Experiments and simulation of shape and thickness evolution in multi-pass tube spinning

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\textbf{Abstract.} The primary objective of this study is to predict the geometric shape and thickness change during multi-pass tube spinning to a hemispherical shape. Interrupted spinning experiments are performed at room temperature on cylinders of 6061-O aluminum alloy. The shape and thickness after 2, 4, 6 and 8 spinning passes are measured. An axisymmetric finite element model of the tube spinning experiments is described. Uniaxial tensile tests are conducted for the development of the material model. The post-necking hardening curve of the material is identified using a hybrid experimental-numerical method. The stress-strain identified in this way is fitted to a combined Swift-Voce model. The results of the simulation are compared to the interrupted spinning experiments. Good agreement is obtained on the shape evolution in multi-pass spinning. The effect of roller paths on shape and thickness change during multi-pass tube spinning targeting a hemispherical shape with uniform thickness were predicted by axisymmetric modeling and validated with experimental results.

Keywords: Tube Spinning, Shape, Thickness, Roller Pass, Axisymmetric modeling, AA6061-O

\textbf{1. Introduction}

Recent developments in the field of tube spinning process have led to a renewed interest in producing seamless, dimensionally precise axis-symmetrical products like a pressurized spherical fuel tank. In the tube spinning, a critical requirement is to control the uniformity of the wall thickness and shape during high deformation, and to do this a multi-pass spinning was recommended by previous researchers\cite{1-4}. Among the various process parameters of tube spinning, the spinning tool, or roller, path plays the vital role in the successful manufacturing of the desired product. Since tube spinning simulations involve large strains, the pre-necking true stress-strain curve obtained by the tensile test is not sufficient. For this reason, pre-necking hardening curves were extrapolated by conventional strain hardening models to forecast the response at large strains\cite{2}. But the tensile data after the maximum load does not follow any specific hardening model. For observing actual material response after maximum load, the precise identification of the hardening response of materials at large strain is required\cite{5}.
Due to the complex, incremental plastic forming in tube spinning and the very time-consuming simulation by the 3D method, axisymmetric modeling for simulating shear spinning was proposed [6]. The axisymmetric model can predict very close results to the 3D simulation and experiments [7]. In this paper the availability and limitation of axisymmetric model as a prediction method of the final shape and thickness in mandrel-free, multi-pass tube spinning has been examined through FE method and experiments. The effects of roller pass number on shape and wall thickness have been evaluated.

2. Methods

2.1. Material Modeling

For material modelling, firstly Swift [8] (Eq. 1) and Voce [9] (Eq. 2) hardening equations were optimized separately by curve fitting method up to the maximum loading point of the tensile test; then, post necking region with hybrid Swift-Voce equation (Eq. 3) parameter (a) was optimized by FEM, comparing the nominal stress-nominal strain relation from the tensile test of dogbone specimens cut from the tube, as shown in Fig.1(a). The figure shows that the pre-necking and post necking results of FEM simulation fully fitted with experimental results. FEM simulation identified the maximum local plastic equivalent strain (PEEQ) 62% up to the fracture point (i.e., 22% nominal strain). Finally, the true stress vs. true plastic strain at large strains that shown in Fig. 1(b) was obtained by extrapolating the hybrid Swift-Voce equation (Eq. 3) with parameters of Table-1.

Swift hardening law \[ \sigma = k_0 (\varepsilon_0 + \varepsilon_t^p)^n \] (1)
Voce hardening law \[ \sigma = l_0 - q \exp(-\beta \varepsilon_t^p) \] (2)
Hybrid Swift-Voce hardening law \[ \sigma = a(k_0 (\varepsilon_0 + \varepsilon_t^p)^n) + (1-a)(l_0 - q \exp(-\beta \varepsilon_t^p)) \] (3)

Table-1: Hybrid Swift-Voce hardening parameters

| Swift hardening parameters | Voce hardening parameters | Swift-Voce hardening |
|----------------------------|----------------------------|----------------------|
| \( k_0 \) (MPa) | \( \varepsilon_0 \) | \( n \) | \( l_0 \) (MPa) | \( q \) (MPa) | \( \beta \) | \( a \) |
| 260.49 | 0.00003 | 0.23 | 186.5 | 103.92 | 20.84 | 0.65 |

Fig. 1. (a) The nominal stress-nominal strain curve of the material. (b) The true stress-true plastic strain curve of the material. Inversely identified by FEM using hybrid Swift-Voce hardening curve using experimental data beyond the maximum nominal stress.
2.2. FEM model for tube spinning
In the FEM model, the workpiece was considered elastic-plastic deformable solid. The length of the model was considered up to the clamp of the experimental setup; in this case, the workpiece length is 350mm and the external diameter 418mm. The roller model was defined as analytical rigid, with the same dimensions as experimental roller, i.e., diameter 158mm, nose radius 12.5mm and contact angle 45°. For meshing, the CAX4R element (a 4-node bilinear axisymmetric quadrilateral reduced integration) was considered. The number of elements in the thickness direction was six. The boundary conditions were considered fixed at the clamped end and free at the lower end. The friction coefficient between the contacting surfaces of roller and tube was neglected. The spinning pass was designed to have a linear roller movement for achieving the hemispherical shape. The displacement of the rigid roller for each spinning pass was given according to design target shape as shown in Fig 2(a). Figure 2(b) shows the detailed arrangement of finite element model for multi-pass tube spinning pass.

2.3. Experiments
In the experimental study, the spinning process was performed at room temperature, on an annealed AA6061-O tube of 418mm OD and 2.92mm thickness. The spinning was interrupted after 2, 4, 6 and 8 passes and shape and thickness measurements were conducted for verifying the FEM analysis results. The experimental deformed shape was then drawn from the measured coordinates by the 3D contact gauge. The thickness of the deformed tube was measured by evaluating the distance between inner surface and outer surface using coordinates of 3D contact gauge results.

3. Results and Discussion
3.1. Evaluation of shape change by comparing results of simulation and experiment
Figure 3 shows the final shape of interrupted spinning for pass-2, pass-4, pass-6 and pass-8. The tube is progressively developing a hemispherical shape. The toolmarks from the contact with the roller can be seen on that hemispherical surface. More importantly, wrinkling of the free end was observed, see pass-8 in Fig. 3. This wrinkling prevented performing more passes for the interrupted spinning experiments, to avoid damage to the spinning equipment.
Figure 4 describes the comparison of the deformed shape of outer specimen surface for the experiments and simulation results. Final coordinates of the same spinning pass from simulation results have been drawn as the deformed shape in simulation. From this figure, it is shown that the experiments and FEM simulation results of the deformed shape in the hemispherical region are perfectly fitting with each other for all spinning passes (2, 4, 6 and 8). However, in the tapered cylindrical shape region, the predicted radius is about 1%, 1%, 2% and 2% smaller than the experimental results for spinning pass 2, 4, 6 and 8 respectively.

Fig.3. Photograph of (a) tube, and experimental final shape after spinning (b) pass-2, (c) pass-4, (d) pass-6, and (e) pass-8.

Fig.4. Comparison of deformed outer shape in experiments and FEM simulations for pass-2, pass-4, pass-6 and pass-8

By comparing the two results, some discrepancy has been found in the tapered cylindrical region between the experiments and the simulation results due to the differences in contract conditions between simulation and experiment. In the axisymmetric modelling, the roller was considered around the whole cylinder, but in the experiments, the roller contacts the workpiece over a short length only. The axisymmetric simulation predicts lower spring back due to high compressive plastic hoop strain caused by this extended roller contact length than the experimental one. The deformed shape in the hemispherical region shows good agreement because the plastic deformation at the hemispherical region of each spinning pass mainly occurs from the bending action of the roller contact force. This bending induced deformation is free from the difference in contact conditions between simulation and
experiment. Axisymmetric modelling overestimates the amount of compressive plastic hoop strain over the contact region of each spinning pass due to the limitation of contact condition. But the upward (hemispherical region) of that contact region, the FEM prediction is good agreements with experimental one.

3.2. Evaluation of thickness change by comparing results of simulation and experiment

The final wall thickness changes of the deformed shape obtained from the FEM simulation model are compared with the measured values from the interrupted spinning experiments, for pass 2, 4, 6 and 8, as shown in Fig.5 (a)-(d). These figures show that the thickness of the tube remains the same value in the clamped end, while the thickness in the hemispherical region is gradually increased with the increasing of the spinning pass, in both experimental and simulated results.

Fig. 5.: Comparison of thickness changes in experiments and FEM simulations for (a) pass-2, (b) pass-4, (c) pass-6, and (d) pass-8.

The thickness change has been occurred due to a combination of circumferential compressive and axial tensile deformations; the material starts to flow in the radial direction, causing thickening. It is noted that in experiments the constant thickness change and its abrupt decrease are observed in the lower part of the hemispherical region and the boundary between the hemispherical region and the tapered cylindrical region due to high contact of cylinder and roller at last contact point of the spinning path.
The simulation can reproduce the increase in thickness change with the increase in number of the spinning pass and make a slope between the boundary of hemispherical region and tapered cylindrical region. But the amount of abrupt decrease cannot be predicted by FEM. The amount of abrupt change in thickness predicted by FEM is about, 0.5%, 1%, 3 % and 5% smaller than the experimental one for spinning pass 2, 4, 6 and 8 respectively.

4. Conclusions
The paper describes a combined numerical/experimental effort to predict the plastic deformation during room temperature spinning of AA6061-O tubes for producing the hemispherical shape. The results lead to the following conclusions:

1) Axisymmetric modeling can generally predict the significant plastic deformation of complicated tube spinning process, including the shape and thickness changes of the spun tubes.
2) The main problem in axisymmetric modeling is the roller contact with the whole cylinder. For this reason, the predicted shapes in the tapered cylindrical region are different than the experimental ones.
3) The thickness of the spun part is increased with the increasing number of the spinning pass. During the experiments, a sudden change of wall thickness at the boundary between the hemispherical and tapered cylindrical region was observed. But the simulation predicted a smaller amount of that abrupt change in thickness than the experiments.

Finally, it can be concluded that the axisymmetric model can give the idea of thickness and shape change predictions, which can be a precious tool when real parts are to be manufactured.

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