Spin forming process optimization and microstructure of stainless-steel welded pipe

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Abstract
Defects, such as cracks, typically occur in the spinning process of ternary catalyst shells. This study investigates the optimization of spinning process parameters to prevent such defects. In this regard, an orthogonal simulation was performed using a finite element model of the spinning process of a ternary catalyst shell. Moreover, spinning tests using a 439 stainless steel welded pipe were conducted to verify the simulation results. Thus, the microstructure, hardness, and quality of formed parts are analyzed. The simulation and test results showed that when the spinning temperature is 1000 °C, the roller fillet radius, roller speed, and feed ratio are 5 mm, 40 r s−1, and 1.2 mm r−1, respectively. In addition, the error rates of the forming thickness, port diameter, and roundness error are 1.37%, 1.25%, and 4.8%, respectively. These results verified the accuracy of the simulation. Furthermore, no defects were generated during spinning, and the spinning quality was high. The feed ratio was the main factor affecting the roundness error, followed by the roller speed. As deformation increased, hardness increased, and the crystal size decreased. The results of this study can provide crucial theoretical guidance for practical spinning applications.

1. Introduction
Spin forming is an advanced manufacturing technology that integrates extrusion, drawing, and bending [1–3]. This technology can be used to easily manufacture all types of thin-walled rotating parts and pipe parts. Further, it is widely used in national defense, machinery, automobile industry, and other fields because of its good forming quality, excellent performance, and low manufacturing cost [4–6]. Ternary catalyst shells are a typical thin-walled rotating part. In particular, spin forming benefits the manufacture of ternary catalyst shells. Recently, owing to the continuous improvement of automobile life cycle and performance, improving the spinning quality of ternary catalyst shells has become necessary.

Owing to inappropriate processing parameters, ternary catalyst shells frequently exhibit eccentricity, wrinkling, depression, cracks, and other defects. These defects strongly affect the service life and performance of ternary catalyst shells [7–10]. Numerous researchers have studied how to improve the spinning quality of these shells. For instance, Liang W et al used ABAQUS software to simulate the stress-strain distribution in the spinning process, optimized the spinning process parameters through experiments, and realized the high-quality spinning manufacturing of magnesium alloy cylinder parts [11]. Gao X C used DYNAFORM dynamic display analysis technology to simulate spinning deformation and obtained the variation laws of strain and wall thickness during spinning [12]. Moreover, Liu Y et al studied the hot spinning deformation law of variable cross-section thin-walled conical parts and the influence of process parameters on the forming quality and surface straightness. The optimal combination of process parameters is obtained [13]. Wang L et al proposed a tool compensation spinning method and optimized the process parameters through simulation and experiments.
The proposed method could effectively prevent material from wrinkling during spinning [14]. Furthermore, Guo Y et al. used multi-pass hot spinning process to hot spin 7A04 aluminum alloy sheet, and carried out finite element simulation research on process parameters such as forming temperature, feed ratio, roll diameter and roll shape. The optimal process parameters are obtained and verified by experiments [15]. Zhang T simulated deformation during neck spinning using ANSYS, obtained the change law of the stress and strain of parts under different wall thicknesses, and discussed the influence of the spinning angle on forming [16]. Wen X et al. realized long-range stable spinning of large-diameter ultra-thin wall cylinder by optimizing process parameters [17]. Guo H et al. significantly improved the spinning quality by changing the feed ratio [18]. In addition, Xia Q X et al. simulated the spinning closing of cylindrical parts using the MARC finite element software and analyzed the changes in the starting rotation point and wall thickness during the spinning deformation of a tube blank [19, 20]. Finally, Zhang T T et al. obtained well-formed magnesium alloy tubes through strong hot spinning [21].

However, few studies have considered the effect of the process parameters on the spinning quality of welded pipes. Therefore, this study simulates the spinning of 439 stainless steel welded pipes using ABAQUS software. ABAQUS is used to simulate spinning forming under different process parameters. The effect of the process parameters on spinning forming is studied to provide guidance and theoretical reference for practical spinning applications.

## 2. Simulation of spinning process

### 2.1. Spinning model

The three-dimensional model of spinning is shown in figure 1. Table 1 lists the dimensions of the welded pipe and roller. The density, elastic modulus, and Poisson’s ratio of the welded pipe are 7.8 kg m$^{-3}$, 1.71 × 10$^5$ MPa, and 0.3, respectively. The material properties were modeled considering the Johnson–Cook damage parameters [22]. Moreover, the mesh was generated using the sweep method. The welded pipe grid model contained a total of 13983 nodes and 9164 solid elements. The welded pipe and fixture were considered stationary, and the rotary roller rotates around the welded pipe. The friction coefficient between the welded pipe and fixture was 0.2, and that between the welded pipe and roller was 0.1. The workpiece could be severely deformed if the feed rate during forming is extremely high. Thus, spinning was performed seven times.

### 2.2. Optimization of spinning process parameter

Spinning quality is affected by the spinning temperature, roller fillet radius, roller speed, and feed ratio. Therefore, the interaction between various parameters was evaluated using an orthogonal numerical simulation.

![Figure 1. Three-dimensional model of spinning closure.](image)
Figure 2. Spinning simulation cloud diagram of optimal process parameters.

Table 2. Orthogonal simulation scheme.

| Number | Spinning temperature $T$ (°C) | Roller fillet $r$ (mm) | Roller speed $n_r$ (r s$^{-1}$) | Feed ratio $f$ (mm r$^{-1}$) | Roundness error (mm) |
|--------|-------------------------------|------------------------|-------------------------------|---------------------------|-----------------------|
| 1      | 950                           | 5                      | 25                            | 1.2                       | 0.54                  |
| 2      | 950                           | 6                      | 30                            | 1.5                       | 0.655                 |
| 3      | 950                           | 10                     | 40                            | 1.63                      | 0.97                  |
| 4      | 1000                          | 5                      | 30                            | 1.63                      | 0.835                 |
| 5      | 1000                          | 6                      | 40                            | 1.2                       | 0.3                   |
| 6      | 1000                          | 10                     | 25                            | 1.5                       | 0.66                  |
| 7      | 1050                          | 5                      | 40                            | 1.5                       | 0.4                   |
| 8      | 1050                          | 6                      | 25                            | 1.63                      | 2.63                  |
| 9      | 1050                          | 10                     | 30                            | 1.2                       | 0.74                  |
| $K_1$  | 0.722                         | 0.392                  | 1.277                         | 0.327                     |                       |
| $K_2$  | 0.598                         | 1.195                  | 0.743                         | 0.572                     |                       |
| $K_3$  | 1.257                         | 0.79                   | 0.557                         | 1.478                     |                       |
| $R$    | 0.659                         | 0.603                  | 0.720                         | 0.951                     |                       |

Major factor: $D>C>A>B$

Optimal combination: $A_2B_1C_3D_1$
The simulation considered four factors and three levels and the roundness error set as the objective. The simulation scheme is summarized in table 2.

The effect of the factors on the spinning quality decreases in the following order: feed ratio $f$, roller speed $n_m$, spinning temperature, roller fillet radius $r$. The best combination is $A_2B_1C_3D_1$. When the spinning temperature is 1000 °C, the roller fillet radius, rolled speed, and feed ratio are 5 mm, 40 $r$ s$^{-1}$, and 1.2 mm r$^{-1}$, respectively. The smallest roundness error is obtained in this case. The spinning simulation results for the optimal process parameters are shown in figure 2. The spinning process is stable, and stress gradually increases with deformation.

The strain curve of the spinning process is shown in figure 4. As spinning continues, the strains of the weld and BM gradually increase, and the difference between these strains gradually decreases. The weld strain is 1.77, and the base metal strain is 1.63, where the minimum strain difference is 0.14. After spinning, the strains of the weld and BM are 1.77 and 1.63, respectively, where the minimum strain difference is 0.14, and the elongation rates of the weld and BM are 30.1% and 27.74%, respectively.

The variation law of the wall thickness during spinning is examined by selecting 15 points in the axial direction. The positions and directions of the points are shown in figure 5. The thicknesses of the BM and weld were measured to observe the changes in the thickness at different positions after spinning. Figure 6 shows the...
The wall thickness increases with deformation, and the wall thickness of the parallel section first decreases and then increases. The difference between the thicknesses of the weld and BM at the closing is 0.056 mm. Figure 7 shows the roundness error. The forming diameter is 79.17 mm, and the roundness error is 0.065 mm.

3. Spinning tests and results

3.1. Materials and methods

The H-D-B40 machine tool was used for performing spinning tests. The tool consists of a hydraulic system, high-torque spindle, automatic control system, and electrical console. It can spin stainless steel, copper plates, aluminum alloys, and other materials. The deformation of different parts after coreless spinning varies significantly. Thus, the microstructures at different points of the welded pipe were analyzed. In this regard, a welded pipe was fabricated from 439 stainless steel. The sample diagram is shown in figure 8, while the sample’s composition is listed in table 3. The quality inspection standard of welded pipe was no eccentricity, wrinkle, depression, and crack after spinning. The diameter and wall thickness were $d_0 = 122.4$ mm and $1.2$ mm,
respectively. Moreover, a sample with dimensions of 4 mm × 2 mm × 1 mm was obtained using the WEDM machine tool. The sample is polished, and then, the oil stains and impurities on the sample surface are removed. The sample was corroded by an FeCl₃ (1g FeCl₃ solid + 10ml HCl + 40ml alcohol) solution. Furthermore, its structure was analyzed using a DM2700M optical microscope, and the grain size distribution before and after spinning was observed. Finally, a hardness test was conducted using the MH-60 micro-Vickers hardness tester. The measurement pressure was 300 g, maintained for 10 s, and the distance between measurement points was 0.5 mm.

3.2. Forming wall thickness and roundness error

The required diameter deformation was 0.3d₀, i.e., at least 36.72 mm. According to the spinning simulation results, the diameter after spinning is 79.17 mm, and the diameter deformation is 43.23 mm, more than 36.72 mm. In addition, the wall thicknesses at the weld and BM are 1.496 mm and 1.44 mm, respectively. Therefore, tests were conducted to verify the accuracy of the spinning simulation process. Figure 9 shows the part development via spinning. The wall thicknesses at the weld and BM are approximately 1.66 mm and 1.46 mm, respectively. Moreover, the diameter is approximately 78.18 mm. The error rates between the simulation and test results of the BM thickness and diameter are 1.37% and 1.25%, respectively, which are within the allowable error range. This result verifies the simulation accuracy.

Figure 10 shows the curve of the wall thickness obtained via the test. The change laws of the wall thickness of the test and simulation are the same. The wall thickness is small in the large deformation section and large in the parallel section. The reason is that the material accumulates in the front of the roller owing to the large friction during processing. The wall thickness decreases owing to the axial force in the large deformation section. In contrast, the deformation of the parallel section was stable, and the wall thickness increases uniformly.

The spinning roundness is shown in figure 11. In particular, the roundness error is 0.062 mm, which is less than the that obtained via the simulation (0.065 mm). Therefore, the roundness error meets the processing requirements in terms of the surface quality and wall thickness. Furthermore, the elongation rate measured in the test is 30%, and the roundness error obtained in the simulation is 4.8%. Thus, the numerical simulation

| Element | C     | Si    | Mn    | P     | S     | Cr    | Ti    | N     | Nb    | Fe    |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Composition | 0.012 | 0.36  | 0.22  | 0.019 | 0.01  | 17.56 | 0.17  | 0.06  | 0.18  | Balance |

Figure 7. Roundness error of spinning forming.
results are accurate, and they show that instability or local elongation can easily occur at the port, strongly affecting the use of the formed parts. This phenomenon could be prevented by appropriately removing the port machining allowance and ensuring the roundness of the port.
3.3. Microstructure and mechanical properties
The microstructures of the welded pipe before and after spinning are shown in figure 12. In particular, figures 12(a) and (b) show that the crystal size at the weld is smaller than that at the BM, and the crystal size distribution is uneven. During spinning, coarse crystals viscously slide along the crystal boundary. Thus, the material presents creep properties. After spinning is performed multiple times, the crystals of the weld and BM are refined. The closer to the part ends, the more crystal because of the fluidity of the material and the spinning accumulation of the material during spinning. As shown in figures 12(d), (e), (g), and (h), the crystal size increases in the following order: outer layer, inner layer, and middle layer. The reason is that the roller directly acts on the outer layer of the tube blank and transmits the spinning pressure to the inner layer of the tube blank. As a result, the spinning force gradually diffuses from the outer side to the inner layer along the direction of the thickness, and stress gradually decreases. Thus, the deformation of the outer layer is larger than that of the inner layer, the heat dissipation in the middle layer is slower than that in the outer and inner layers, and the crystal size is relatively large. As shown in figures 12(c), (f), and (i), as deformation increases, the size of the transition zone
and the crystal size both decreases. These results indicate that the fatigue performance of the material is significantly improved; however, work hardening can easily occur.

After spinning, the hardness test was conducted at points with different deformations. The surface hardness curves of the formed parts are shown in figure 13. The exact value of hardness is shown in table 4. The weld and BM hardness are 464.8 HV and 452.1 HV, respectively. Thus, hardness is significantly improved after spinning. The weld hardness in the spinning arc section is larger than the BM hardness. The average hardness of the weld and BM is 738.6 HV and 494.7 HV, respectively. Within the allowable range of pressure, hardness gradually increases with deformation.
The hardness of each layer in the direction of the thickness (radial) is shown in figure 14. Moreover, the value of hardness is shown in table 5. The hardness of the outer layer is the largest, followed by the inner layer and middle layer. Hardness gradually increases with deformation. This result indicates that the crystal size determines hardness, i.e., hardness decreases as the crystal size increases.

4. Conclusion

In this study, the spinning process of a 439 stainless steel welded pipe was optimized through simulations and experiments. The quality and microstructure obtained after spinning were analyzed. The main conclusions are as follows:

(1) Process parameters affect the roundness error in the following order: feed ratio \( f \), roller speed \( n_{rot} \), spinning temperature, and roller fillet radius \( r \). When the spinning temperature is 1000 °C, the roller fillet radius, roller speed, and feed ratio are 5 mm, 40 \( r \cdot s^{-1} \), and 1.2 mm \( r^{-1} \), respectively, and the spinning forming quality is good without defects.

(2) After parameter optimization, the wall thicknesses at the weld and BM were 1.66 mm and 1.46 mm, respectively, and the roundness error was 0.062 mm. The error rates of the forming thickness (weld and BM) and roundness error are 1.37%, 1.25%, and 4.8%, respectively, which are in good agreement with the test results.

(3) The deformation of the spinning parts strongly affects hardness and the crystal size. As deformation increases, the crystal size decreases and hardness increases. The average hardness of the weld and BM is 1044.5 HV and 956.8 HV, respectively.

Acknowledgments

This work was financially supported by Jilin Scientific and Technological Development Program (No. 20190302022GX).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Table 5. Hardness curve in thickness direction of formed parts.

| Part               | Outer layer | Middle layer | Inner layer |
|--------------------|-------------|--------------|-------------|
| Spinning arc section hardness/HV | 890.1       | 777.5        | 804.5       |
| Spinning straight section hardness/HV | 1056.2      | 961.8        | 1016        |
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