Research on Preparation Method and Mechanism of Cylinder Ultra-fine Crystal Metal Spinning

Yu Yang, Yanyan Jia
Changchun University of Science and Technology, Changchun, Jilin Province, 130022, China
yangyu1983@sina.com

Abstracts: Modern industry requires metal materials with high forming quality and excellent mechanical properties. Ultra-fine grain metal makes ordinary steel obtain good comprehensive performance, reduce the consumption of high-performance metal, improve material utilization and performance, and is of great significance to the manufacturing industry. In this paper, the body-shaped cubic metal 20# steel cylinder parts are taken as research objects. By exploring the forming principle of ultra-fine crystal structure cylindrical parts, the finite element simulation of the strong spinning process of the cylindrical parts is carried out. And the forming process experiment of ultra-fine grain structure spinning and heat treatment experiment are also carried out. Thus, the plastic deformation mechanism is revealed, and a method for preparing an ultra-fine grain material based on combination of strong spinning and recrystallization annealing is proposed. The research reveals the relationship between mechanical properties and microstructure of ultra-fine grained materials. The research results have great scientific significance for promoting the development of ultra-fine grain metal material preparation technology.

1. Introduction

With the continuous advancement of technology, in the fields of passenger car manufacturing, high-speed rail construction, ocean-going vessels, deep-sea exploration and engineering machinery, the requirements of the metal for reliability are getting higher and higher in the harsh conditions of high temperature, speed, pressure, corrosive medium and heavy load. There are data showing that the annual losses caused by metal failure in China account for about 3% of the total output value of the national economy[1]. The development of ultra-fine grain metal materials can overcome the above problems. Therefore, China's 13th Five-Year Plan also clearly pointed out that it is necessary to vigorously develop nano-functional high-end materials such as ultra-fine crystal materials.

Severe plastic deformation is the main method for preparing ultra-fine grained metal materials. However, traditional high-pressure torsion, equal-angle extrusion, multi-directional forging and cumulative stacking are mainly based on face-centered cubic metal and close-packed hexagonal metal, while the research with strong spinning method on body-centered cubic metal ultra-fine is less[2]. Regarding the preparation of ultra-fine grained metal by spinning, China is still in the laboratory development stage. Japan has applied ultra-fine grain materials in the manufacture of passenger cars.

In this paper, marten-site is to used as the initial structure for preparing ultra-fine grained metal to reduce the strain required to refine the grain to the ultra-fine grain level, and combine the strong spinning and annealing process to obtain the cylindrical piece with ultra-fine grain structure. The dynamic model of the ultra-fine grained metal was revealed by using the cylindrical part to strongly
rotate the simulation model and supplemented by the spinning process experiment to explore the metal flow and the equivalent strain distribution. Through the study of the microstructure during the plastic forming process of ultrafine-grained metal, the variation of grain evolution characteristics, dislocation density and storage energy during the preparation process was obtained, and the ultra-fine grain metal formation was explored from the macroscopic forming process and microstructure. This method breaks through the limitation of the traditional severe plastic deformation method which can only prepare small-volume ultra-fine crystal materials, and explores a new method for preparing ultra-fine crystal cylindrical parts under small strain conditions.

2. Finite element simulation

When the ultrafine-grained metal material is prepared by the strong spinning method, the grain size of the material is closely related to the spinning process parameters. The magnitude of the spinning pressure is the main basis for the setting of the spinning process parameters. The usual calculation method for the rotational pressure is the Thamasett algorithm[3-4]. The algorithm assumes the stable continuous flow of metal in the axial direction. However, the poor flow of metal during actual spinning will change the deformation rate, which will cause the algorithm to deviate. In this paper, based on a large number of process experiments, the deviation law of the algorithm is found and corrected. Based on the modified algorithm, a powerful spinning simulation model was established using Hypermesh and Ansys.

2.1. Algorithm correction

The currently used Thamasett algorithm has its radial force $P_r$ expressed as:

$$P_r = \frac{\Delta t \sigma_m \cdot \sqrt{R_y fctg\alpha_p}}{\eta}$$  \hspace{1cm} (1)

The axial force $P_z$ is expressed as:

$$P_z = \frac{\Delta t fctg\alpha_p \sigma_m \cdot \sqrt{R_y}}{\eta}$$  \hspace{1cm} (2)

Tangential force $P_t$ is expressed as:

$$P_t = \frac{\Delta t \sigma_m}{\eta}$$  \hspace{1cm} (3)

In this paper, the deviations between the calculated and measured values of the Thamasett algorithm on the radial, axial, and tangential rotational pressures are found by a large number of process experiments. The deviations are shown in Table 1. The deviation in the radial direction is about 15%, the deviation in the axial direction is about 25%, and the deviation in the tangential direction is 200%.

| Measurements(N) | Theoretical value(N) |
|-----------------|----------------------|
| Axial force     | Radial force         | Tangential force   |
| 902             | 1127                 | 129               |
| 1470            | 1519                 | 137               |
| 2362            | 2166                 | 211               |

Table 1. Table of rotational pressure measurement and theoretical value deviation
According to this law, the parameters of the Thamasett algorithm are modified, and the radial force of the rotating wheel is:

\[ P_r = \frac{\Delta t \sigma_m \cdot \sqrt{R_z \cdot fctg \alpha_p}}{\sqrt{2} \cdot 2.5 \eta} \]  

(4)

The axial force of the rotating wheel is:

\[ P_z = \frac{\Delta t g \alpha_p \cdot \Delta \sigma_m \cdot \sqrt{R_z \cdot fctg \alpha_p}}{\eta} \]  

(5)

The tangential force of the rotating wheel is:

\[ P_t = \frac{5 \Delta t f \sigma_m}{4 \eta} \]  

(6)

2.2. Simulation model establishment

Based on the modified algorithm, a simulation model is established using Hypermesh and Ansys. The simulation model is shown in Figure 1.

2.3. Ultra-fine crystal preparation process experiment

The material used in the experiment was 20# steel, and the blank specification φ76mm×4mm×80mm was hot-rolled seamless steel pipe. The initial grain of ferrite is uniform and the size is about 40 μm.

This paper uses 20# steel to explore the preparation method of ultra-fine crystal strong spinning of body-centered cubic metal cylinder parts. The finite element simulation is used as the basis for the spinning process parameters, and combined with the engineering practice experience, the spinning preparation scheme is finally determined as followed, three passes of strong spin, recrystallization heat treatment, two passes of general rotation and recrystallization annealing. The experiment takes the double-rotation wheel offset. The first three passes are large and thin, strong spinning, so that the blank is reduced by about 70%, then it is heated to about 600 °C, and kept for 1 hour. After the crystal grains are recrystallized and the residual stress is removed, recrystallized and the residual stress is removed, the two-pass reduction of the small reduction amount causes the blank to be reduced by

|        |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|
| 1470   | 1519   | 137    | 1578   | 3381   | 111    |
| 1784   | 1950   | 210    | 1705   | 3646   | 170    |
| 2274   | 2528   | 352    | 2323   | 4978   | 286    |
| 1695   | 2871   | 336    | 1980   | 9349   | 297    |
| 3254   | 2185   | 358    | 2626   | 5155   | 279    |
about 5%, and finally recrystallization annealing, and the grain is refined to the nanometer level. The specific process parameters are shown in Table 2.

| Feed ratio | Spindle speed | Axial offset | Pass rate |
|------------|---------------|--------------|-----------|
| 0.6mm/r    | 108r/min      | 2.5mm        | 75%       |

4. Experimental results and analysis

4.1. Forming quality analysis

Through the spinning process experiment, it is found that the axial, radial and tangential directions of the contact area between the rotating wheel and the blank have undergone severe shear deformation. From the start to the final rotation, the slip surface formed by the slip line follows the external force. Organizational heterogeneity is exacerbated. Ultra-fine grain material spinning products are shown in Figure 2. Metallographic analysis is shown in Figure 3. a) Metallographic map of unformed material area. b) Metallographic diagram of the material in the deformation zone. c) Metallographic map of the formed zone material. d) Metallographic diagram of the material after annealing.

![Figure 2. Simulation and spinning products](image)

![Figure 3. Metallographic map](image)

It can be seen from the metallographic diagram that after the first three passes of the large reduction of the amount of spinning, the metal grains are broken and elongated. After the subsequent two small reductions of spinning and annealing, the metal material produces fine equiaxed crystals having an average grain size smaller than 1μm.

4.2. Microstructure evolution analysis

Through the observation of the microstructure, after large and thin plastic deformation, the ferrite and pearlite in the crystal are gradually elongated along the deformation direction to form a fibrous structure, and then some ferrite grain boundaries are broken[5-6].

Through the analysis of the results of transmission electron microscopy, most of the pearlite sheet crystals are spheroidized into granular cementite after the metal material is strongly rotated by a large reduction. After the annealing process, the grain morphology tends to be equiaxed, and most of the cementite fragments are transformed into cementite particles. The microstructure evolution is shown in Figure 4. a) Blank microstructure. b) Microstructure after extensive thinning. c) Microstructure after annealing.
5. Conclusion
In this paper, the preparation method of superfine-grained strong spinning of body-centered cubic metal 20# steel tubular parts is studied. The metal plastic deformation mechanism and grain size morphology are analyzed. The relationship between mechanical properties and microstructure of ultra-fine grained materials is revealed. Main conclusions are got as followed.

(1) Simulation study on preparation of ultra-fine grained metal by strong spinning method
The Thamasett algorithm was modified through a large number of process experiments. Modeling and spinning simulation experiments were performed by Hypermesh and Ansys.

(2) Experimental study on preparation of ultra-fine grained metal by strong spinning method
Ultra-fine metal is prepared under small strain conditions by quenching, strong spinning, recrystallization annealing, and ordinary spinning. Process parameters are set based on simulation, optimized by spinning test.

(3) Study on the microstructure evolution of ultra-fine grained metal prepared by strong spinning method
Through metallographic experiments and transmission electron microscopy, the evolution characteristics of grain size and morphology were studied, and the evolution law of microstructure was revealed to clarify the conditions for the formation of ultra-fine grained metals.

Acknowledgement
This paper is supported by the 13th Five-Year Science and Technology Research and Planning Project “Study on Preparation Method and Mechanism of Strong Spinning of Cylindrical Ultra-fine Grain Metal” of the Jilin Provincial Department of Education. Item Number JJKH20181128KJ.

References
[1] Yang Yu, Ge Anlu, Wu Xixi, et al. (2018) Study on preparation methods of ultrafine-grained metal materials. J. Light Industry Science and Technology.12:40-41.
[2] Yang Baolian. (2013) Study on the Mechanism of Nano/Ultrafine Crystalline Cylindrical Parts Prepared by Strong Staggered Spinning.D.Guangzhou.South China University of Technology.
[3] Yang Yu, Cao Guohua. (2012) Parameter Amendment and Simulation on Spinning Force Thamasett Algorithm for Steel Cylinder Shape Parts. J. Ordnance Material Science and Engineering.35:84-87.
[4] Yangyu, XuHongji. (2010) The general analysis on laser lineup system of geometrical optics mathematical model. In: 2010 the 2nd IEEE International Conference on Information Management and Engineering. Chengdu. pp. 527~529.
[5] Yang Baolian, Xia Qinxiang, Cheng Xiuquan, et al. (2012) Feasibility Study on Superfine-grained Cylindrical Parts Prepared by Powerful Rotary Compression. J.Functional materials.43:266-269.
[6] Yu Yang, Hongji Xu. (2010) Overview of Metal Spinning Process. In: The 2010 IEEE International Conference on Information and Automation. Harbin.pp. 2502~2507.