The International Journal of Advanced Manufacturing Technology (2018) 97:345–352
https://doi.org/10.1007/s00170-018-1934-9

ORIGINAL ARTICLE

Effects of the material and its temperature state on the tooth morphology in gear rolling

Jin Li [1] · Guangchun Wang [2] · Tao Wu [2]

Received: 23 November 2017 / Accepted: 19 March 2018 / Published online: 30 March 2018

Abstract

The "rabbit ear" defect in gear rolling is closely related with the flow state of the metal in local area. The material of the blank and its temperature state affect the flow state of the metal directly, thus affecting the tooth morphology. In this paper, the quantitative evaluation index of the tooth morphology in gear rolling is established. Through the numerical simulation, the change law of the tooth morphology with different materials such as carbon steel, pure aluminum, and wrought aluminum and that with different forming temperatures are acquired and the reasons are analyzed. Using self-developed gear rolling experiment device, the experiment study of gear rolling is done while pure aluminum, Al_2017, and lead are selected as the material of the blank; the simulation results are verified experimentally. The results provide a scientific basis for the choice of the blank's material and the forming temperature, controlling the rabbit ear defect and improving the forming quality of gear rolling.

Keywords Gear rolling · Tooth morphology · Blank material · Temperature state · Finite element analysis · Experimental study

1 Introduction

Aimed to reduce the great deformation resistance in gear forging, scholars put forward solutions, such as the application of the principle of shunt in cold precision forging of spur gears proposed by Ohga et al. [1], the floating concave die adopted in gear cold precision forging process raised by Tuncer et al. [2], and a two-step gear forging process put forward by Choi et al. [3], Jung et al. [4], Kondo et al. [5], Kou et al. [6]. Although the proposed methods by the above studies have reduced the deformation resistance, the gear forging process still has many problems such as easily damageable dies, incomplete filling of the tooth corner, and difficult withdrawal from the die because of a larger load. To overcome the problems mentioned above, the gear rolling process is proposed for consideration. The gear rolling process is an emerging forming technology, based on generating motion principle, combined with rolling and scrubbing process. The gear rolling process can overcome the above defects in gear forging, because the blank is extruded locally and continuously by the gear rollers, the deformation resistance is smaller and corner parts are easier to be filled. In conclusion, the gear rolling process has better prospects.

As shown in Fig. 1, two gear rollers (gear mold) are installed symmetrically on two sides of the blank in parallel; they contact the outer edge of the blank initially and rotate in the same direction to drive the blank rotate reversely, at the same time, the gear rollers feed along the radial direction to extrude the blank and make the metal flow to form the tooth.

In the gear rolling process, because of generating motion relationship between the gear rollers and the blank, the blank should be formed into the envelope tooth of the gear roller; however, the metal on the surface of the blank is extruded; thus, its flow state is inconsistent with the flow state of the metal inside, which causes the rabbit ear and other defects to affect the tooth morphology of the rolled gear, as shown in Fig. 2.

Related researches about tooth morphology in gear rolling have been carried out. Zhu established the quantitative evaluation index of tooth tip pulling, with the numerical simulation, the tooth tip pulling in different working

✉ Guangchun Wang
wgc@sdu.edu.cn

1 School of Mechanical and Electrical Engineering, Shandong Jianzhu University, Jinan 250101, China

2 Key Laboratory for Liquid-Solid Structural Evolution and Processing of Materials of Ministry of Education, Shandong University, Jinan 250061, China

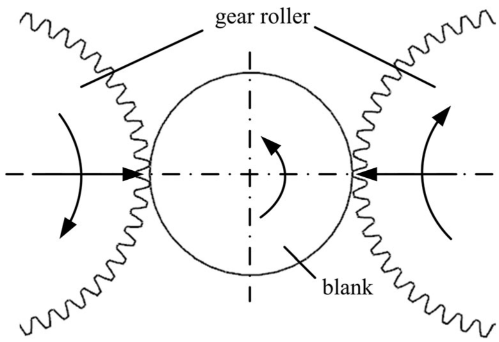


Fig. 1 Schematic diagram of gear rolling

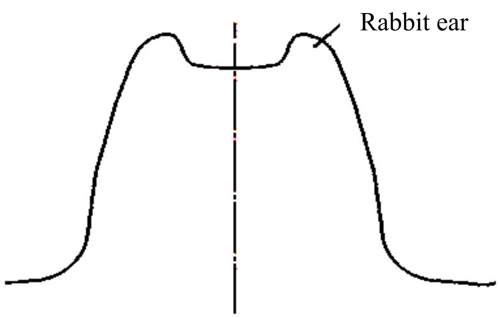


Fig. 2 The rabbit ear in gear rolling

conditions and the significant influence of the process parameters in hot gear rolling were analyzed [7]. Zhu et al. analyzed the change of the relative friction direction on the tooth profile and its influence on the metal flow direction of the tooth profile based on theory analysis, simulation, and experiments [8]. Wang et al. proposed a method of eliminating the rabbit ear defect by adding cylinder wheel [9]. Kamouneh et al. proposed a way to increase tooth filling quantity by forward and reverse rotation of gear rollers, with simulation and measurement; it is confirmed that when the proportion between the positive rotation and the reverse rotation is 7:3, the tooth filling amount is the biggest [10].

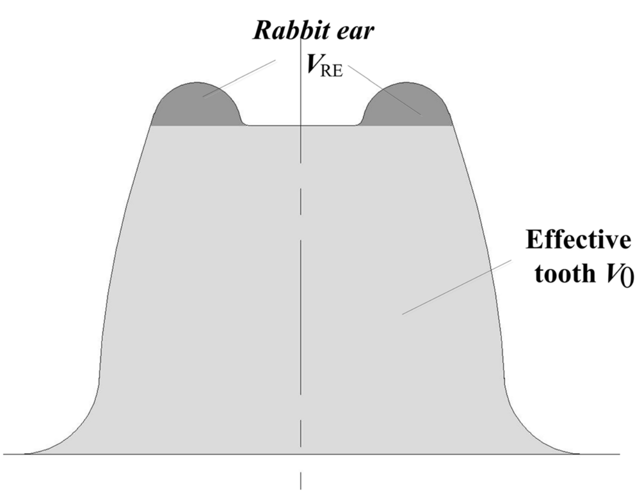


Fig. 3 Volume distribution schematic diagram of the rabbit ear and the effective tooth

Table 1 Basic parameters of gear rolling in FEM model

Basic parameters	Number of teeth on the gear to be formed	Number of teeth on the gear roller	Friction factor	Forming temperature	Blank grid
Value	31	51	0.10	20 °C	100,000

Li et al. analyzed the stress state, deformation zone distribution, and flow of material to acquire the forming mechanism of rabbit ear defect, by finite element simulation of gear rolling process, and verified by experiment [11]. Li et al. give the influence law of process parameters, such as the feed of the gear roller, the friction factor, and the tooth number of the gear roller on the rabbit ear in gear rolling by simulation combined with experiments [12]. Although papers above are focused on the tooth morphology of rolled gear, but most are about the formation of rabbit ear, not about the impact of the blank material, forming temperature on the tooth morphology.

The flow behavior of the metal is closely related with material and its status; therefore, in this paper, the gear rolling process with the blank of different materials and in different forming temperatures is studied, the quantitative evaluation index of tooth filling degree is established, the change law of the tooth morphology with different materials and different forming temperatures is analyzed and acquired, the results can provide a scientific basis for a reasonable choice of the material of the blank and the forming temperature, increasing the filling rate of the tooth and improving the forming quality of the rolled gear.

2 The evaluation index of the tooth

The filling rate of the tooth has an important influence on the forming quality of the gear, so the filling rate is used as the index of the tooth, by which to measure the effect of various process conditions on tooth morphology.

As shown in Fig. 3, V_0 is the effective tooth volume of one tooth, V_{RE} is the rabbit ear volume of one tooth, the ratio of the effective tooth volume to the total tooth volume should first be worked out, and then the average value of the ratio from all the forming teeth is used as the filling rate of the rolled gear, which is the evaluation index of the tooth, as shown below

$$F_0 = \frac{\sum_{i=1}^{n}\left(\frac{V_0{}^i}{V_0{}^i + V^i{}_{RE}} \times 100\right)}{n}\% \tag{1}$$

where n is the tooth number of the gear to be formed.

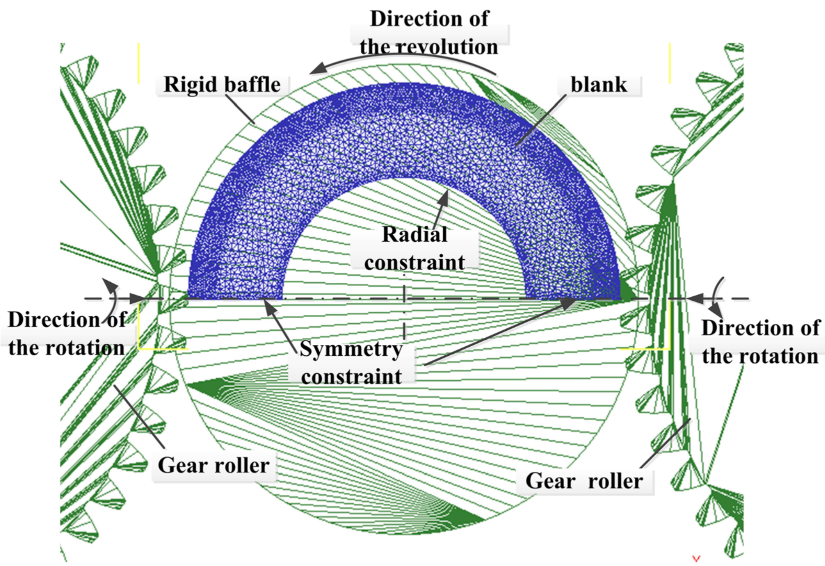


Fig. 4 Rabbit ear morphology in gear rolling at the different rolling feed

3 The finite element model of the gear rolling process

The gear rolling process is simulated by Deform-3d software. The basic parameters and environment variables are shown in Table 1. Specific settings are as follows: the gear to be formed and gear rollers are standard, the modulus is 1, the pressure angle is 20 degree, the thickness of the blank is 4 mm, the blank diameter is acquired according to the principle of equal chord length; a shearing friction model is set on the contact

Table 2 The volume percentage of the total tooth the effective tooth occupies with different materials from the simulation results

Blank material	Al_1100	Al_2017	DIN_C45
The volume percentage of the total tooth the effective tooth occupies (%)	99.92	98.10	97.32

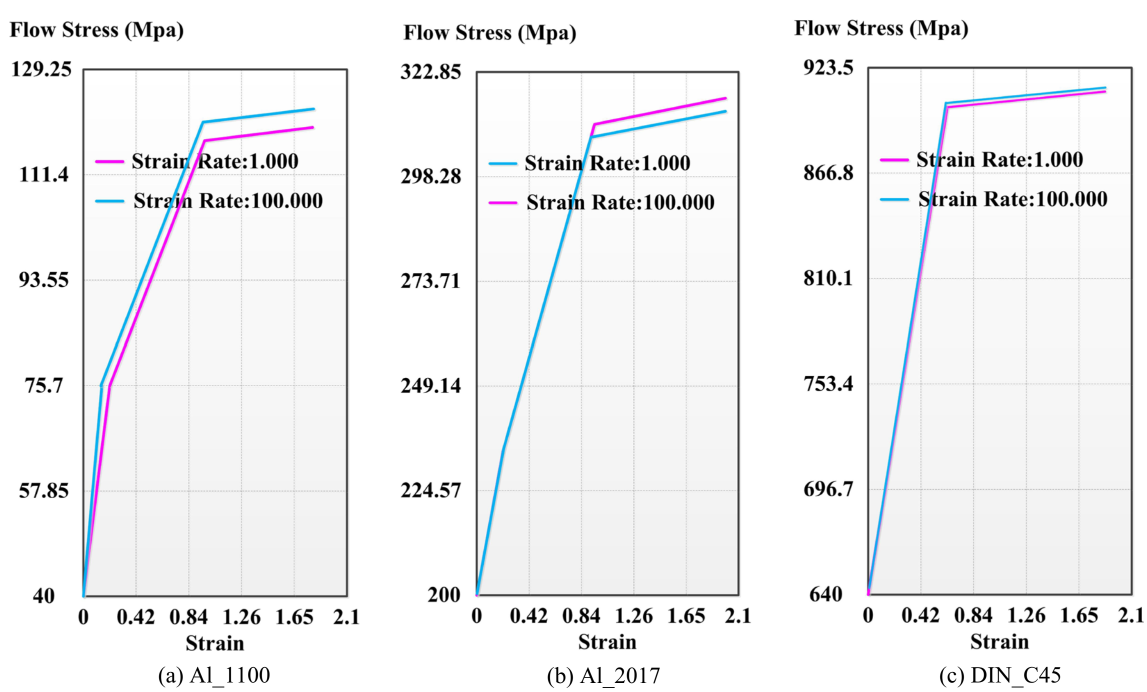
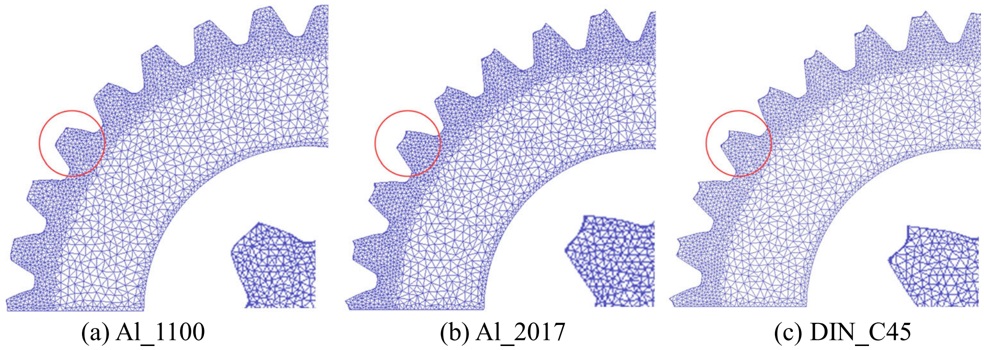


Fig. 5 Constitutive relationship of three different materials. **a** Al_1100. **b** Al_2017. **c** DIN_C45

Fig. 6 The tooth morphology of rolled gear with different blank materials. **a** Al_1100. **b** Al_2017. **c** DIN_C45



surface between the gear roller and the blank, and the friction factor is set as 0.10; because deformation of the metal is centrosymmetric, deformation concentrates in the annular region of the outer circle in the gear rolling process, and the axial deformation is ignored; in order to improve the efficiency of simulation, only the semi annular blank with 1/2 axial thickness and 7 mm radial thickness is simulated, and the symmetry planes are set constraints. The grid number of the blank is set 100 thousand, and the outer circle of 5-mm radial thickness, that is the main deformation region, is refined, and the mesh density ratio is 0.01. In order to prevent axial overflow, rigid baffles are arranged. The rigid gear rollers drive the blank and the slipping is ignored, which can be simplified as the blank is fixed, and the gear rollers rotate and revolve around the center of the blank. The radial feed of gear roller is 0.15 mm/s. The revolution speed of the gear roller is π rad/s, the rotational line speed of the gear roller is ensured equal to the revolution line speed. The geometric relation is shown in Fig. 4.

4 The influence of the material of the blank on the tooth morphology in gear cold-rolling

In this paper, the gear cold-rolling process with Al_1100, Al_2017, and DIN_C45 (material type as shown in Table 2) selected as the material of the blank is simulated, and the tooth morphology of the rolled gear is studied. The constitutive models of three different materials are shown in Fig. 5.

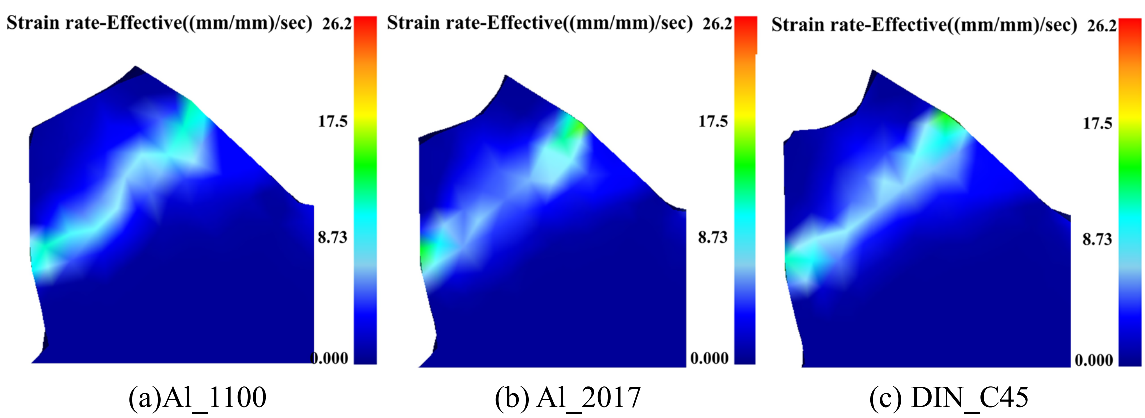
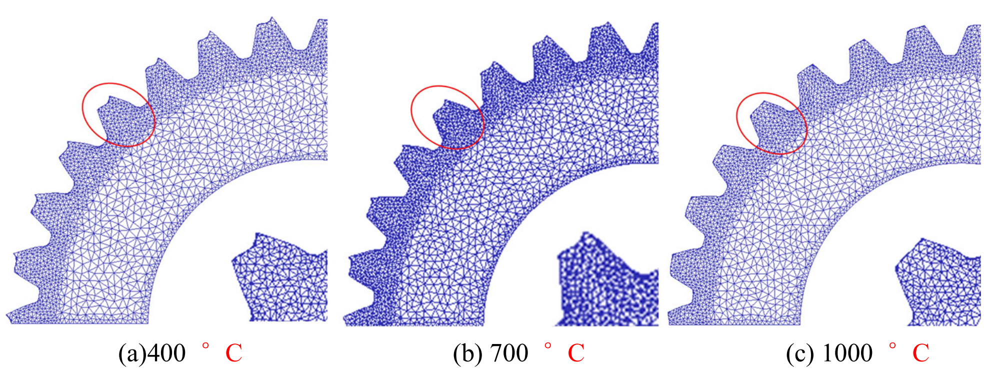


Fig. 7 Equivalent strain rate of rolled gear with different blank materials. a Al_1100. **b** Al_2017. **c** DIN_C45

Fig. 8 The tooth morphology of rolled blanks with DIN_C45 selected as blank material in different forming temperatures. **a** 400 °C. **b** 700 °C. **c** 1000 °C



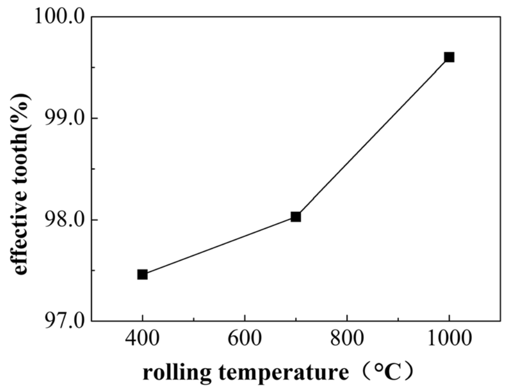


Fig. 9 Changes in the effective tooth volume percentage with different forming temperatures

From Fig. 6, it can be seen, as the feed of the gear roller is 1.00 mm, when the material is Al_1100, the tooth top of the rolled gear is smooth, no obvious protrusions; when the material is Al_2017, there are slight protrusions on both sides of the tooth top; when the material is DIN_C45, obvious protrusions appear on both sides of the tooth top.

Figure 7 is the equivalent strain rate diagram of rolled gear with different materials when the feed of the gear roller is 1.00 mm. As can be seen from Fig. 7, larger deformation exists on the flank of the blank which is extruded by the gear roller, where equivalent strain rate is larger, and the equivalent strain rate decreases towards inside along the normal direction of contact surface. While the difference of the equivalent strain rate between the tooth flank and the inside is smaller, besides metals on the surface, metals inside flow towards the tooth top, protrusions on both sides of the tooth top are smaller, and the proportion of the effective tooth is larger, as shown in Fig. 7a. And with the increase of the difference of the equivalent strain rate, only metals on the surface flow towards the tooth top along the direction of the tooth flank, the deformation of metals inside is smaller, therefore the protrusions are bigger, the rabbit ear is obvious, the proportion of the effective tooth is smaller, as shown in Fig. 7b, c.

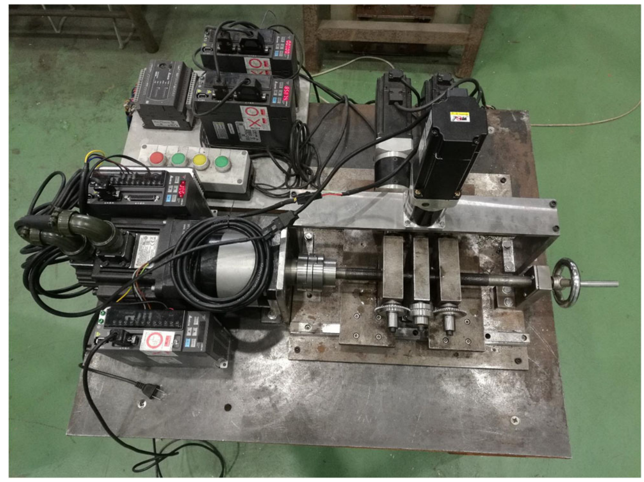


Fig. 11 Gear rolling experimental apparatus

5 Influence of forming temperature on tooth morphology

Metals in different forming temperatures show different statuses; thus, the forming temperature has a direct influence on the tooth morphology. The gear rolling process with DIN_C45 selected as the blank material in different forming temperatures is simulated; the tooth morphology of the rolled gear in different forming temperatures is analyzed.

In order to analyze the effect of the forming temperature on the tooth morphology, the gear rolling process in 400, 700, and 1000 °C is simulated. Figure 8 shows the tooth morphology with the same feed of the gear roller in different forming temperatures. From the figure, it can be seen when the forming temperature is 400 °C, the protrusions on the tooth top are obvious; when the forming temperature reaches 700 °C, the protrusions are not obvious; when the forming temperature is 1000 °C, the protrusions almost disappear. From the tooth morphology of the rolled gear, we can see that with the increase of forming temperature, the volume of the protrusions decreases, and the proportion of the effective tooth volume gradually increases.

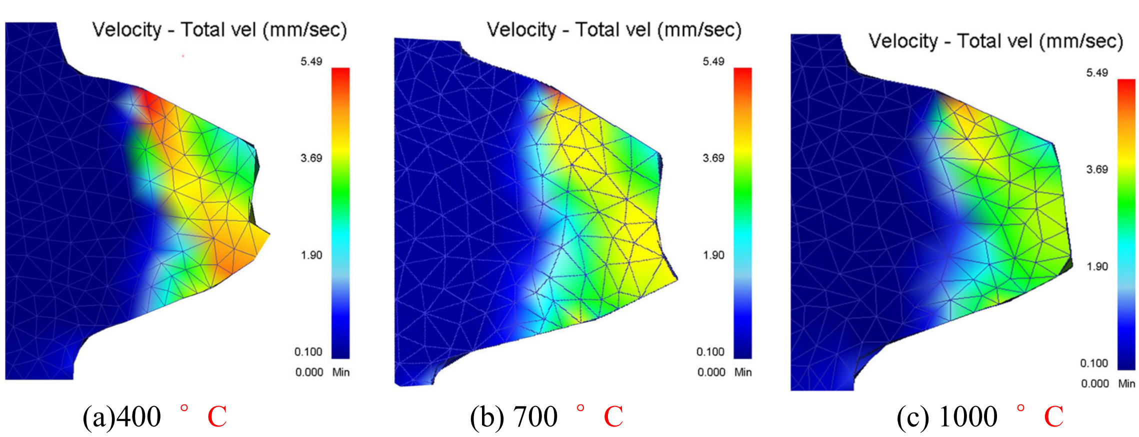


Fig. 10 Isochromatic image of velocity field of the rolled blank in different forming temperatures. **a** 400 °C. **b** 700 °C. **c** 1000 °C

Fig. 12 The tooth morphology of the specimen with different materials. **a** Al_1100. **b** Al_2017. **c** Lead

The simulation results, that is, the volume percentage of the total tooth the effective tooth occupies as a function of the forming temperature is shown in Fig. 9.

It can be seen from Fig. 9 that with the increase of the forming temperature, the volume percentage of the total tooth the effective tooth occupies increases. Figure 10 is the isochromatic image of velocity field when the feed of the gear roller is 1.00 mm in different forming temperatures. It can be seen from Fig. 10, when the forming temperature is lower, the flow velocity of the metal on the right side of the top tooth is faster than that in the center and on the left side of the tooth top, leading to protrusions on the right side of the tooth top, that is the rabbit ear, as shown in Fig. 10a; with the increase of the forming temperature, the difference of the velocity gradually decreases, so the aggregation of metal on the right side of the tooth top diminishes, the right rabbit ear is smaller, as shown in Fig. 10b; when the temperature is increased to 1000 °C, the velocity is consistent, no protrusions form on the tooth top, no rabbit ear appears, as shown in Fig. 10c. It can be explained by the principle of the plastic yield area variation with the temperature. When the forming temperature is lower, the hardness of the materials is higher, only the metal on the surface yields to deform, the fluidity of the metal on the surface of the flank is better, therefore, much more metals flow to the two sides of the top tooth, and the fluidity of the metal in the center is poor, less metals flow to the center of the tooth top, the rabbit ear forms, the volume percentage of the total tooth the effective tooth occupies is smaller; when the forming temperature is higher, the hardness of the metal is lower, deformation zone extends from the interface to the inside, the fluidity of all the metals in the tooth is better, the same amount of metals flow to two sides of the tooth top and to the center of the tooth top, therefore, there is not metal gathering on the tooth top, no obvious protrusions appear, the rabbit ear is small or disappearing, the volume percentage of the total tooth the effective tooth occupies is larger.

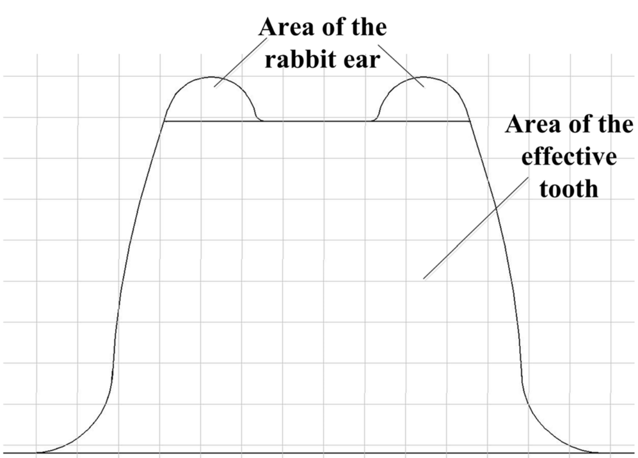


Fig. 13 The diagram of the tooth area acquired with the mesh tool in Flash software

As we all know, the hardness of DIN_C45 decreases gradually with the increase of the forming temperature. As can be seen from Fig. 9, with the increase of the forming temperature, the hardness of the blank decreases, the volume percentage of the total tooth the effective tooth occupies increases. At room temperature, in order of their hardness, Al_1100 is the least, and Al_2017 is second to Al_1100, while DIN_C45 is the most [13, 14]. As can be seen from Table 2, the volume percentage of the total tooth the effective tooth represent decreases gradually with the increase of hardness of material. Therefore, from simulation results of different blank materials and different forming temperatures, we can draw the following conclusion: in the gear rolling process, the volume percentage of the total tooth the effective tooth occupies has the tendency of increasing with the decrease of the blank's hardness. The above conclusion is further analyzed from the

Table 3 The volume percentage of the total tooth the effective tooth occupies with different materials in experiment

The specimen material	Al_1100	Al_2017	Lead
The volume percentage of the total tooth the effective tooth occupies (%)	99.56	92.22	99.92

mechanism of the rabbit ear. In the gear rolling process, the surface metal on the tooth flank is extruded by the gear roller and flows towards the two sides of the tooth top based on the principle of least resistance. The difference of flow velocity between the two sides of the tooth top and the center results in the formation of the rabbit ear [11]. When the hardness of the material is smaller, the inner metal will also deform and flow when the tooth flank is extruded by the gear roller, the difference of the velocity between the surface metal and the inner metal is smaller, so the volume percentage of the total tooth the effective tooth occupies is larger. On the other hand, when the hardness is larger, the fluidity of the inner metal is poor, and the difference of the velocity is larger, which leads to larger rabbit ear, the percentage of the total tooth the effective tooth occupies is smaller.

6 Experiments

Based on the principle of gear rolling, a set of gear rolling experiment device with double gear rollers is designed and processed, as shown in Fig. 11. The roll force provided by the experimental device is limited, no heating equipment; therefore, only the specimen of Al_1100, AL_2017, and lead whose property is similar to that of DIN_C45 in hot forming are rolled at room temperature. Experimental conditions are set as follows: the number teeth of the gear roller is 51, the number teeth of the gear to be formed is 31, both the modulus are 1, the pressure angle are both 20 degree, the rotation speed of the gear roller is set as 18 r/min corresponding with the simulation, the feed speed of the gear roller is 0.15 mm/s, the tooth morphology is observed while the feed of the gear roller is 1.00 mm.

As shown in Fig. 12, from the photos of the specimens, it can be seen, while the material is Al_1100, the tooth top is smooth; while the material is Al_2017, protrusions appear on both sides of the tooth top; the tooth morphology of rolled gears with Al_1100 and Al_2017 selected as material in the experiment is consistent with that in simulation. When the material is lead, the tooth top of the specimen is flat, and there is no protrusion on both sides, which is consistent with the simulation result of DIN_C45 in hot rolling. By Flash software, the photos of the specimens are imported into the software, a single tooth is cut out using the cutting tool, as shown in Fig. 13, the area of the rabbit ear and the effective tooth of every tooth is estimated with the mesh tool, so as to obtain quantitative values of the filling rate with different materials, as Table 3 shows. It can be seen from the result of the experiment, three kinds of materials, with the increase of the hardness, the volume percentage of the total tooth the effective tooth occupies decreases, which is consistent with the simulation result.

7 Conclusions

According to the motion relationship between the gear rollers and the blank in gear rolling, the numerical model of gear rolling is established, the gear rolling process is simulated with different metals selected as blank material such as Al_1100, Al_2017, and DIN_C45. The gear rolling process of DIN_C45 in different forming temperatures is simulated too. And the gear rolling process is studied experimentally. The corresponding conclusions are as follows:

1) The tooth filling rate as the quantitative evaluation index of the tooth is established in gear rolling, that is, the ratio of the effective tooth volume to the total tooth volume should first be worked out, and then the average value of the ratio from all the forming teeth is used as an index to evaluate the tooth morphology;
2) The simulation result of gear cold-rolling with different metals shows that when Al_1100, Al_2017, and DIN_C45 is selected as the blank material in turn, the volume percentage of the total tooth the effective tooth occupies gradually decreases;
3) The simulation result of gear rolling in different forming temperatures shows that when DIN_C45 is selected as the blank material, with the increase of the forming temperature, the volume percentage of the total tooth the effective tooth occupies increases;
4) From the simulation results of different materials and different forming temperatures, it can be seen that the volume percentage of the total tooth the effective tooth occupies increases with the decrease of the hardness of the blank material;
5) The gear rolling experiment shows that when Al_1100 and Al_2017 is selected as the blank material in turn, the volume percentage of the total tooth the effective tooth occupies decreases, which is consistent with the simulation; when lead is selected as the blank material, the rabbit ear is small, the volume percentage of the total tooth the effective tooth occupies accounts for 99.92%, which is consistent with the simulation result of DIN_C45 in hot rolling; the volume percentage of the total tooth the effective tooth occupies in experiment also increases with the decrease of the hardness of the metal, which is consistent with the simulation.

Funding information This project was supported by the National Natural Science Foundation of China (Grant No. 51475271 and No. 51775311).

References

1. Ohga K, Kondo K (1982) Research on precision die forging utilizing divided flow: first report, theoretical analysis of processes utilizing flow relief-axis and relief-hole. Bull JSME 25:1828–1835
2. Tuncer C, Dean TA (1987) Die design alternatives for precision forging hollow parts. Int J Mach Tools Manuf 27:65–76
3. Choi JC, Choi Y (1999) Precision forging of spur gears with inside relief. Int J Mach Tools Manuf 39:1575–1588
4. Jung SY, Kang MC, Kim C, Kim CH, Chang YJ, Han SM (2009) A study on the extrusion by a two-step process for manufacturing helical gear. Int J Adv Manuf Technol 41:684–693
5. Kondo K, Ohga K (1995) Precision cold die forging of a ring gear by divided flow method. Int J Mach Tool Manu 35:1105–1113
6. Kou SQ, Yang SH, Huang LJ, Fu PF (1999) Research on net-shape forming of spur gears. Hot Work Technol 29–31
7. Zhu XX, Wang BY, Fu XB (2016) Influencing factors for tooth tip pulling of hot roll forming gear. J Shenyang Univ Technol 38:410–415
8. Zhu XX, Wang BY, Yang LY, Zuo B, Li Z (2014) Effect of relative sliding on tooth profiles metal flow during gear roll forming. J Univ Sci Technol Beijing 36:246–251
9. Wang GC, Li J (2015) A gear rolling method for improving the defect of the rabbit ear. Patent. China. CN104438993A
10. Kamouneh AA, Ni J, Stephenson D, Vriesen R, DeGrace G (2007) Diagnosis of involute metric issues in flat rolling of external helical gears through the use of finite-element models. Int J Mach Tools Manuf 47:1257–1262
11. Li J, Wang GC, Wu T (2017) Numerical-experimental investigation on the rabbit ear formation mechanism in gear rolling. Int J Adv Manuf Technol 91:3551–3559
12. Li J, Wang GC, Wu T (2017) Effect of process factors on the rabbit ear based on numerical simulation and experimental study in gear rolling. Int J Adv Manuf Technol 94:4055–4064
13. Lin G, Lin HG, Zhao YT (2006) Aluminum alloy application manual [M]. China machine press
14. Teng CC (2010) Iron and steel manual [M]. Standards Press of China