Finite element study on spinning process of an aluminium tube

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Abstract. This article aims to have a glimpse into the effect of the spinning tool parameters (focusing on its diameter, attack angle, nose radius, and feed) by applying the explicit code of the commercial finite element analysis software LS-DYNA. The preliminary results show that the greater the axial feed, the greater the loads generated in the axial, the tangential, and the radial directions. At the same time, the larger the axial feed, the more the elements are parallel to the axial direction from the inflection point to the tube opening. Furthermore, using a larger axial feed will also cause the flaring of the tube opening and make the flaring more obvious. In addition, using a larger axial feed will not only cause a greater material accumulation in front of the attack angle, but also a larger material accumulation at the tangential rear of the nose radius. Moreover, the greater the attack angle, the greater the axial load. There is no further significant effect of the corner radius of the spinning tool on the spinning load.

1. Introduction  
In the wheels of vehicles such as motorcycles, automobiles, buses, trucks, etc., rims used to mount and support tires were mainly made of steel in the early days. After the steel sheet was wrapped and welded, it was rolled to form a rim, and then welded with the spokes of a stamped steel sheet stamping to make a steel wheel. However, due to the poor roundness, weak heat dissipation, and heavy weight of the steel rims, cast aluminum rims have come out, which have good roundness, excellent heat dissipation, and light weight after CNC machining. However, because castings are prone to poor microstructures with small pores, forged wheels came into market. In addition to eliminating pores and providing a dense microstructure, the forged rim can also form an integral rim blank that can be rolled out of the rim by the spinning process to create various rim structural designs and to compose the market for wide flat wheels, which makes the spinning process get more inquiry from the factory chain. As a result, the research and development of the spinning process by the forged wheel industry is in the ascendant. In the spinning process as shown in Figure 1 [1], an axisymmetric workpiece is first fixed to the rotation axis of the spinning machine, then the rotation axis rotates, and subsequently the spinning tool is applied to the surface of the workpiece with an axial or radial movement to make the workpiece partially deform under load, which is an incremental forming process. It is usually supported by a mandrel, so that the inner surface of the workpiece in contact with the mandrel replicates the geometry of the mandrel, and the outer surface of the workpiece is formed by the trajectory of the spinning tool, so that the geometry and thickness distribution of the workpiece can be made within the requirements of the product.
However, in the spinning process, the indentation of the spinning tool per pass and the feed per revolution are related to the workpiece material, the rotation speed, the processing amount in the previous pass, the geometry of the spinning tool, and so on [2]. Although there were investigations on the configuration of spinning tools [3], flaring formation [4], and lubrication characteristics [5] in the literature, the influence of feed and geometry of the spinning tool on the spinning process has still not been completely determined. Therefore, this research aims to use finite element analysis to focus on the feed and geometry of the spinning tool in the spinning process of aluminum alloy tubes, especially the diameter, nose radius and angle of attack of the spinning tool, and explore the relationship between them and the spinning results.

2. Research settings

Table 1 shows the parameters for this research, which are extended from the experiments conducted in [6] to explore the geometry and process parameters of the spinning tool on the spinning of aluminum alloy tube, by using the explicit code of the commercial finite element analysis software LS-DYNA.

| Parameter                     | Value |
|-------------------------------|-------|
| Tube blank inner diameter (mm)| **35** |
| Wall thickness (mm)           | **2.5** |
| Height (mm)                   | **25** |
| Spinning tool diameter (mm)   | 27, 54, 108 |
| Attack angle (°)              | 20, 25, 30 |
| Relief angle (°)              | 5 |
| Nose radius (mm)              | 1, 3, 5 |
| Tailstock load (kN)           | 3 |

Table 1. Finite element analysis model parameters used in this research.

*Based on [6]

Figure 2 shows a finite element analysis model created in the research. The tube is modelled by solid elements with aluminum alloy A6063, which behaviours elastoplasticity according to the material given in [6], while the mandrel, tailstock and spinning tool are modelled with rigid shell elements to reflect their characteristics of almost zero deformation while thinning the tube walls.
The element sizes of the tube in the radial direction and the axial direction are the same as that in [6], being both 1.4 mm, but 90 elements are taken in the circumferential direction, and the element size in the circumferential direction of the outer diameter is also about 1.4 mm. The nose radius between the attack angle and the relief angle of the spinning tool is segmented such that each element has less than 4.5° in order to show its curvature characteristics. The spinning tool has 120 elements in the circumferential, so the element size in the circumferential direction is also about 1.4 mm.

The motion setting between the spinning tool and the tube in this study is contrary to the literature [6]. In [6], the tube, mandrel and tailstock are still, while the spinning tool rolls around the tube so that the spinning tool has not only a revolution about the rotation axis of the spinning machine but also a rotation about its own axis. In this study, the pipe, mandrel and tailstock are actively rotated about the rotation axis of the spinning machine and the spinning tool is driven to rotate about its own axis, which is fixed in the modelled space as shown in Figure 2, to reflect the fact that the angular velocity of the spinning tool’s rotation still would change due to the friction between the tube and the spinning tool. In addition, to reduce the computation time, the rotation speed was accelerated from 30 rpm in [6] to 5,550 rpm for this study, but the spinning tool can still pass through a single element at least 1,000 steps to ensure accuracy and quasi-static forming characteristics. In addition to the speed, some settings are different from those in [6] as well, such as the setting of the boundary conditions to the tools using a contact (instead of directly setting the constraints of the nodes) to correctly demonstrate the flaring effect [7]. The friction there is described with a coefficient of 0.125 for Coulomb friction.

As for the three-dimensional solid element describing the tube, a single integration point is used for analysis to reduce computing time. To prevent the results from showing negative hourglass energy, appropriate hourglass types and parameters are selected to make the ratio of the hourglass energy to the internal energy less than 5%, so that the correctness of the analysis results is ensured.

3. Results and discussions

The finite element analysis results, which was carried out according to [6], at the end of the process can be shown in Figure 3. Figure 3 (a) shows the relationship of the workpiece to the mandrel and the spinning tool. It can also be seen that the initial radial cross section is completely tilted and deformed at the end of the spinning process, which can be shown by taking one of the cross sections outlined on the outer surface (the black line shown in Figure 3 (b)) to compare with three radial planes (the white lines in Figure 3 (b)). The bottom one is the radial plane tangent to the initial cross section at the position lagging behind the most, while the middle one is the plane coinciding with the initial cross section on the tube bottom and the top one is where the initial cross section was originally located. Moreover, it can be seen as well that the corners at the tube bottom appear to be rounded and pushed towards the bottom to form a cup-bottom-rim-like ridge as shown in Figure 3 (b). From these two pictures, it can be shown that at the beginning of the spinning process, the material at the bottom corner is pushed inwards and toward to the tube bottom, where the material can freely flow because the mandrel does not support or constrain there, and thus less material accumulates in front of the spinning tool. However, the greater the axial feed and the closer the tool to the mandrel, the less the material freely flows and the greater the flow in front of the tool, so that the material is pushed back faster and thus it looks like it is forging ahead. Once the space for the material to freely flow disappears, the amount of the material accumulating in front of the tool is maintained and hence the drag rate between the tool and the tube top end is retained until the tool crosses over the tube end. Furthermore, most of the inner part of the tube bottom stays undeformed. That means that the initial cross section there is located in the same radial plane.

Figure 4 shows the evolution of the angle of the radial plane for the position on the tube bottom and the position lagging behind the most, respectively, as measured from the initial radial cross section at the tube top end during the spinning process. It can be seen that in the initial stage of the spinning process, when the stroke of the spinning tool is less than the tube thickness, that there is no obvious tilt angle at the two places. That means that the initial radial section can be maintained as a plane at this stage. The radial plane on the position lagging behind the most shows a tilt angle of 0.5° first at an axial feed stroke of the spinning tool about 5 mm, twice the tube thickness on the tube bottom, and a dramatic tilt angle of 6.0° at 9 mm followed with an almost constant rate of 0.37°/mm increasing until the spinning tool comes closer to the tube end at 35 mm. In contrast, the tilt angle for the tube bottom has no such abrupt
increasing but rises with almost the same constant rate as that on the position lagging behind the most. Without such an abrupt increase in the tilt angle, the tube bottom acts like it is forging ahead of the position lagging behind the most. When the spinning tool comes closer to the tube end, the material can easily flow there as well because of a reduced constraint toward the tube end, so that no obvious drag can be found there.

**Figure 3.** Finite element analysis results at the end of the process carried out according to [6]: (a) the tube related to the tools, (b) the initial radial cross section (black line) related to three reference radial planes.

**Figure 4.** Tilt angle of the radial plane for the position on the tube bottom and mostly lagging behind, respectively, to their initial radial cross section at the tube top end during the spinning process.

The radial cross-sectional views generated by different axial feed stroke of the spinning tool in the tube spinning process is shown in Figure 5: (a) at 12 mm, where the position mostly lags behind, (b) 22 mm, about halfway, (c) 27 mm, about two thirds, and (d) at the end of the total stroke of the spinning tool. As shown in Figure 5 (a) and (b), there is still some material accumulating on the surface of the attack angle of the spinning tool, but when the tool approaches the tube end, the material accumulation becomes inconspicuous, as shown in Figure 5 (c). The material that was not accumulated stays undeformed. In Figure 5 a neutral flow plane of the spun tube can be found just at the bottom surface of the mandrel, where material flows either toward the tube bottom or the tube end. Around the corner, the inner wall of the tube bottom does not contact the mandrel, while at the tube end, the outer surface extends more than the inner wall and has more shear strain as well.

**Figure 5.** The radial cross-sectional views generated at the axial feed stroke of the spinning tool (a) 12 mm, (b) 22 mm, (c) 27 mm, and (d) 40 mm.

In addition to the results obtained for the model as [6], for which the parameters are the diameter of the spinning tool 54 mm, the angle of attack 25°, the nose angle of 3 mm, and the feed 0.1 mm/rev, this article also discusses the influence of the spinning tool geometry and process parameters described in
Table 1 on the spinning results, such as the diameter of the spinning tool being 27 mm or 108 mm, the attack angle being 20° and 30°, the nose angle being 1 mm or 5 mm, and the axial feed of the spinning tool being 0.5 mm/rev or 1.0 mm/rev.

Figure 6 shows the radial, axial and tangential loads over the axial stroke of the spinning tool during the spinning process with different spinning tool diameters. It can be seen that the maximum of the loads occurs at the axial stroke of the spinning tool at about 6 mm. On average, the larger the diameter of the spinning tool, the larger the radial and axial load, but the smaller the tangential load. However, the difference of the average load does not exceed 10%, meaning that the influence of the diameter of the spinning tool on the load is not significant. According to the results, the larger the diameter of the spinning tool, the larger the contact projection area and the greater its load. If the projection of the spinning tool and the tube is taken in the axial direction, they are two circles intersecting each other. The axial load is dependent on their intersection area, while the tangential load is dependent on their contact length projected on the plane connecting the axes of the tool and the tube. Therefore, the larger the tool diameter, the larger the intersection area and the larger the axial load, and the shorter the projection of the contact length and thus the smaller the tangential load. Furthermore, it can be shown that the contact projection area in the radial direction is the largest, in the axial direction is second largest, and the tangential direction is the smallest, and so are correspondingly the loads in the radial, axial, and tangential directions. Therefore, when observing the load on the spinning tool with different axial feeds, it can be seen from the results shown in Figure 7 that the difference is very significant: the greater the feed is, the larger the loads all in the radial, axial, and tangential directions. The results are associated such that if viewing in the radial direction, the larger the axial feed of the spinning tool, the larger the intersection area between the tool and the spun tube part, and the more material is needed to be pushed aside and thus the larger the load needed.

![Figure 6. Load evolutions in the radial, axial, and tangential direction over the axial stroke of the spinning tool with different diameters.](image_url)

![Figure 7. Load evolutions in the radial, axial, and tangential direction over the axial stroke of the spinning tool with different feed rates.](image_url)

It can be observed further in Figure 7 that the loads in the smallest feed of 0.1 mm/rev are decreasing after their maximum values at the axial stroke of about 6 mm, while in the larger feed of 0.5 mm/rev and 1.0 mm/rev the loads are still increasing until the stroke of about 16 mm, where their maximum value appears, and then they drop sharply with a negative slope, like the initial increasing stage, until the stroke length about 27 mm and then slows down to the end of the stroke. Namely, the latter two have a deformation mechanism as shown in Figure 8 different than the former one, which in turn affects their contact behaviours with the spinning tool, changes the effective contact area, and causes changes in the load. In Figure 8, the radial cross-sectional views for the larger feed of 0.5 mm/rev (a, b, c) and 1.0 mm/rev (d) are captured at the same axial feed strokes as in Figure 5. No cross-section at the stroke of 12 and 22 mm for the feed of 1.0 mm/rev is shown in Figure 8, because they are similar to those for 0.5 mm/rev. Compared with the result of the feed rate of 0.1 mm/rev shown in Figure 5 (a), the material accumulated on the attack angle surface of the spinning tool is not only thicker, but also longer in axial direction, so that the loads in the directions are larger. However, as the stroke increases, the accumulated material under the action of the attack angle surface forces the tube end to disconnect from the mandrel and form a flaring as shown in Figure 8 (b), gradually expanding the inner diameter of the tube end until...
the accumulated material is exhausted as shown in Figure 8 (c). If the axial feed rate is large enough, the tube outer wall will be stuck onto the attack angle surface as shown in Figure 8 (d). The axial stroke in Figure 8 (b) is halfway and roughly comparable to the position where the radial load shown in Figure 7 suddenly drops, while that in Figure 8 (c) and (d) corresponds to the kink point of the radial loads. Obviously, although the final spun tube obtained from the larger axial feed rates fits the mandrel as shown in Figure 9, the inner wall of the tube might not be able to completely fit during the process. This kind of flaring due to high feed rate can induce a stress state at the tube end that might cause an inexplicable process problem or forming limit such as wrinkles and cracks.

Figure 8. The radial cross-sectional views captured at the axial feed stroke of the spinning tool (a) 12 mm, (b) 22 mm, and (c) 27 mm with a feed rate of 0.5 mm/rev, as well as (d) 27 mm with 1.0 mm/rev.

The deformation patterns shown in Figure 9 on the tube outer surface seem similar to each other but different to that obtained with 0.1 mm/rev shown in Figure 3 (a), in that the position of the initial radial cross section that is lagging behind the most is shifted to a larger feed stroke about 15 mm at a tilt of 25.4° (0.5 mm/rev) or 18 mm at a tilt of 18.0° (1.0 mm/rev) instead of 9 mm at a tilt of 14.6° (0.1 mm/rev). Furthermore, the position of the initial radial cross section without a significant tilt (1°) is about 3.4 mm (0.5 mm/rev) or 5.5 mm (1.0 mm/rev) to the tube end instead of 1.7 mm (0.1 mm/rev). Thus, it seems hard to conclude by induction that there is a correlation of the spinning deformation to the feed rate, because the deformation induced by a larger feed rate at affects their contact behaviours with the spinning tool, which in turn influences the deformation recursively and causes changes in the load, as mentioned previously.

Figure 10 shows some axial cross sections captured in the axial view from the tube bottom to the tube end at the nose of the spinning tool, at the position that has accumulated or piled up the most on the attack angle surface, and at the tube end under different axial feed rates as the axial strokes comes 22
mm, about halfway of the total stroke, where the spinning process demonstrates its typical deformation. In Figure 10, the spinning tool is located on the middle right side where it contacts the tube (shown in cyan) and the mandrel (shown in blue), both of which rotate clockwise. It can be seen in Figure 10 that at the nose (a, d, g), the material has been severely sheared, so that the original radial lines deformed like logarithmic spirals. At the larger feed rate, a pile up of the material is found in front of the spinning tool and there is no contact between its inner wall and the mandrel. At the position where the material is piled up the most on the attack angle surface, the material is already sheared to a certain extent, and at the larger feed rate, there is no contact of the inner wall to the mandrel as well. It can be observed that the thickness there obtained by the larger feed rate is apparently thicker. At the tube end, there is no evident shear found. Furthermore, the larger the feed rate, the more evident there is no contact between the inner wall and the mandrel at the tube end, and thus more end flaring is present there.

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Because using a slower axial feed results in a lower productivity, but using an excessively fast axial feed might cause a serious flaring, therefore in the following investigations the middle axial feed rate of 0.5 mm/rev is applied. Figure 11 shows the load evolution with spinning tools having different nose radii, while Figure 12 shows those obtained with tools having different attack angles. It can be seen that the nose radius has no significant effect on the loads, because the material projection area in any direction does not visibly change. In contrast, the greater the attack angle, the greater the axial load but the attack
angle still has no obvious effect on the tangential load as well as on the radial load, because by increasing the attack angle, the projection area of the piled up material increases only in the axial direction.

![Figure 11. Load evolutions in the radial, axial, and tangential direction over the axial stroke of the spinning tool with different nose radii.](image1)

![Figure 12. Load evolutions in the radial, axial, and tangential direction over the axial stroke of the spinning speed with different attack angles.](image2)

4. Conclusion
In this study, the spinning process with aluminum alloy A6063 tube having an inner diameter of 35 mm, a wall thickness of 2.5 mm, and a height of 25 mm was conducted with the explicit code of the commercial finite element analysis software LS-DYNA and a conclusion is drawn as follows.

The axial feed has a significant impact on the loads. The larger the axial feed, the greater the radial, axial, and tangential loads. Furthermore, the axial feed can change the deformation pattern of the initial radial section on the tube outer surface during the spinning process. But there is a correlation of the spinning deformation to the feed rate, because there is a flaring found at the tube end if a larger feed rate is applied, which makes the contact between workpiece and tools complicated and thus the deformation complicated as well. The greater the axial feed, the more obvious the flaring at the tube end. In addition, using a larger axial feed will not only cause more material to be piled up on the attack angle surface of the spinning tool, but also more material to accumulate rear to the nose of the spinning tool in the tangential direction.

The attack angle of the spinning tool has no significant effect on the radial and tangential loads, but the larger the attack angle, the greater the axial load. There is no significant effect of the diameter and the nose radius of the spinning tool on the loads in any direction.

In the future, the influence of the material and length of tube as well as the feed rate of the spinning tool on the forming limits of the tube spinning process, especially the countermeasures related to the end flaring, will be further investigated.

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