An experimental and analytical study on dome forming of seamless Al tube by spinning process

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Abstract

The thickness distribution of a spin formed dome in an Al pressure vessel was studied experimentally and a simple formulation to predict the thickness distribution of the dome was proposed. The ends of the seamless Al tubes, which are widely used as liners in high pressure FRP composite vessels, were closed by spin forming. The thickness of the boss part of the dome may not be sufficient after forming operations, especially for high pressure vessels in which a deep thread cut is necessary for accommodating a pressure gas valve. Thus, a two-step spin forming of the Al tube end closure was proposed to improve and thicken the boss. First, the boss was deformed to a diameter smaller then the desired one. Later the dome was modified to obtain a greater boss diameter. The second forming provided a greater and better thickness distribution around the boss. Experimental work was carried out to compare the thickness distribution obtained with the conventional process and using the proposed two-step spin forming process. The ends of Al 6061-O tubes were deformed to dome shapes at an elevated temperature using a spinning machine. A simple analytical model, which was based on geometrical shape changes and an assumption of material constancy during forming, was formulated to predict the final thickness distribution of the dome. The results indicate that the proposed two-step spin forming provides a greater boss thickness than that of conventional forming.

Keywords: Spinning; End closure of tube; Pressure vessel; Dome forming; Analytical model; Boss thickness; Large deformation

1. Introduction

Spinning is a process in which a flat circular sheet or a tubular form is turned and forced by a roller to deform to a predefined circular shape with or without a mandrel. The spin forming process can also be classified as shear spinning, spin forging or necking, depending on how the forming takes place. Developments in NC and CNC control technology allow the production of more complicated precise shapes using spinning technology. Automotive parts such as two- and three-piece wheels, rims, disks, and shaft covers, single or multi pulleys, and pressure accumulators and home appliances such as rice cookers and large speaker bodies are specific applications of spinning processes. In some processes, spinning is the only shaping operation with little or no change in thickness between the initial blank and the finished parts.

Little research has been conducted on the spinning process compared with other forming processes such as deep drawing. Human controlled rollers are used in spin forming, and production need highly skilled workers until NC and CNC controlled machines became available. The human factor in the process, with big shape changes under large deformations, made analytical modeling of the spinning process more complicated. Only a very small number of studies have been conducted. These studies are broadly concerned with the conventional spinning process, and studies relating to specific applications of the spinning process are very rare. Mainly, cone spinning is the interest of researchers. Especially in the 1960s, several reports focusing on analytical modeling of cone shape spinning have been published. Kalpakcioglu \cite{1} assumed a shear mechanism for the deformation and presented a formulation involving the shear strain, shear strain rate, and tangential force to predict the parameters. The wall thickness distribution of aluminium blanks in a cone spinning process was studied by Sortais et al. \cite{2}. They reported the effect of the roller setting on the thickness distribution in under spinning, shear spinning, and over spinning.
Kalpakcioglu studied the maximum reduction of tubes and presented an experimental setup [3]. Several other studies have been conducted to explain the mechanics of the spinning process [4–8]. Recently, developments in numerical analysis have yielded better simulations, although numerical simulation needs sophisticated software and hardware systems. Further studies related to modeling of the spinning process using FEM are reported in refs. [9–12].

One of the important industrial applications of spin forming process is to deform the end of the Al tubes to dome shape and boss to manufacture vessel or liner for FRP + Al liner composites. Such vessels and liners need a certain thickness distribution because the dome and boss accommodate tubing equipment, fittings, or gas pressure valves. A higher and constant thickness distribution is preferable in a boss because this is required for the safety of high-pressure vessels. In the present study, two-step forming of the dome part of the tube is presented.

### 2. Spin forming process experiments

Several experiments were performed to form the closed ends of a pressure vessel. The aim of the experiments was not only to close the end of the tube but also to obtain the thickness necessary for screw cutting at the boss part of the dome. The experiments were carried out in three steps. The dome part was formed in step 1. In step 2, an initial boss was obtained by deforming the dome to a smaller boss diameter than that required. Then a second boss, with diameter greater than that of the first boss, was formed. The aim of this process was to avoid material flow along the Z-axis. Fig. 1 shows the three steps of the deformation sequence of the aluminium tube. As seen in the figure, the roller movement is from outside to inside the tube during the deformation process.

Experiments were carried out on a VF-650C–CNC–T4–Z4 (Nihon Spindle) spinning machine. This is a CNC controlled machine and has an interface program to define the roller forming path. The forming paths created are shown in Fig. 2 to illustrate better the difference between one-step and two-step forming of the boss. The Al tubes were of A6061-O material. The physical properties of A6061-O are given in Table 1. The tube dimensions were 100Ø, 450L, 3t (diameter, length, thickness in mm). The Al tubes were heated to a temperature of around 180 °C using acetylene burner before deformation. The roller feeding speed was 120 mm/min and the aluminium tube turning speed was 250 rpm during the spin forming process. The roller radii were 400 and 10 mm for the radial and axial directions, respectively. The roller start point was set 5 mm outside of the tube to form the end point better.

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Tension properties</th>
<th>Shear strength</th>
<th>Breaking strength</th>
<th>Plastic coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2% Elastic limit (MPa)</td>
<td>Ultimate strength (MPa)</td>
<td>Elongation (%)</td>
<td>(MPa)</td>
</tr>
<tr>
<td>Al</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061</td>
<td>55</td>
<td>120</td>
<td>25</td>
<td>65</td>
</tr>
</tbody>
</table>

Fig. 1. Deformation steps of the Al tube in spin forming process: (a) closure of the dome; (b) first boss forming; (c) second boss formation and thickening of the boss.

Fig. 2. Forming paths of Al tubes for (a) conventional boss forming; and (b) two-step-forming to thicken the boss.
Table 2
Geometrical parameters of end closure of Al tubes by spin forming process (nomenclature is given in Fig. 3)

<table>
<thead>
<tr>
<th>Exp. no.</th>
<th>Forming</th>
<th>Initial dome radius</th>
<th>Boss radius and length</th>
<th>Final dome radius</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( R_0 )</td>
<td>( R )</td>
<td>( l_1 )</td>
</tr>
<tr>
<td>1</td>
<td>Dome</td>
<td>100</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Dome</td>
<td>80</td>
<td>10</td>
<td>51.25</td>
</tr>
<tr>
<td>3</td>
<td>Dome + boss</td>
<td>100</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Dome + boss</td>
<td>80</td>
<td>10</td>
<td>19.28</td>
</tr>
<tr>
<td>5</td>
<td>Dome + two-step boss</td>
<td>100</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Dome + two-step boss</td>
<td>80</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

A total of six Al tubes were experimentally spin formed to make end closures of three types. All geometrical parameters and the different types of forming are shown in Table 2. Tubes 1 and 2 were only dome formed, whereas tubes 3 and 4 were dome formed with a small boss diameter. Tubes 5 and 6 were first dome formed, and then a small-diameter boss was made and the dome was modified to obtain the final boss with a constant thickness. The dome radii for tubes 1 and 2 were 100 and 80 mm, respectively. At the same area, the dome radius was reduced gradually to 50 mm from test 3 to 6.

3. An analytical model to predict dome thickness distribution

A simple analytical model based on the geometrical changes in the tube under spin forming deformation is formulated. Although numerical models predict the deformation parameters better, they are more complicated and need special computers and software. Apart from being simple, the present model can be used to follow the geometrical changes of more complicated modeling which considers the material properties.

The following assumptions have been made before formulation:

- The volume of the test piece under deformation is constant.
- The tube under deformation is a part of a circular shape in the section along the longitudinal axis.
- The deformed part under the roller is a part of a circle inside and outside the tube.
- The difference between the inner and outer circles is the thickness.

The deformed shape with the above assumptions is given in Fig. 3. Here, \( R_0 \) and \( r_0 \) are the outside and inside diameters of the initial tube, respectively. \( A \) is the part of the curve that is generated by the spinning path program for roller movement, and the radius of curve \( A \) is \( a_0 \). \( L \) is the full length of the end closure, and the dome length along the Z-axis, \( L' \), can be defined if the boss radius \( R \) is known. \( a_1 \) and \( a_2 \) are the outer and inner radii on the longitudinal axis of the deformed shape, and \( h_1 \) and \( h_2 \) are the lengths of the same arcs on the same axis. Finally, \( h_3 \) is the thickness of the part and \( \rho \) is the roller corner radius. Fig. 3 shows the geometrical parameters of the dome with the above notations.

The volume of the deformed part, \( V \), before deformation is given by:

\[
V = (R_0^2 - r_0^2)\pi L_0
\]
The total volume of the deformed part after deformation can be found by adding the boss volume, \( V_1 \), and the dome volume, \( V_2 \).

The volume of the boss, \( V_1 \), can be calculated as:

\[
V_1 = (2R_R - r_0)\sqrt{L - L^*}
\]  

\( a_1 \) and \( a_2 \) are needed to find \( V_2 \), the volume of the dome. Considering the geometry in Fig. 3, \( a_1 \) and \( a_2 \) can be calculated from Eqs. (3)–(5):

\[
L^2 + [(R + \rho) - (R_0 - a_1)]^2
\]

\[
= (a_1 + \rho)^2 \Rightarrow a_1
\]

\[
= L^2 + R_0^2 + R^2 + 2R_0 - 2(R + \rho)R_0
\]

\[
= \frac{2(R_0 - R)}{\pi}
\]

and the same formula written for \( a_2 \):

\[
L^2 + [(R + \rho) - (r_0 - a_2)]^2
\]

\[
= (a_2 + t + \rho)^2 \Rightarrow a_2
\]

\[
= L^2 + r_0^2 + R^2 + 2(R_0 - (R + \rho)r_0 - \theta)
\]

\[
= \frac{2(r_0 - (R + t)}{\pi}
\]

From the geometry, the boundaries of the inner and outer dome shape are:

\[
h_1 = a_1 \sin \theta_1 = \frac{a_1 L^*}{a_1 + \rho}
\]

\[
h_2 = a_2 \sin \theta_2 = \frac{a_2 L^*}{a_2 + t + \rho}
\]

Looking at the geometry of the dome, the dome geometry can be divided into four curves between 0 and \( L^* \) as \( f_1, f_2, g_1 \) and \( g_2 \). Using Eqs. (3)–(5), the inner and outer contours can be calculated by following Eqs. (6)–(9):

\[
f_1(z) = (R_0 - a_1) + \sqrt{a_1^2 - z^2} \quad (0 \leq z \leq h_1)
\]

\[
f_2(z) = (R + \rho) - \sqrt{\rho^2 - (L^* - z)^2} \quad (h_1 \leq z \leq L^*)
\]

\[
g_1(z) = (r_0 - a_2) + \sqrt{a_2^2 - z^2} \quad (0 \leq z \leq h_2)
\]

\[
g_2(z) = (r_0 + t) - \sqrt{\rho^2 - (L^* - z)^2} \quad (h_2 \leq z \leq L^*)
\]

The above-defined outer and inner curves are used to calculate the dome volume by revolving them around the length axis. The outer volumes, \( V_{2201} \) and \( V_{2102} \), and the inner volumes, \( V_{2111} \) and \( V_{2222} \), can be obtained as:

\[
V_{2201} = \pi \int_{h_1}^{L^*} [f_2(z)]^2 \text{d}z
\]

\[
= \pi \int_{h_1}^{L^*} \left[ (R_0 - a_1) + \sqrt{a_1^2 - z^2} \right]^2 \text{d}z
\]

\[
= \pi \left[ (R_0 - a_1)^2 h_1 + a_1^2 h_1 - \frac{1}{2} h_1^3 + (R_0 - a_1) \times a_1^2 \sin^{-1} \frac{h_1}{a_1} + h_1 \sqrt{a_1^2 - h_1^2} \right]
\]

\[
V_{2111} = \pi \int_{h_1}^{L^*} [g_1(z)]^2 \text{d}z
\]

\[
= \pi \int_{h_1}^{L^*} \left[ (\rho + R) - \sqrt{\rho^2 - (z - L^*)^2} \right]^2 \text{d}z
\]

\[
= \pi \left[ (\rho + R)^2 (L^* - h_1) + \rho^2 (L^* - h_1) - \frac{1}{3} (L^* - h_1)^3 \right.
\]

\[
\left. -(\rho + R) \left[ \rho^2 \sin^{-1} \frac{L^* - h_1}{\rho} + (L^* - h_1) \sqrt{\rho^2 - (L^* - h_1)^2} \right] \right]
\]

\[
V_{2222} = \pi \int_{h_2}^{L^*} [g_2(z)]^2 \text{d}z
\]

\[
= \pi \int_{h_2}^{L^*} \left( (r_0 + t) - \sqrt{\rho^2 - (L^* - z)^2} \right)^2 \text{d}z
\]

\[
= \pi \left[ (\rho + R)^2 (L^* - h_2) + (\rho + t)^2 (L^* - h_2) \right.
\]

\[
\left. - \frac{1}{3} (L^* - h_2)^3 - (\rho + R) \left[ \rho^2 \sin^{-1} \frac{L^* - h_2}{\rho} + (L^* - h_2) \sqrt{\rho^2 - (L^* - h_2)^2} \right] \right]
\]

The total volume of the dome after deformation is given by

\[
V_2 = V_{2101} + V_{2201} - V_{2111} - V_{2222}
\]

The volume difference, between before and after deformation of the tube, \( V(t) \), can be written as a function of thickness:

\[
V(t) = V - V' = V - (V_1 + V_2)
\]

Eqs. (1)–(5) and (12) depend on the thickness \( t \) of the deformed part. The dome volume should be taken out of the total volume to obtain the boss thickness. The above formulation depends simply on the change in geometry during deformation and does not consider the material flow along the Z-axis. The material properties and material flow should also be included for more precise calculations. This is also necessary for analyzing the forming process, especially at elevated temperatures, for warm deformation.
4. Results and discussions

Experimental work was carried out to improve the thickness distribution of end closures formed by spin forming, and a simple one-step analytical formulation that was obtained from geometrical changes and volume constancy was proposed.

Fig. 4 shows the thickness distribution of four spin-formed tubes numbered 3–6. The thickness distributions of tubes numbered 3 and 4 are conventional and are widely used in industrial applications. This thickness distribution may be enough for some types of applications in which a deep screw cut is not necessary. However, a higher thickness is necessary for some applications in which the internal pressure of the vessel is very high, requiring deep screw cuts for the valve boss connection. The proposed two-step spin forming of the boss is a good way of improving the boss thickness. Experiments 3 and 4 (one-step boss forming) result in thicknesses of around 5.25 and 6.75 mm at the junction of the dome and the boss (Fig. 4). However, a sharp reduction in thickness along the length, which is not desirable, appears in this type of forming. The two-step forming also provides almost the same thickness around the same area but with a very uniform thickness distribution along the length of the boss. A sharp increase in the thickness is seen toward the end of boss 2, where boss 1 and boss 2 join. This is thought to be caused by material flow that is toward the outside of the boss. The small diameter of the boss formed by the first step forming blocks the material flow from the second step forming area, resulting in material accumulation, and increases the thickness in the same area. This makes the inlet area of the boss stronger than the rest of the part. Experiments 3 and 5 have different boss lengths compared with experiments 4 and 6. A comparison of the final thickness distributions of the tubes in Fig. 4 also indicates that a longer boss length results in a higher thickness. To illustrate this, the pictures of the dome forming, one-step forming, and two-step forming are shown in Fig. 5a–c, respectively.

Fig. 6 compares the analytically calculated thickness distribution with that obtained from experiments. This figure indicates that the proposed simple analytical model, which is based on the change in geometry during the deformation process, gives a reasonably good prediction of the final thickness distribution. The results show a greater deviation from the experimental results where the deformation along the Z-axis is greater. Considering Fig. 2, in which the rolling path is given, it is evident that the axial (Z-direction) deformation is higher in the areas shown from dashed lines in Fig. 6. The higher slope of the forming curve in Fig. 2 increases the contact between the roller and the tube. Thus, the proposed formulation, which purely depends on the change in radial geometry, may not be useful for calculation of the thickness, which results from a large deformation along the Z-axis. The boss thickness obtained from the simulation has a constant value along the boss length, whereas it is not constant in the experiments.
5. Conclusions

The end closures of Al tubes, which consist of dome and boss parts, were performed experimentally. A two-step boss forming was proposed to improve the thickness distribution of the boss. A simple analytical formulation was presented to predict the thickness distribution of the dome and the boss. The following conclusions were obtained from this study:

1. The thickness distribution of a boss obtained from two-step forming is more uniform than that of one obtained using conventional one-step forming. The thickness with one-step forming is high at the junction of the dome and the boss but gradually reduces toward the end of the boss.

2. Two-step boss forming results in some thickening at the junction of the small boss and the big boss. This may be useful during thread-cutting processes.

3. The boss length has an effect on the final thickness of the boss. A longer boss length provides greater boss thickness.

4. An analytical model based on volume constancy and the change in shape during forming is presented. The model was efficient in the areas where small deformations took place.

The model should be improved to predict the thickness distribution where greater deformations take place.

Future work should consider material properties in the analytical model. Experimental work and analytical models should also be compared with FEM simulations to understand the effect of the forming parameters to optimize the process.

References