Analysis on flow control forming of magnesium alloy wheel

M J Zhao¹, Z L Wu¹ and Z R Chen², X B Huang¹

¹The School of Mechanical Engineering, Nanjing University of Science & Technology, Nanjing, China
²Nanjing Hub Electromechanical Technology Co., Ltd, Nanjing, China

E-mail:wuruinan-1994@mail.njust.edu.cn

Abstract. Deformation force and forming quality are the important research focus in process of Magnesium (Mg) alloy wheel. In this paper, a process model of flow control forming (FCF) for the wheel was built, and its finite element model was given to simulate the FCF process at different extrusion speed (5 mm/s, 10 mm/s, 15 mm/s and 20 mm/s). The simulated results show that the FCF method for the wheel can reduce deformation force to less than 22000 kN, while there are cracks on rim of the wheel. The results are verified by the experiment and the cracks predicted by simulation are in good agreement with the experimental results.

1. Introduction

Mg alloy is one of the most attractive structural light metal, especially for automobile applications, due to its appealing properties including low density excellent specific strength and specific stiffness, high damping capacity, high thermal conductivity, reducing fuel consumption and decreasing pollution [1,2]. Because of the above merits, there is an increasing trend in automotive in automotive industries [3-5]. Currently, Mg alloy can be divided into cast Mg alloy and wrought one in terms of difference in processing[6]. Wrought Mg alloy had greater advantages over cast ones in structural components[7,8]. However, it usually exhibits poor plastic formability at room temperature because of their hexagonal close-packed (HCP) structures and the limited number of slip systems, which restricts its large-scale applications [9], particularly in complicated parts, such as Mg alloy wheel.

The current studies on plastic forming of Mg alloy wheel were mainly as follows. [10] presented a kind of plastic forming technology: roughness forging, blocker forging, finishing forging, T6 treatment and spinning process, of which the billets was the cast Mg alloy with average crystalline particle size of not greater than 100 μm. Meanwhile, the forging was carried out at a temperature within the range of 300—420°C. [11] provided a process of pre-forging, finishing forging and flaring, and [12] provided a more effective technique with only including roughness forging and finishing forging, but the above methods focused basically on forming efficiency of Mg alloy wheel. For reducing the forming load, [13,14] showed a new extrusion process of Mg alloy automobile wheels which can reduce the maximum forming load, but the method was only achieved through processing billet. In addition, [15,16] adopted the technology of combined extrusion and expanded forming, which saved working procedure and investment in equipments. [17] applied roughness extrusion, finishing extrusion and expanded forming, and further analyze the mechanical performance of the Mg...
alloy wheel. However, it is still one of difficulties to reduce the deformation force. Meanwhile, with the thin and bending wall of the rim being easy to crack, guaranteeing forming quality of the rim is also one of the difficulties in plastic forming processes of Mg alloy wheel.

To solve these problems, the above forming methods of Mg alloy wheel shared one common feature that the rim was formed by extrusion and flaring, while a new alternative method: the Flow Control Forming (FCF) will be introduced in the present paper, and then was analyzed and investigated by the finite element method and experiment. The good result is acquired in reducing forming force, besides, the simulated results is well agree with the experimental results.

2. FCF process of Mg alloy wheel

In this study, the FCF method of Mg alloy wheel consisted of two main steps: forming of the rim and the forming of spokes. According to the stress characteristics of forming process for the wheel, the FCF method can be subdivided into relatively simple process: cylindrical compression (CC), a process from Fig.1(a) to Fig.1(b), backward extrusion (BE), a process from Fig.1(b) to Fig.1(c), extrusion-shearing (ES), a process from Fig.1(c) to Fig.1(d) and closed-die forging (CDF), a process from Fig.1(d) to the end, as shown in Fig.1. In actual forming processes, Mg alloy cast was prepared and heated to a given temperature; next, billet was extruded to the Fig.1(b), and then form the rim, as shown in Fig.1; the last spokes was forged successfully through closed die forging. The die assembly of the Mg alloy wheel is shown schematically in Fig.2. And the arrow represented the direction of punch movement and female die movement respectively.
It was the key point of FCF method to control the metal flow direction, the forming sequence and the forming force [18]. During the forming process of Mg alloy wheel, the rim material flow of the wheel was firstly controlled and forced to flow into a certain position, as shown in Fig. 3(b), and then the billet was further extruded to final rim shape, as shown in Fig. 3(c). Besides, because of the weight loss in isothermal forming, it should guarantee that the volume of the portion "I" was slightly more than portion "II", and the shape of portion "II" was nearly to shape of portion "III", which shorted the flow path of Mg alloy during the forming process, reduced the flow resistance, and was beneficial to forming of the wheel.

3. FEM simulation on forming process of the wheel
The materials of the punch, bottom die, female die, die sleeve were made of H13 steel and the billet was Mg alloy AZ80, of which physical characteristics referred to [19]. And the constitutive equation given in [20] was adopted to describe the hot compression of magnesium alloy AZ80, as follows:

\[ \varepsilon = 2.9 \times 10^6 \left[ \sinh(0.0174\sigma) \right]^{6.965} \exp \left[ - \left( \frac{154.6 \times 10^5}{8.314T} \right) \right] \]

Due to the rapid forming process, the model of FEM simulation was assumed to be isothermal process and the thermal boundary condition was set at 415°C. Since the normal pressure is commonly greater than the yield stress of billet during high pressure processes[21], constant friction model was adopted in this paper, and the friction factor was set to 0.21, according to [22]. And the simulation parameters was arranged in table 1.

| Simulation No. | Initial temperature (°C) | Extrusion speed (mm/s) | Friction factor | Outer diameter (mm) | Height of the wheel (mm) |
|---------------|---------------------------|-----------------------|----------------|---------------------|------------------------|
| Simulation 1  | 415                       | 5.0                   | 0.21           | 440.6               | 200.4                  |
| Simulation 2  | 415                       | 10.0                  | 0.21           | 440.6               | 200.4                  |
| Simulation 3  | 415                       | 15.0                  | 0.21           | 440.6               | 200.4                  |
| Simulation 4  | 415                       | 20.0                  | 0.21           | 440.6               | 200.4                  |

Punch, bottom die, female die, die sleeve were rigid parts, and the billet was plastic part in the simulation model. During the simulated processes, the first step was the process from Fig.3(a) to Fig.3(c), which the punch move down, and the second step was the process from Fig.3(c) to Fig.3(d),
which the female die move up. The simulations was conducted by DEFORM-3D software, and the model of billet was meshed by tetrahedron element with the maximum size being equal to 4 mm. The sum of element was 78544.

4. Results and analysis

It is quite significant work to predict the formability of Mg alloy wheel. The load-stroke curves for the forming processes of Mg alloy wheel were shown in Fig.4, 5. And the curves at different extrusion speed showed the same change trend, that is, the forming force on punch appeared three wave crests with stroke, as shown in Fig.4. The first crest appeared in backward extrusion, the second crest in extrusion-shearing, and the third in closed-die forging. Besides, the maximum force all appeared during closed-die forging and the minimum force all during extrusion-shearing. The forming force on female die increased slightly, smoothly and increased rapidly in the later stage, as shown in Fig.5.

![Fig. 4 Load-force curves (Load force of punch)](image)

![Fig. 5 Load-force curves (Load force of female die)](image)

Forming force on punch increased slightly with the increase of the extrusion speed, which accorded with the law of stress-true strain in [23]: the stress is higher with higher strain rate at elevated temperature. while the higher the extrusion speed is, the higher strain rate is. And the forming force on female die was in line with the above results.

Because of thin wall of the rim and its complicated shape, it often happened to crack in its forming process. The simulation found that the rim of Mg alloy wheel could appear to crack on the near end course of forming process. It can be illustrated by Fig.6 and Fig.7. On the one hand, the effective stress in the rim was more than 56.3 MPa at elevated temperature, while according to GB/T 5153-2003, the yield stress was less than 35 MPa. Therefore, the rim was in the state of plastic, meanwhile, there were maximum stresses value in the point "A", "B" and "C", nearly to 113 MPa, as shown in Fig.6. On the other hand, the maximum principle stress in the rim was more than 75 MPa at elevated temperature, while according to GB/T 5153-2003, the tensile strength was less than 65 MPa, as shown in Fig.7. Therefore, the maximum principle stress was more than the tensile strength at points "A", "B" and "C". A forming experiment of Mg alloy wheel was conducted to validate the above analysis, and the experimental condition was set in line with the simulation condition, the experimental equipment was shown in Fig. 8. The experimental results showed that there existed three cracks on the rim of Mg alloy wheel, as shown in Fig.9,10, and these agreed well with the predicted point by the finite element simulation.
5. Conclusions
In the present paper, the FCF method for Mg alloy wheel was introduced, besides, the process was theoretically subdivided into cylindrical compression, backward extrusion, extrusion-shearing and closed-die forging in terms of its stress characteristics. Based on the above analysis, a finite element
simulation was carried to study the deformation force and formability of Mg alloy wheel. The simulated results show that the maximum deformation force is only less than 2200T in the whole processes, and slightly changes with extrusion speed. Meanwhile, the cracks of the wheel were predicted, of which accuracy have been validated by the actual experiment for Mg alloy wheel. On the whole, the FCF method for Mg alloy wheel has effect in saving deformation force, but need still improve the formability of the rim. In addition, the influences of extrusion-shearing on the wheel are in need of further study.

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