version 6.13). A 2D axisymmetric explicit model was used based on [12] (Figure 2) with following assumptions: isotropic material; negligible thermal influence; constant friction condition between the contact pair. Coulomb friction was assumed despite the expected high normal forces as it was used and discussed in former literature [6, 7, 12 and 13]. The processing parameters in this FE model are shown in Table 1.

Table 1 Parameters of the experimental settings.

Name	Value	Unit
d_0	20	mm
d_1	15	mm
f_{st}	37.5	Hz
h_T	1	mm
v_{f500}	500	mm/min
v_{f2000}	2000	mm/min

In the model, the material was steel alloy (1.0308) whose plastic properties were from literature [15], the values of s_0 were 3, 4, 5, 6, 6.5 and 7 mm. A square shaped CAX4RT mesh was used on the workpiece. The

Fig. 2. FE model in ABAQUS 6.14, $s_0 = 7$ mm [12].

length of the workpiece with fine mesh was 70 mm. This section that was involved in the deformation was meshed according to the initial wall thicknesses and radius. Remeshing was disabled. In this FE model, for thicker tubes with s_0 higher than 5 mm more radial meshes were used as a common measure to avoid hourglass phenomenon [14]. Consequently, different mesh sizes were deployed. The length for each square was: $s_0/20$ for $3 \text{ mm} \leq s_0 \leq 5 \text{ mm}$, $s_0/30$ for $6 \text{ mm} \leq s_0 \leq 7 \text{ mm}$, $s_0/40$ for the rod [12]. According to literature the friction coefficient value of lubricated contact pair steel - steel is around 0.1 [16], so $\mu = 0.1$ was used in this study. After the simulations were finished, the values of $s_{1\text{-fem}}$ were measured at a point 35 mm from the end of undeformed material (A-A section in Figure 3), where the material was supposed to have experienced the whole deformation process after the stable phase was established.

In a detailed view, the shape change of mesh elements in axial and radial directions was analyzed as a measure of axial and radial deformation at A-A section. In Figure 3 the shape change of a mesh at the outer surface is illustrated. In this study, the shape changes of meshes from the outer surface to the inner surface were investigated.

As different mesh sizes used in the FE model, the changes of mesh shape in axial and radial direction were normalized by the initial dimensions:

$$\Delta z_p = 100\% * (z_1 - z_0) / z_0 \quad (1)$$

$$\Delta y_p = 100\% * (y_1 - y_0) / y_0 \quad (2)$$

Δz_p is the axial deformation, due to the features of rotary swaging, the workpiece should always be elongated, so the values of Δz_p should always be positive. But according to former research the radial deformation for the meshes could be stretched or compressed, which means that the values of Δy_p could be either positive or negative. It is supposed there might be an area where the value of Δy_p is zero, which could be named as radial neutral boundary (R_n) whose location could be marked as R_{nr} . The radial relative position according to s_1 could be

calculated as R_{np} as equation (3), which represents the radial ratio of R_{np} from the outer surface.

$$R_{np} = 100\% * (d_1/2 - R_{nr}) / s_1 \quad (3)$$

Fig. 3. Shapes of mesh before and after deformation (A-A section for measuring $s_{1\text{-fem}}$).

In the experiments, the tubes were manufactured from rods ($d_0 = 20$ mm and $l_0 = 300$ mm) by drilling to ensure equal starting conditions (Figure. 4). The length of drilling was $l_h = 80$ mm. For each s_0 three workpieces were prepared. Conventional swaging dies with tungsten carbide layer in the reduction zone were used [5], the contact pair was lubricated with oil (Condocut KNR 22). During the process the workpieces were fed into the center of the dies with a length of 70 mm. Then they were pulled back. After the process, the geometry of the workpiece was changed as shown in Figure. 4.

Fig. 4. Section view of the workpiece before and after the process, $s_0 = 7$ mm. (A-A section for measuring $s_{1\text{-exp}}$).

After the experiments the values of $s_{1\text{-exp}}$ were measured at A-A section. The physical probes were measured by preparing metallographic specimens. A laser microscope was used to take five times enlarged photos of the cross sections. Based on the micrographs the values of s_1 were measured eight times for each of the three samples and the average value and variance were calculated. For the

validation of the FE model, the values of relative error were calculated by the differences between the s_1 values from simulation and experiment divided by the value from experiment (equation (4)).

$$\delta = 100\% * (S_{1-fem} - S_{1-exp}) / S_{1-exp} \quad (4)$$

The percentage of the wall thickness development (Δs_p) was calculated by (equations (5)).

$$\Delta s_p = 100\% * (s_1 - s_0) / s_0 \quad (5)$$

3 Results and discussion

No matter which s_0 was used, the length of the workpiece increased. So, the axial material flow is discussed firstly. The resulting values in axial direction Δz_p for v_{f500} are shown along the radius (Y-axis) in Figure 5. These values of Δz_p for both rod and tubes could be treated as constant values regardless of their locations in radial direction. Thus, the axial material flow is homogeneous. The mean values of Δz_p are shown in Figure 6. Δz_p increases almost linearly with higher value of s_0 ; the influence of the feeding velocity v_f is low and vanishes with higher s_0 . The reason for increasing Δz_p along with s_0 could be the increasing radial resistance due to more material to be deformed.

Fig. 5. Axial elongation Δz_p of meshes for different wall thicknesses of tubes and rod for the feeding velocity v_{f500} at the position A – A.

With the same value of s_0 , higher v_f led to an earlier contact between the dies and the workpiece during each stroke. Also, the contact length in the reduction zone was shorter and its center was shifted to the undeformed part; in the same time, due to an earlier contact the distance between the calibration zone and the deformed workpiece was longer, thus the friction resistance worked later compared to the situation with lower v_f . Due to this reasons, the material flow towards axial direction was easier for higher v_f .

Fig. 6. Mean values of Δz_p of tubes with different s_0 for v_{f500} and v_{f2000} .

Figure 7 shows the values of Δy_p over the radius. In contrast to the axial direction, the material flow in radial direction was not homogeneous with the exception of rods. For tubes, the radial material flow depended on s_0 . For s_0 equalled 3 and 4 mm, the values of Δy_p were always positive, which means over the whole radius the material was radially stretched. For tubes with higher values of s_0 , the values of Δy_p changed from positive to negative from inner surface to outer surface. In this case, there was a radial neutral boundary (R_n) that distinguished the radial material flow into local radial compression ($\Delta y_p < 0$) and local radial stretching ($\Delta y_p > 0$).

Fig. 7. Radial shape changes Δy_p along the radius for v_{f500} .

The ratios of R_n (R_{np}) in radial direction (Y axis) for both v_f with s_0 from 5 mm to 7 mm were determined and shown in Figure 8. The relative locations of this R_{np} shifted towards the central axis with bigger s_0 . Thus in thicker tubes more radial material had the similar behavior to that of rods as expected. For both v_f the location of R_n was almost linearly dependent on s_0 ; with the same value of s_0 the location of R_n from higher v_f was always nearer to the inner surface. So the effect of increasing v_f was forcing more material flow to axial direction. The effect of v_f in changing radial material flow could help to control the inner profile, for example

by using two v_f during the process might create stepped inner structures.

Fig. 8. Ratio of R_{np} according to s_1 for both v_f with different s_0

According to former discussion, increasing the wall thickness affected the material flow more than increasing the feeding velocity. Nevertheless, the trend could be derived that the more material to be deformed in one stroke, the harder for material to flow in radial direction. This should be caused by higher resistance against deformation in radial direction or a lower resistance in axial direction. The axial elongation of material could be treated as to be linearly dependent on s_0 .

For the experimental results, two photographs of tubes (s_0 equals 3 mm and 7 mm) deformed with v_{f500} are shown in Figure 9. The values of s_1 measured from experiments and FE model are shown in Figure 10, the value of variance of each measurement of experiment is in terms of error bars. In Figure 10 it could be found that the values of simulation is always higher than those of experiment. The over-valuation of s_1 of FE model could be caused by no-ideal material flow in circumferential direction in 2D-axisymmetric model or by a discrepancy of material property values. Also a simulation in an extended research shown by increasing the friction coefficient from 0.1 to 0.2 the values of s_1 were reduced, and a former research shown dry rotary swaging of tubes resulted in larger elongation and thinner walls [17]. Hence, the friction coefficient value might be underestimated in the present study. Nevertheless, the maximum value of δ was 6.7% for s_0 equalled 4 mm with v_{f500} while the average values were 4.44% and 3.30% for v_{f500} and v_{f2000} . Thus a good agreement between experiment and FE model was achieved and so the FE model was validated.

To view the changes of wall thickness based on both FE model and experiment, the values of Δs_p were shown in Figure 11. According to Figure 11 the thickening of the wall (positive values of Δs_p) decreased linearly with increasing s_0 up to an initial wall thickness of about

$s_0 = 6$ mm. Above this threshold the wall thickness decreased by the rotary swaging process ($\Delta s_p < 0$). Also, with a processing parameter dependent value of s_0 a not changing wall thickness was observed, which agreed with the simulation results. In addition, it could be verified that higher v_f led to a lower value of s_1 , thus increasing v_f increased the resistance for material flow towards radial direction and forced more material flow towards axial direction. This result agreed with former experimental research of tubes ($s_0 = 2$ mm) [17].

Fig. 9. Cross section of deformed tubes of v_{f500} (position A-A); (a) $s_0 = 3$ mm, $s_1 = 3.63$ mm; (b) $s_0 = 7$ mm, $s_1 = 6.50$ mm.

Fig. 10. Comparison of simulations and experiments.

Fig. 11. Relative change of the wall thickness Δs_p at position A-A as a function of the initial wall thickness s_0 . Positive values indicate an increase.

5 Conclusions and outlooks

In this paper the axial and radial material flow of steel tubes in mandrel free infeed rotary swaging process were investigated. A 2D-axisymmetric FEM model was built, the shape changes of the deformed meshes were calculated. The experimental validation was carried out by comparing the wall thickness change after the process. Several conclusions could be drawn:

- 2D-axisymmetric model is reliable to study the radial and axial material flow in mandrel free tube rotary swaging process;
- axial elongation of the material in mandrel free tube infeed rotary swaging process is homogeneous over the radial position;
- increase of the wall thickness increases the radial material flow more than increasing the feeding velocity;
- the material flow in radial direction near the inner surface of tubes increases with higher initial wall thickness;
- for tubes with a certain wall thickness, there is a radial neutral boundary (R_n) where the material is neither compressed nor stretched, the location of R_n is nearer to the outer surface with lower v_f .

Based on the conclusions, the next research should be focused on the validation of radial neutral boundary, and if it affects the mechanical properties that are known to be affected by the actual material flow. Also, more friction conditions should be considered. Other processing parameters like stroke height or frequency are also needed to figure out their influences, which could help to control the material flow. The influence of feeding velocity should be investigated due to the potential to change the wall thickness.

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7 References

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