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To cite this article: Long Li *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **490** 052019

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# Effects of mass scaling on finite element simulation of the cold roll-beating forming process

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**Abstract.** The cold roll-beating forming is a cold plastic forming technology for shaping external teeth of parts. The study aims to improve the simulation efficiency of the cold roll-beating forming process. Based on the principle of the roll-beating forming process, the finite element model of a representative simplified tooth groove forming process was established. Through the simulation results, the forming force and the metal plastic deformation are clearly revealed. Meanwhile, the effect of mass scaling on simulation efficiency and precision are discussed. And the experiments are carried out on a specialized forming equipment. Comparing finite element results with the experimental results, it shows the reasonable selection of mass scaling can effectively improve the simulation efficiency with the certain calculation precision. This study provides a reasonable and efficient finite element model and numerical calculation method for relative researches of cold roll-beating forming technology.

## 1. Introduction

Through plastic forming, metal can be directly produced to meet or close to the final shape of the parts, and not only has high material utilization but also can improve the mechanical properties of the product to a certain extent<sup>[1,2]</sup>. The numerical simulation methods are widely used to obtain the numerical solution with sufficient accuracy to describe various forming processes<sup>[3,4]</sup>. And among many numerical simulation methods, the finite element method has already been developed comparatively mature, which has been used to analyze the complex plastic forming process<sup>[5-8]</sup>.

Cold roll-beating forming technology is an incremental cumulative plastic forming technology, Using the technology the external teeth of the gear, spline shaft, and other functional elements can be fabricated at room temperature. Meanwhile, it just needs small forming force and low energy consumption<sup>[9,10]</sup>. Recently, the numerical simulation of this technology has been studied by some scholars. Li<sup>[11]</sup> simulated both the temporal temperature distribution and the equivalent stress and strain distributions of the 40Cr high-speed cold roll-beating forming process by the finite element software ABAQUS. Liang<sup>[12]</sup> established a simplified finite element model and analyzed the deformation forces during the forming process of different ways of rolling. Cui<sup>[13,14]</sup> analyzed the flow of metal for the involute spline forming, and given the characteristics and rules of the stable forming area by finite element simulation.

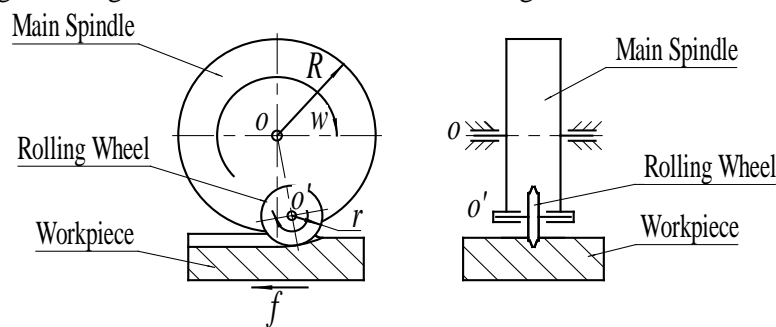
In consideration of the cost of computing and convenience of engineering application, these studies were carried out by using single or local multi roll-beating model. The simplified model difficult to describe the complete forming process. In view of the above review, it is necessary to get a finite element model of cold roll-beating forming which can effectively describe forming force and the whole metal plastic deformation. So this paper will establish a general finite element model to



simulate cold roll-beating forming external tooth of solid parts and discuss the effect of mass scaling on simulation time and accuracy.

## 2. Principle of forming

The rolling wheel is eccentrically on a main spindle. The main spindle rotates to drive rolling wheel revolution and to beat the workpiece. The rolling wheel rotate by the friction during the rolling wheel beats the workpiece. The continuous feeding of the workpiece make the plastic deformation of every beating to gradually accumulate. Finally, the shape of the tooth profile is formed. In addition, a variety of parts, like an external spline, external gear, and lead screw or other parts, can be formed by additional different rotating forms to the workpiece. But for all the parts mentioned above, the forming process of any single tooth groove is consistent, as shown in figure 1.



**Figure 1.** Schematic of cold roll-beating forming.

## 3. Mass scaling and calculation efficiency

The forming process of cold roll-beating is a kind of large deformation forming process, which involves solving the nonlinear dynamic problem. So the dynamic explicit algorithm is used to solve this forming process. The algorithm is a recursive calculation based on time step, not require iterative computation. In the application the time step is not greater than the critical time step  $\Delta t_{\min}$ , which is decided by the equations (1). Otherwise, the algorithm will not converge.

$$\Delta t_{\min} = L_{\min} / \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (1)$$

$L_{\min}$ -Minimum length of an element in a mode,  $\rho$ -Density,  $E$ -Young's modulus,  $\mu$ -Poisson ratio

The number of minimum incremental steps  $n_{\min}$  that need to calculate can be expressed as formula(2):

$$n_{\min} = T / \Delta t_{\min} \quad (2)$$

$T$ -Actual forming time

Formula(2) shows for reducing the number of incremental steps, the actual forming time  $T$  need be shortened or increase the critical time step  $\Delta t_{\min}$ . Under the premise of not changing the impact speed and the number of beating per unit length, to shorten the actual time the feed speed of the workpiece has been increased by increasing the number of the rolling wheels when the calculation model was established.

And to further improve the computational efficiency, the critical time step  $\Delta t_{\min}$  must be increased, without changing the number of meshes the mass can be changed by mass scaling. because of the law of volume constancy, to increase the mass is to increase the density. According to equation (1) density increases  $\eta$  times,  $\Delta t_{\min}$  will increase  $\eta^{0.5}$  times. However, the too large mass scaling can generate a large virtual inertia force, which affects the results of the calculation and even makes the calculation can not converge, and large time step leads to the distortion of the result. Therefore, it needs to pay attention to select mass scaling.

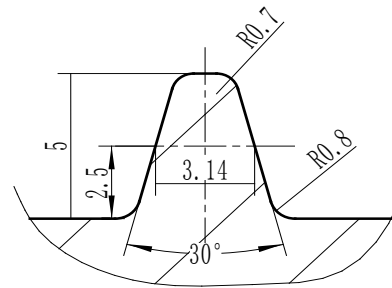
## 4. Finite element model and experiment

### 4.1. Finite element model

ABAQUS/ explicit 6.13 is used to simulate cold roll-beating forming process. To further reduce computing time, the finite element model has the four rolling wheel uniformly distributed along the axis of the main spindle, so under the precondition that the impact speed of beating and the number of beating per unit length of the workpiece are singles rolling wheel model, the workpiece feed speed is increased by 4 times, as shown in figure 2. The basic radius of rolling wheels  $R$  and revolution radius  $r$  is 24mm and 72mm respectively. Figure 3 gives the design tooth profile of rolling wheel. In the course of calculation, the rolling wheels set as the analytical rigid. The  $L$ ,  $B$ , and  $H$  of the workpiece are respectively 40mm, 14mm and 10mm. The feeding speed of the workpiece is defined on its bottom surface along the positive direction of axis  $y$ . The side wall of workpiece constrains the freedom degree on  $z$  directions. The workpiece is meshed by using C3D8R element, The length of the element is 0.25mm. The friction factor set as 0.15. In view of the larger local deformation in the forming process, the adaptive mesh is adopted in this calculation.



**Figure 2.** Finite element model.



**Figure 3.** Tooth profile of rolling wheel.

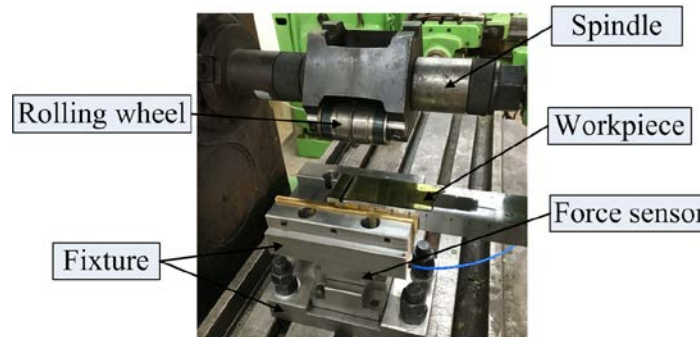
The materials used in this study was ASTM 1045 steel. The material density, elasticity modulus, and poisson ratio are 8900kg/m<sup>3</sup>, 124GPa and 0.34 respectively. And the material properties are described by J-C constitutive equation, as shown in formula (3).

$$\sigma = \left[ 525.4 + 541.625 \varepsilon^{0.4296} \right] \left[ 1 + 0.0212 \ln \left( \frac{\varepsilon'}{0.008} \right) \right] \left[ 1 - \left( \frac{T - 25}{1475} \right)^{1.2018} \right] \quad (3)$$

$\sigma$ -Flow stress;  $\varepsilon$ -Strain;  $\varepsilon'$ -Equivalent plastic strain rate;  $T$ -Workpiece temperature

In the calculation, the spindle speed, feed speed and forming depth are 960 mm/min, 475 r/min and 2.5 mm, respectively.

### 4.2. Experimental device

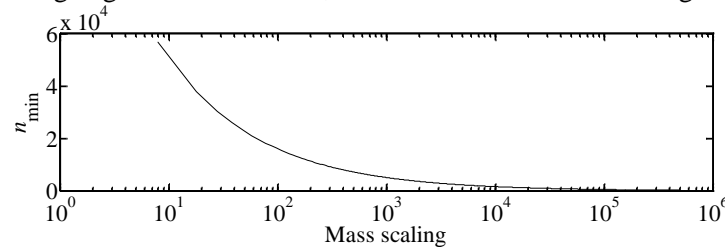


**Figure 4.** Experimental device.

The horizontal milling machine X62 was transformed for this study, as shown in Figure 4. The main geometric parameters of experimental setup is consistent with the computational model. The rolling wheel material is 20CrMnTi and the carburizing treatment is carried out to improve the surface hardness and wear resistance.

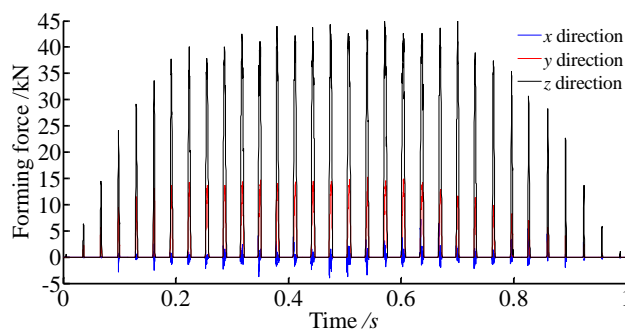
## 5. Results and discuss

With different mass scaling the required minimum number of incremental steps  $n_{\min}$  show in Figure 5. It present that in the range of mass scaling less than 1000  $n_{\min}$  with the increase of mass scaling reduces rapidly, and the decreasing trend becomes to slow down when mass scaling is in 1000-10000. Then when the mass scaling is greater than 10000,  $n_{\min}$  almost remained unchanged almost.

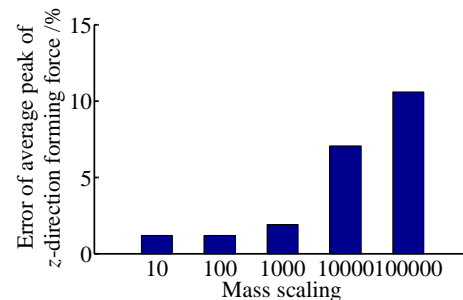


**Figure 5.** Effect of mass scaling on minimum number of incremental steps.

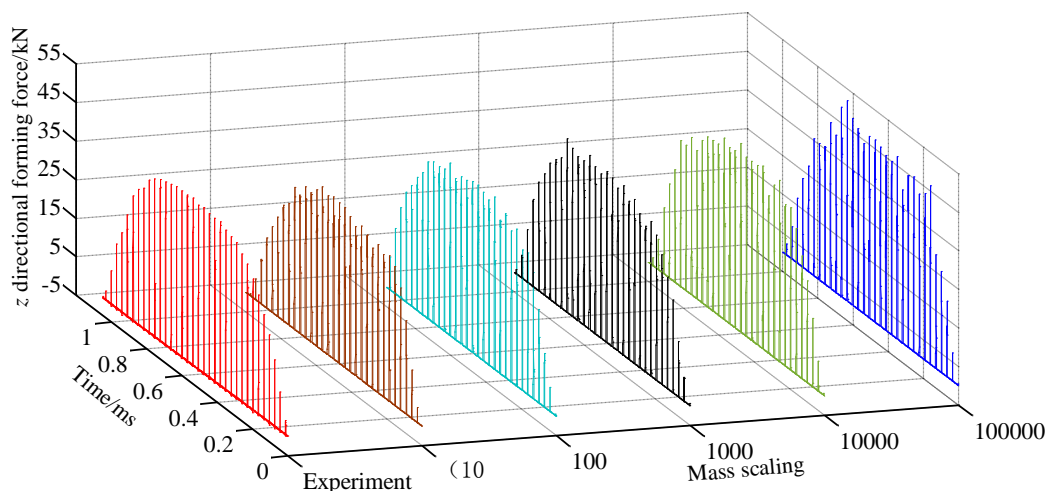
The numerical simulation results of the forming forces when the mass scaling is 1000 were shown in the figure 6. Compared to the forming force of the other two directions, the  $z$  directional forming force is the main forming force. At initial forming stage, the rolling wheels begin to gradually intrude into the workpiece. So the contact area increase gradually and the three directional forming force are also gradually increased. At the stable forming stage, the contact area and the deformation of each impact gets the max and no longer increase. The peak of forming forces of each beating keeps at maximum. Finally at Forming end stage rolling wheels begin to gradually roll-beat the parts near the other boundary of the workpiece. At this stage, because the contact area of impact and the volume of metal involved in the forming is gradually reduced, the peak value of the forming forces are gradually reduced.



**Figure 6.** Forming force of numerical simulation.



**Figure 7.** Error of average peak of  $z$ -direction forming force in stable forming stage.

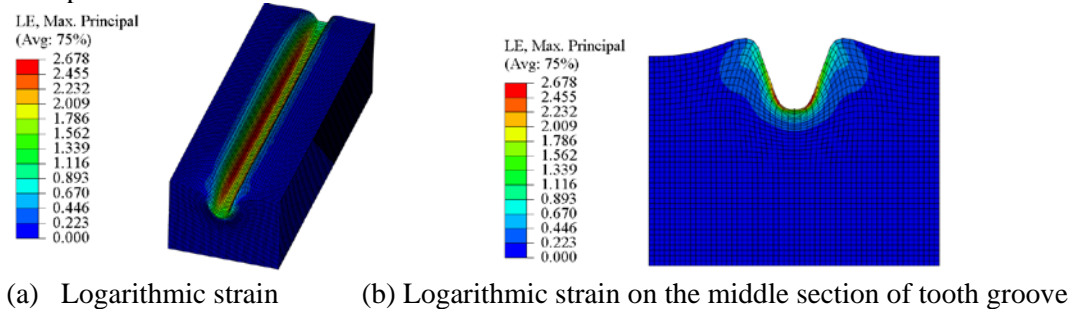


**Figure 8.** Effect of mass scaling on simulation results of  $z$  directional forming force

For stable forming stage under different mass scaling, simulation results indicate that when the mass scaling is less than 1000, the error of simulation results is less than 10% and the  $z$  directional forming

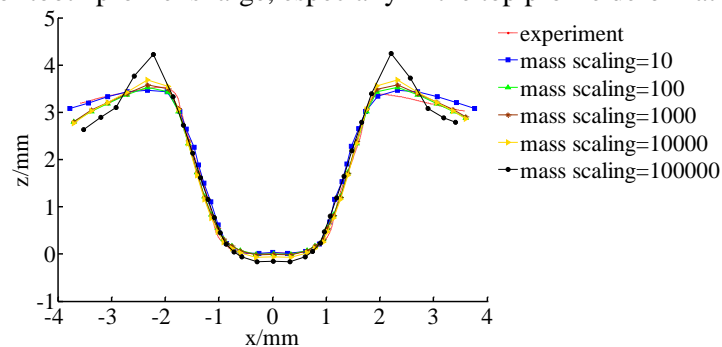
force changes of forming process are basically the same, as shown in figure 7. Increasing mass scaling the simulation error will increase and the simulation results of  $z$ -direction force change during stable forming stage begin to fluctuate when the mass scaling is 10000. If the mass scaling set in 100000, the result has a larger error which does not have the reference value, as shown in figure 8.

Figure 9 shows the final deformation of the material. It presents that at the stable forming stage a large  $z$  directional compressive strain and  $x$  directional tensile strain occurred at the bottom of the tooth, and on the tooth side there is a large  $x$  directional compressive strain and  $z$  directional tensile strain reached the maximum, as shown in Figure 9. All of these indicate how the tooth shape is formed. The metal of tooth bottom was roll-beaten, which made the metal stretched along the axial and form the bottom of the tooth. At the same time, the metal close to the tow sides of the tooth root was pulled to the bottom to form tooth wall. Then the metal of tooth wall was compressed and extension to tooth crest, which uplifted and formed tooth crest.



**Figure 9.** Final deformation of the material.

The tooth groove profile of stable forming stage is extracted from the simulation results with different mass scaling, as shown in Figure 10. Increasing the mass scaling from 10 to 1000, there is little effect on the simulation results. However, when the mass scaling factor is increased to 100000, the simulation error of tooth profile is large, especially in the top profile deformation.



**Figure 10.** Effect of mass scaling on the tooth groove profile.

## 6. Conclusion

In simulation of the forming forces and the final formed tooth profile of cold roll-beating forming, increasing mass scaling can obviously improve the simulation efficiency when mass scaling is less than 10000. Under the different mass scaling, main forming force and tooth profile of stable forming stage were obtained and analyzed. Comparing with the experimental result it indicates that increasing mass scaling the simulation error will increase, and the mass scaling is greater than 10000, the accuracy of the calculation results began to obviously decrease. When the mass scale reaches 100000, the result is distorted.

## Acknowledgments

This work was financially supported by National Natural Science Foundation of China (Grant No. 51475366, 51475146), Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2016JM5074), and Ph.D. Innovation fund projects of Xi'an University of Technology (Grant No. 310-252071601).

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