A Study of Large Sheave Counter-Roller Spinning Force

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Abstract. In this paper, a counter-roller spinning method is presented, which is designed to produce relatively thin-walled large sheaves. The large sheave counter-roller spinning force is poorly studied. And the forming forces have a significant influence on industrial applications. Herein, theoretical analysis and numerical simulation methods were utilized to explore the large sheave counter-roller spinning process and spinning force. Anisotropy of the material was considered by the Hill-48 anisotropic yield criterion. Numerical simulation has been demonstrated to correspond to experimental values. The spinning forces in the simulation and experiment matched well and steadily increased throughout the process. The roller and mandrel have similar spinning forces, and the radial spinning force is much larger than other forces. Finally, a theoretical model to compute the spinning force was constructed.

1. Introduction

Large sheaves are a category of basic components used in heavy industry and other domain. Thin-walled plate-type sheaves are designed instead of traditional cast parts to improve quality and reduce costs. A common method to produce these thin-walled sheaves is welding a tube with grooves and several spokes. The groove forming process is of particular interest in sheave manufacturing.

The traditional counter-roller spinning process is a rarely used manufacturing method for rocket motor cases [1]. The counter-roller spinning method is developed to produce large sheaves [2]. The large sheave counter-roller spinning is shown in Fig. 1. The main advantages of this method are a high degree of forming flexibility with the perfect interior quality of the products [3]. Small mandrels with special grooves in this method replace single inner rollers in the traditional counter-rollers spinning method. During the spinning process, the tube blank is rotated by the turntable. All rollers and mandrels rotate passively. The rollers move in both the axial and radial directions. The grooves are shaped one by one. After creating a new groove, the rollers move to a new position.

The spinning force is important to the shaping process and determines the structure of the spinning equipment. Thus, it is important to study the counter-roller spinning force. Different from the traditional spinning process, the small mandrels in the counter-roller spinning process are working molds as rollers. And these small independent mandrels can’t counteract major spinning forces as the large mandrel in the traditional spinning process. It is necessary to obtain both the mandrel force and roller force model for designing appropriate spinning parameters and spinning equipment.
Figure 1. Large sheave counter-roller spinning process: (a) top view, (b) front view.

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Numerous research studies have been performed on general metal spinning processes. Xiao et al. found a way to obtain nano/ultrafine-grained structures by using power spinning and quenching [4]. Shi et al. experimentally investigated the spinnability of DP600 steel under various feed ratios and other parameters [5]. Lexian and Dariani presented a theoretical contact model of tube spinning and tested it via simulations and experiments [6]. But the studies on the large sheave counter-roller spinning force are few. In this study, theoretical analysis and a numerical simulation were conducted to explore the counter-roller spinning force.

2. Simulation and Experiment

2.1. Material model
Q235 steel is a widely utilized material for sheaves. This steel has medium plasticity and strength. It is chosen to study the counter-roller spinning process.

The material anisotropy of the thin-walled sheave was considered in the numerical simulation. The material property of Q235 in three directions (0°, 45°, 90°) was obtained by tensile testing. The experiment and samples are shown in Fig. 2.

Figure 2. Anisotropy elastoplasticity testing.
The Lankford r-value is utilized for building the anisotropy elastoplasticity model. The coefficient of the normal anisotropy is defined as

\[ r_n = \frac{r_0 + 2r_{45} + r_{90}}{4} \]  

where \( r_n \) is the normal anisotropy coefficient, \( r_0 \) is the Lankford r-value in the 0° direction, \( r_{45} \) is the Lankford r-value in the 45° direction, and \( r_{90} \) is the Lankford r-value in the 90° direction.

The mechanical properties in each direction were shown in Table 1. Mechanical properties in the 0° direction were the best of all. Yield stress and ultimate strength of the Q235 steel in the 0° direction are 310 MPa, 607 MPa, respectively. Average Lankford r-values are listed in Table 1. \( r_n \) is 1.170. The Hill-48 anisotropic yield criterion is suitable for this material.

| Direction | 0°     | 45°     | 90°     |
|-----------|--------|---------|---------|
| \( r \) [MPa] | 1.33   | 1.23    | 0.90    |
| \( \sigma_s \) [MPa] | 310    | 294     | 283     |
| \( \sigma_b \) [MPa] | 607    | 461     | 446     |

2.2. Numerical simulation model

A scale numerical model of the counter-rolling spinning process is shown in Fig. 3. The diameter scaling factor between the simulation tube and the experiment tube is 0.1. The 1000 mm diameter sheave formed in the experiment is shown in Fig. 4. The simulation tube diameter is 100 mm. The corner radius of the rollers is 5.2 mm. The friction coefficient was 0.1. Rollers and mandrels were rigid bodies in the simulation. Since the tube size was much larger than the groove shape, the tube meshed with continuum shells. The tube element size was 2 mm axially and 10 mm in circumference. The tube blank was tied to the turntable, which auto-rotate at a speed of 40 r/min. The roller shaped grooves one by one.

![Figure 3. Simulation model.](image1)

![Figure 4. A large sheave formed in the experiment.](image2)

2.3. Experimental procedure

The large sheave counter-roller spinning experiments were completed on a CNC counter-roller spinning machine. The thin-walled tube blank had a diameter of 1000 mm and a thickness of 1 mm. The tube blank was fixed on the turntable. All work surfaces were coated with grease before spinning. All spinning parameters were the same as the simulation.
3. Results and Discussion

3.1. General results
The grooves variation in the numerical simulation process is shown in Fig.5. Grooves were formed from the bottom to the top. Although the depth of the groove was somewhat smaller than the design groove, the shape of the groove was similar to the design without wrinkles and other issues. Thus, it is propitious to fabricate large sheaves by the counter-roller spinning process.

The roller spinning force in the experiment and simulation match well. The experiment spinning forces in the radial, axial, and tangential directions were 8.28 kN, 0.89 kN, and 0.35 kN, respectively. The simulation forces in the radial, axial, and tangential directions were 6.54 kN, 0.87 kN, and 0.41 kN, respectively. Deviations from the simulation results in the radial, axial, and tangential directions were -21%, -2%, and 17%, respectively.

3.2. Roller and mandrel influence on spinning force
The spinning forces of the roller and mandrel are shown in Fig.6. The mandrel radial force was its absolute value. The roller force was slightly larger than the mandrel force in all three directions. Before 5.2 s, the roller continued feeding in the axial direction with spinning forces increasing. At 5.2 s, the sizing procedure started. Then all spinning forces began to decrease. The radial force was the most important force, which is approximately 17.3 times and 5.7 times larger than tangential force and axial force, respectively. Considering the spinning force generally is the total force, the radial force can be regarded as the spinning force for convenience. The tangential force and the radial force curve of the roller had a similar form with the force of the mandrel, but larger.

![Figure 5](image1)

**Figure 5.** Tube variation: (a) original shape, (b) first step, (c) second step, (d) third step.

![Figure 6](image2)

**Figure 6.** Roller and mandrel spinning force (R: Roller, M: Mandrel, tan: tangential).

The maximum spinning force values of the roller and mandrel are shown in Table 2. The maximum force of the roller in the radial, axial, and tangential directions was 6.54 kN, 0.87 kN, and 0.41 kN, respectively. The maximum radial force of the roller and mandrel are approximately equal. The maximum tangential force of the roller and mandrel are also approximately equal. The roller has a larger maximum axial force than the mandrel.
Table 2. Maximum values for roller and mandrel spinning force in three directions.

| Force   | Radial [kN] | Axial [kN] | Tangential [kN] |
|---------|-------------|------------|-----------------|
| Roller  | 6.54        | 0.87       | 0.41            |
| Mandrel | 6.28        | 0.48       | 0.39            |
| Ab error| -0.26       | -0.39      | -0.02           |

The tube blank has some rigidity. During the spinning process, the mandrel does not move and the roller feeds inside to form grooves. Their tangent forces thus have the same direction and worth. This small force causes the phenomenon that the roller force is a bit larger than the mandrel force. The radial force of the roller and mandrel are relative forces. So they have similar values with inverse directions. The mandrels and rollers have similar operating conditions in the tangential direction. Therefore, their tangential forces have similar direction and value. The turntable provides an additional axial force. This force and mandrel axial force are together balanced with the roller axial force which is the active force. Consequently, the roller has a greater axial force than the mandrel.

3.3. Groove depth influence

The groove depth is a fundamental factor in sheaves [7]. The roller radial force was regarded as the spinning force. In Fig. 7, the spinning force becomes greater with the depth of the groove increasing. The simulation force and experiment forces are nearby. The materials have deformation limits. When spinning the 9 mm depth groove in the experiment, some concave pits occurred at the groove. Thus, the experimental force increased slowly at the deep groove situation. However, this defect was not present during the simulation. The spinning force in simulation still grew quickly. Thus, the numerical simulation is only suitable for sheaves with small grooves.

\[
F = -92.99h^2 + 2041h + 80.03, \tag{2}
\]

where \( F \) is the spinning force (N), \( h \) is the groove depth (mm). The confidence bound of the equation is 95%. The R-square of the equations is 0.9927.

4. Theory Model

A theoretical model in ideal conditions is chosen to discuss the spinning procedure. The thickness of the tube is rather small relative to the diameter, so it could be regarded as a shell without thickness. The frictional force and other internal forces of the roller and mandrel are ignored. The roller and mandrel are the rigid body. The model of the large sheave counter-roller spinning process is shown in Fig. 8. Based on the principle of symmetry, both spinning methods display just one roller. Both ends of the tube are free. Therefore, the axial condition of the spinning model is symmetric; and the axial force is zero. The spinning force can be seen as in the median plane of the roller.
Figure 8. Theory model: (a) traditional spinning, (b) counter-roller spinning.

The right part of Fig. 8 (a) is the front view of the mandrel spinning. The C point is the start point of spinning, and the EDF line is the section line after spinning. The left part of Fig. 8 (a) is the middle section from the right view side. The line DB is the working line in the middle plane. There is a point G in this line that can be regarded as the equivalent point of total spinning force. The direction of the equivalent spinning force is from G point to O1 point. \( \theta_1 \) is the contact angle of the roller. \( \theta_2 \) is the angle of equivalent spinning force (the angle between the line DO1 and GO1). The \( \theta_2 \) is just above 0 and less than \( \theta_1 \). The radial force \( F_r \) and circumferential force \( F_t \) is the component force of the equivalent force. It is convenient to find that the radial force is much bigger than the circumferential force just like in the simulation and experience. The equivalent force can be obtained by the integral of the normal pressure in the deformation zone. The angle \( \theta_1 \) and \( \theta_2 \) can be obtained by the geometrical relationship conveniently.

\[
F = \int_0^{\theta_2} r l_\theta \sigma, \cos \theta d\theta + \int_0^{\theta_2} r l_\theta \sigma, \cos(\theta - \theta_2) d\theta .
\]  

\[
\begin{aligned}
F_r &= F \cos \theta_2 \\
F_t &= F \sin \theta_2 .
\end{aligned}
\]  

\[
T = \int_0^{\theta_2} r^2 l_\theta \sigma, \sin \theta d\theta - \int_0^{\theta_2} r^2 l_\theta \sigma, \sin(\theta - \theta_2) d\theta = 0 .
\]  

\[
F_t = F_r \tan \theta_2 , \text{ where } 0 \leq \theta_2 < \theta_1 .
\]  

The \( \theta_1 \) could be obtained by the cosine law in Eqn. 7.

\[
\cos \theta_1 = \frac{r_1^2 + (r_1 + R_0 - h)^2 - R_0^2}{2r_1 (r_1 + R_0 - h)} .
\]  

where \( F \) is the equivalent spinning force, \( F_r \) is the equivalent radial force, \( F_t \) is the equivalent circumferential force, \( R_0 \) is the radius of the blank and mandrel, \( r_1 \) is the radius of the roller, \( l_\theta \) is the
length of roller contact line at an angle \( \theta \), \( \sigma_r \) is the equivalent press stress at working zone, \( T \) is the torque of the roller, \( h \) is the feeding depth of the roller.

The left part of Fig. 8 (b) is the counter-roller spinning middle section from the right view side. The mathematical model of rollers is like the traditional model. A distinction between these two models is that the working area of counter-roller metal spinning is somewhat smaller than traditional spinning. Another distinction is that the mandrel and tube blank could be treated as a whole in the traditional spinning process, but the inner mandrel would be regarded as a roller. The roller and internal mandrel can be seen to have similar force conditions. The rotational force of the roller and the inside mandrel is equal to the value. The spinning force could also be obtained by the former equations.

5. Summary

The conclusions can be summarized as follows:

1) The simulation model can be effectively applied to the spinning process. The Hill-48 anisotropy performance criterion is met for Q235 steel. Although the spinning forces obtained in the simulation were slightly larger than the experimental values, the accuracy of the simulation is adequate for industrial applications.

2) Rollers and mandrels used in counter-roller spinning result in similar forces. The roller spinning force value is slightly larger than the mandrel force. The strongest force is in the radial direction.

3) The spinning force has close links with groove depth. A spinning force formula is proposed.

4) According to the theoretical model, the roller spinning force in mandrel spinning and large sheave counter roller spinning is similar.

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References

[1] W. Radtke: American Institute of Aeronautics and Astronautics Vol. 42 (2006), p. 9–12.
[2] C.C. Zhu, D.A Meng, S.D. Zhao and S.P. Li: Materials Vol. 11 (2018), p. 960.
[3] L.P. Troeger, M.S. Domack, and J.A. Wagner: Microstructural and mechanical characterization of shear formed aluminum alloys for airframe and space applications (NASA technical report, US 2004).
[4] G.F. Xiao, Q.X. Xia, X.Q. Cheng and H. Long: Science China Technological Sciences Vol. 59 (2016), P. 1656–1665.
[5] L. Shi, H. Xiao, and D.K. Xu: Conference Series Vol. 896(2017), p. 012119.
[6] H. Lexian and B.M. Dariani: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture Vol. 222 (2008), p. 1375–1385.
[7] C.C. Zhu, S.D. Zhao, S.P. Li, and S.Q. Fan: The International Journal of Advanced Manufacturing Technology Vol. 100 (2019), p. 409–419.