A New Successive Forming Process for Large Modulus Gears

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Abstract

A successive tooth forming process for producing large modulus spur gears ($m \geq 2.5$ mm) was firstly proposed in this paper to break the restrictions of large forming load and large equipment structure of traditional plastic forming. It contains the preforming stage and finishing stage. In the first stage, the die with a single-tooth preformed gear teeth one by one through several passes. In the second stage, the other die with multi-teeth refined the preformed teeth into required shape. The influence of total pressing depth and feed distribution in preforming stage on final forming quality was analyzed by numerical simulation and the reasonable process parameters had been presented. Gears without fold defects were well formed both in simulations and experiments, proving the feasibility of this method. The new process has advantages of smaller forming load and simpler tooling set, which shows a good potential for manufacturing large modulus spur gears.

1 Introduction

Gears are widely used in the transmission of mechanical devices due to their superiorities of high efficiency, compact structure and stability. Modulus of a gear indicate the size of gear teeth. Generally, the gear with the modulus larger than 2.5 mm is called a large modulus gear [1], which is difficult to manufacture for its large dimensions. As one of the primary manufacturing method for large modulus gears, cutting process has weaknesses of low material utilization rate, discontinuous material fiber and poor mechanical properties. Gear shaving is a high-efficiency process on gear work, but the tooth profile concave error of it is difficult to eliminate and has been one of the main factors causing vibration and noise of the gear transmission [2]. The gears produced by sintering process have good dimensional accuracy and surface roughness [3]. But sintering has inherent technical limitations, resulting in lower density of the sintered gears especially the large gears, which seriously affects the mechanical properties of gears such as strength and hardness. Advanced plastic forming methods, such as precision forging and extrusion forming, are capable of achieving high production efficiency as well as good mechanical properties of products which have complete material fiber [4]. However, the large forming load in plastic forming brings lots of unavoidable problems, including the difficulty of mold unloading, the insufficient filling of teeth corner, the short service life of dies and so on.

Researches on reducing forming load in precision forging has been carried out for many years, the main methods of which were divided flow and floating die process [5]. Kondo and Ohga [6] applied the process of dividing material flow to produce ring gears and it was proved to be accuracy and efficiently. Alves et al. [4] developed a flexible tool system for performing cold forging of gear parts based on finite element method, tool design and experimental expertise. Ohga et al. [7] examined the optimum process parameters combination of a two-step precision forging method to enlarge the possibility of applying the process utilizing divided flow with intention of reducing the contact pressure. Relief-cavities with different sizes on the top of die teeth which were used in hot precision forging to promote metal filling were designed [8]. For the same purpose of reducing the difficulty of material filling of gear teeth, Tan et al. [9, 10] promoted the precision forging process and put forward an improved scheme combined with floating die structure based on the theory of restrained divided-flow, which could ensure the decrease of forming load and acquire standard gear teeth.

Gear rolling is a method of partial loading and local deformation which have advantages including low forming force, high material utilization and good surface strength of gears. At present, cold rolling process is only appropriate for small modulus tooth-shaped gears or splines on account of the work hardening phenomenon of metals [11]. Wang et al. [12] studied the problems of non-uniformity teeth graduation in initial forming phase and formation of rabbit ears in later forming stage. Afterwards, Li et al. [13, 14] investigated the main factors affecting slippage problem and analyzed the formation mechanism of rabbit ear, which provided a scientific basis to further explore of controlling rabbit ear defects. Then, a gear rolling process using conical gear rollers was proposed, in which the axial feed applied on the blank replaced the radial feed applied on the roller, achieving better uniform tooth graduation and refining [15]. Landgrebe et al. [16] employed a cross-rolling process characterized by round tools with outer gearings to achieve hot rolling of large spur gears and mathematically analyzed the forming force and momentum to determine the forces and torques required here.

Merklein et al. [17] presented a new approach for the direct forming starting from blanks named “Sheet-Bulk Metal Forming (SBMF)”. The material flow which concern the geometric accuracy and the form filling in SBMF was enhanced by a local increase of the friction as well as the process adapted blanks [18]. Sieczkarek et al. [19] characterized the plastic flow and proposed a closed-form analytical framework to estimate the through-thickness pressure and force in sheet-bulk indentation. An incremental gear forming process by means of double-wedge gear tooth punch was provided [20]. Then, his group analyzed the differences between incipient and repeatable material flow in incremental SBMF of gears, and investigated three influencing factors aiming for a formfilling progress of the first tooth element and an improvement of the teeth heights[21, 22].

The existing cold rolling and no-flash precision forging process are limited by plastic deformation and forming load restrictions in the manufacture of large modulus spur gears. Strong strain hardening during cold working also hinders the application of SBMF. In comparison, these problems can be effectively solved by hot-working and partial-molding methods. Thus, a successive tooth forming process is proposed based on the hot rolling and SBMF, which can form gears by a certain number of rational-pressing passes in the heated state. This process has superiorities of smaller forming load, higher material utilization, simpler tooling set and better mechanical properties of formed gears such as bending fatigue strength, showing a good potential in fabricating large modulus spur gears, especially for those with large axial dimensions.

Finite element method (FEM) was applied to study the influences of total pressing depth and distribution of per-pass feed in the preforming stage on final forming quality. The optimal process parameters were defined by numerical simulations, and the experiments were conducted to verify the feasibility of this newly proposed forming process.

2 Method

2.1 Principle of the successive tooth forming process

The successive tooth forming process includes preforming stage and finishing stage using two different dies, as shown in Fig. 1. The preforming die is designed to be a single-tooth structure whose profile is in accord with the tooth space of the formed gear. The finishing die is similar to the preforming one, but the single-tooth is replaced by the multi-tooth structure. In the preforming stage, the die firstly presses a certain depth into the billet across radial direction and then returns to the initial position. Secondly, after the billet rotates an angle which equals to 360°/z, the die repeats the aforementioned pressing process. The gear teeth will be formed successively through the multi-pass pressing mode. Finally, in the finishing stage, the die with multi-tooth structure is applied to finish the tooth profile following the same procedure. Compared with the double-wedge gear tooth punch designed by Sieczkarek et al. [20], the single-tooth preforming die will put less constraints on the deformation area. At the same time, however, the forming accuracy of single-tooth die is lower than the double-wedge one, requiring multiple passes to be finished.

2.2 Numerical modelling

The successive tooth forming process was numerical simulated by means of Deform-2D. Effects of the pressing depth and the distribution ratio of per-pass feed on the final forming quality were analyzed. Moreover, the reasonable process parameters were presented according to the simulation results.

Table 1 shows the parameters of the formed gear in numerical simulations. Without considering the axial flow of the materials, the deformation process is studied as a two-dimensional plane strain problem and calculated by the sparse solver in all simulations.

Table 1
The basic parameters of the formed gear in FEM model

Modulus m (mm)	Number of teeth z	Reference diameter d (mm)	Pressure angle α (°)	Addendum coefficient h_a*	Crest factor c*	Face width b (mm)
3	45	135	20	1	0.25	13.5

The billet material is selected as AISI-1045 steel and its flow behavior follows the plastic law. According to the constant-volume principle, the diameter of the cylindrical billet is calculated to be 134.58 mm, but it is designated to be 135 mm finally considering leaving a certain working allowance, which is exactly equals to the pitch diameter of the formed gear. The billet is designed to a circular ring shape since the deformation occurs only in its outer part. In addition, due to the symmetry of billet geometry and deformation, 1/15 of the billet (a region including three teeth) is selected as the model to further improve the simulation efficiency. The billet is divided into 10,055 relative elements and the elements of the outer part are partially refined in proportion to 3:1.

To obtain the tooth profile of the preforming and finishing dies, Boolean cutting operations from the formed gear are conducted respectively in CAD software. Two wing structures are designed on both dies to limit the excessive flow of materials.

The initial billet temperature is set to 1100℃,a typical hot forming temperature for steel materials. There are no contact heat conduction at any interfaces. The friction coefficient is 0.3 in the shear friction model between the dies and the billet since this process is in the category of hot forging. In order to further simplify the simulation constraints, a frictionless V-shape groove is employed to limit the undesirable flow of the materials on the inner circle and symmetric sides of the billet. The radial feeding velocity of the dies is selected as 6 mm/s [23]. Figure 2 shows the established FEM simulation model.

3 Results And Discussion

3.1 Influence of total pressing depth of preforming on forming quality

In the preforming stage, the total press-in depth of the single-tooth preforming die has important impact on the quality of subsequent finishing stage. Theoretically, the total pressing depth should be 1.25 times of the formed gear's modulus *m*. But considering the deformation allowance for finishing stage, the preforming depths are set as 1.35, 1.25, 1.15 times of the modulus *m* (marked as Scheme 1–1, 1–2 and 1–3) to find out the optimal procedure. Since the modulus *m* is 3 mm in this study, the preforming depths are 4.05 mm, 3.75 mm, 3.45 mm respectively. The preforming stage of each condition is equally divided into 10 passes, and there is no fold in every pass.

Figure 3a-c shows the partial enlarged teeth during the finishing stage in Scheme 1–1. It can be seen that the shapes of the two teeth tend to be complete. However, the root area has not been fully filled and severe fold which the thickness is 0.22 mm appears here. Fold defect leads to the degradation of dimensional accuracy and surface quality, even causes cracking in the root area as a potential crack source. The thickness is the measurement index for fold [24]. The forming reason of fold defects are analyzed as follows. The larger preforming pressing depth leads to the overlong teeth, thus in the following finishing stage, the addendums has formed a standard shape earlier while the dedendums still has not be completely filled. Materials on both sides of the teeth is seriously squeezed by the finishing die and accumulates towards the root, leading to a severe confluence fold.

Figure 3d-f shows the partial enlarged teeth during the finishing stage in Scheme 1–2. It can be seen that both addendum and dedendum areas are well filled almost simultaneously, whereas the confluence fold at dedendum still existed for the same reason as that of Scheme 1–1. However, the fold is very thin with a thickness of 0.03 mm. It could be ignored in view of the reserved working allowance of the billet.

Figure 3g-i shows the partial enlarged teeth during the finishing stage in Scheme 1–3. It is evident that both sides of the tooth are less squeezed by the finishing die, the accumulation of metal towards root direction is not obvious and no fold appears in the whole finishing process.

The simulation results reveal that the preforming pressing depth should be between 1.15 to 1.25 times of the modulus *m*. In order to reserve a little deformed allowance for the finishing stage, the preferred preforming pressing depth could be set to 1.20 *m*.

3.2 Influence of the per-pass forming depth on the final quality

In the preforming stage, the deformation process is completed by several feeding passes. The forming depth in each pass has important influences on the final forming quality and efficiency.

Based on the simulation results above, the preforming pressing depth is set as 3.60 mm (1.20 times of the modulus *m*). Since the total feed is determined, the per-pass feed is negatively correlated between the numbers of passes. A large feed will cause the two adjacent teeth to interfere with each other's forming process. In addition, it will be more likely to generate fold defects. Thus the feed amount in each pass has an upper limit. The influences of the feed distribution on forming quality and efficiency are analyzed in two different distribution ways.

3.2.1 The uniform forming depth in per-pass

The total preforming feed value was equally divided in the four different schemes as listed in Table 2, together with the simulation parameters and results. The less the number of passes is, the severer the fold defects are. No fold defect occurs under the condition of 6 passes. While the number of passes is 5 or 4, the fold defects only appear in the finishing stage. And when the number of passes is 3, the fold defects generate at the third pass in the preforming stage. It indicates that the folding defects is more likely to occur at the later period during the whole forming process.

Table 2
Simulation parameters and results of different distribution schemes

Scheme No.	Number of passes	Per-pass feed value (mm)	Forming results
2 – 1	6	0.60	Tooth shape is accurate without fold.
2–2	5	0.72	Severe fold appears in the finishing stage.
2–3	4	0.90	Severe fold appears in the finishing stage.
2–4	3	1.20	Severe fold appears in the third pass and finishing stage.

The cause of folding in these schemes is similar. Figure 4 shows the formation of fold in the third pass of Scheme 2–4. A large feed leads to the inward bending of two adjacent teeth. Therefore, the tooth space become smaller, as can be seen from Fig. 4a. When the preforming die presses into the smaller tooth space at the next pass, the materials on the side of the bended teeth will be squeezed into the dedendum.

These materials accumulate in the dedendum and form fold defects, as shown in Fig. 4b. When the feed in each pass is small, the deformation process is similar to the traditional gear rolling. Although tooth bending and fold defects can be avoided, the forming efficiency will be decreased. Therefore, it is not appropriate to adopt the uniform forming depth method in the preforming stage.

3.2.2 The degressive distribution of the feed

When the feed is evenly distributed, it requires at least 6 passes to obtain a gear with an accurate shape. According to the forming results of Scheme 2–3, no fold occurs in preforming, but severe fold appears in finishing stage resulting from the too large feed in the last preforming pass. Thus it is better to reduce the feed value in the later passes while increase it in the initial passes, that is, the feed distribution should follow a degressive rule.

Four different feed distribution schemes following the degressive rule were designed and simulated to find out the optimal distribution ratio, as listed in Table 3. The last pass should have a small feed for reducing the tilt of gear teeth, which is beneficial to the finishing forming quality. Among the four schemes, Scheme 3 – 2 has the best forming results while others all have different degree of fold defects. Simulation results of each preforming pass and finishing stage in Scheme 3 – 2 are shown in Fig. 5. It is worth noting that the teeth are formed in a clockwise sequence beginning with the intermediate dedendum, the upper dedendum is eventually formed and causes the intermediate dedendum to be squeezed again and narrowed. Gears could be precisely shaped by merely 4 passes in degressive rule, the forming efficiency is improved obviously comparing with the uniform distribution way.

Table 3
Per-pass forming depth and the simulation results of the final quality

Scheme No.		Steps of passes				Forming results
		1	2	3	4	
3 – 1	Feed (mm)	1.62	0.90	0.72	0.36	Large fold forms in the third pass and still present in the subsequent process.
	Ratio (%)	45	25	20	10	
3 – 2	Feed (mm)	1.80	1.08	0.54	0.18	The teeth profile is accurate without fold.
	Ratio (%)	50	30	15	5	
3–3	Feed (mm)	1.98	0.90	0.54	0.18	Small fold forms in the second pass and still present in the subsequent process.
	Ratio (%)	55	25	15	5	
3–4	Feed (mm)	1.98	1.26	0.36		Severe fold forms in the second pass and still present in the subsequent process.

4 Experimental Verifications

Successive tooth forming experiments were carried out on the gear forming device shown in Fig. 6. The experiments aimed to verify the optimal simulation results of the successive tooth forming process. Due to the limitation of the experimental equipment and conditions, lead was selected as the billet material instead of the steel AISI-1045. The flow behavior of lead in room temperature is similar to that of steel in the stage of hot forming. The parameters of the formed gear are consistent with those in the simulations. In order to prevent the billet material from flowing along the axial direction, two baffles are applied out of both end faces of the billet.

Figure 7 shows the experimental process of preforming stage and finishing stage. According to the optimal numerical simulation's results, the process parameters of Scheme 3 – 2 were applied in the experiment. The detailed procedure is listed in Table 4.

Table 4
The feeding values in each preforming pass and finishing stage

	Total feed (mm)	Steps of passes	Feed per pass (mm)
Preforming stage	S_P = 1.20 m = 3.60	1	S_{P1} = 50% S_P = 1.80
		2	S_{P2} = 30% S_P = 1.08
		3	S_{P3} = 15% S_P = 0.54
		4	S_{P4} = 5% S_P = 0.18
Finishing stage	S_F = 0.05 m = 0.15		

The sample configurations of each pass in preforming stage are shown in Fig. 8, while the 3D solid model of the finally formed gear is shown in Fig. 9a. The solid model was acquired by encapsulating the point cloud data obtained by scanning the sample using 3D laser scanner EinScan-pro. The sample and a standard gear were put into the Geomagic Qualify 2013 software for analysis, and the dimensional deviation nephogram of the sample is shown in Fig. 9b. A positive value in the scale represents that the size is smaller than the standard value. The teeth are evenly distributed basically. The incremental SBMF of gears designed by Sieczkarek et al. [21] was focused on evaluating the influence of material sideway spread on the evolution of the load with displacement, so its blank holders were used to position the sheet but didn't impose constraints on the forming area of the edge of the blank, however, the baffles here are designed to prevent the widening of end faces. Due to the restriction of experimental conditions, the baffles are not thick enough to work effectively. Therefore, the axial thickness of the sample's edge areas is larger and the radial size is a little smaller than the standard values shown in Fig. 9b. As measured by Geomagic Studio software, the addendum circle diameter is 138.64 mm, smaller than the standard value of 141 mm, and the axial thickness of the edge areas is 1.26 mm thicker than the standard value of 13.5 mm.

Figure 10 shows the complete and detailed tooth profile of the sample obtained from simulations and experiments. The experimental gear profile and its dimensional deviation with a standard tooth were obtained from the 3D solid model. Average tooth height and average tooth width of the sample are 6.63 mm and 4.70 mm, smaller than the standard value of 6.75 mm and 4.71 mm, respectively. The addendum is not completely filled on account of that the material flows in the axial direction and produces end faces widening or flashing. This phenomenon can be avoided in actual production by strengthening the baffles to prevent end face widening, deepening the groove areas of the finishing die to insure the full filling of addendums with a reasonable working allowance. The tooth is slightly tilted, which is caused by the uneven tooth graduation as a result of the equipment's insufficient precision. Nonetheless, the accuracy of the tooth graduation can be improved by Programmable Logic Controller (PLC) system and other methods in the industrial manufacture easily.

Figure 11 shows the verification result of fold caused by unreasonable preforming feed distribution, taking the above Scheme 2–4 as an example. Only four consecutive teeth were formed to represent the whole gear for simplifying the experiments. When the blank was preformed clockwise to the middle dedendum, a large folding defect resulting from the accumulation of side materials could be observed, which is in good agreement with the simulation results shown in Fig. 4.

In summary, although the successive forming model hasn't been verified for steel samples, the current experimental results are in good consistent with those in simulations. The proposed successive tooth forming process for large modulus spur gears is basically feasible and has potential application prospect in the future.

5 Conclusions

A successive tooth forming process for manufacturing large modulus spur gears was proposed in this paper. Different total preforming pressing depths were designed and the effects on the final forming quality at the finishing stage were analyzed by FEM. Successive tooth forming experiments were carried out utilizing lead samples. Based on the FEM and the experiential results, the following conclusions can be reached:

(1) The new forming process was divided into preforming and finishing stages, and the preforming stage included several cyclic passes. Different dies were designed severally according to their functions in this process.

(2) It was found from the numerical simulations that the reasonable value of preforming pressing depth was 1.20 times of the formed gear's modulus m. Feed distribution in the preforming stage should follow the degressive rule. The optimal feed distribution scheme were presented, that is 50%, 30%, 15% and 5% of the total preforming pressing depth in turn.

(3) Complete gear profile and teeth shape without fold defect could be obtained experimentally by adopting the optimal scheme in FEM. The experiment results were consistent with that of the simulations,

showing the feasibility and potential practicality of the successive tooth forming process for large modulus spur gears.

Declarations

Availability of data and materials

The raw date and processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Competing interests

The authors declare no competing financial interests.

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Authors' contributions

GW was in charge of the whole trial; YL conceived the idea and completed most of the research work, then wrote the manuscript; TW guided the verification experiments. All authors read and approved the final manuscript

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Figures

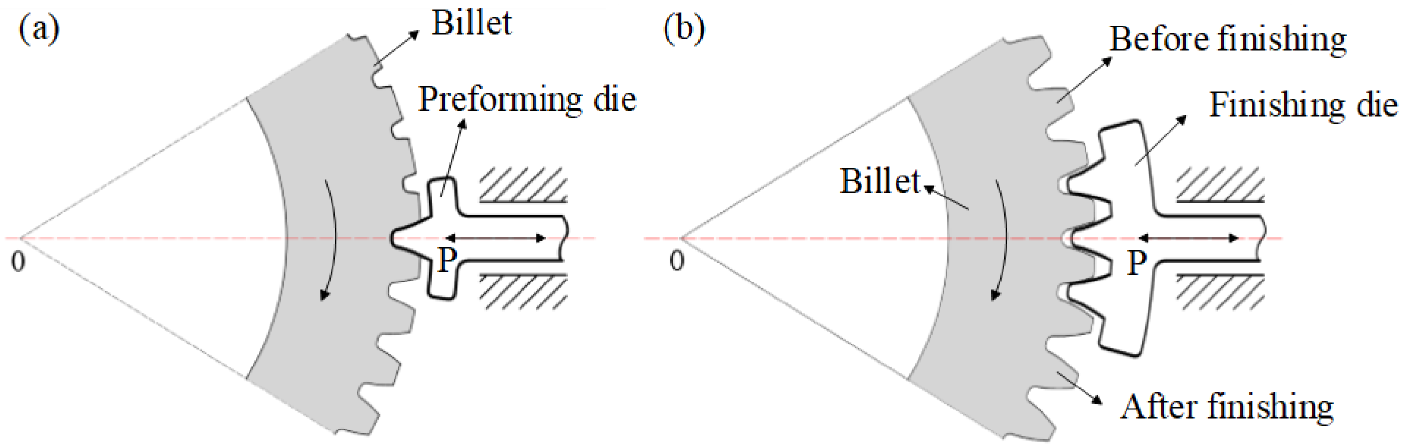

Figure 1

Principles of two stages: a preforming stage and b finishing stage

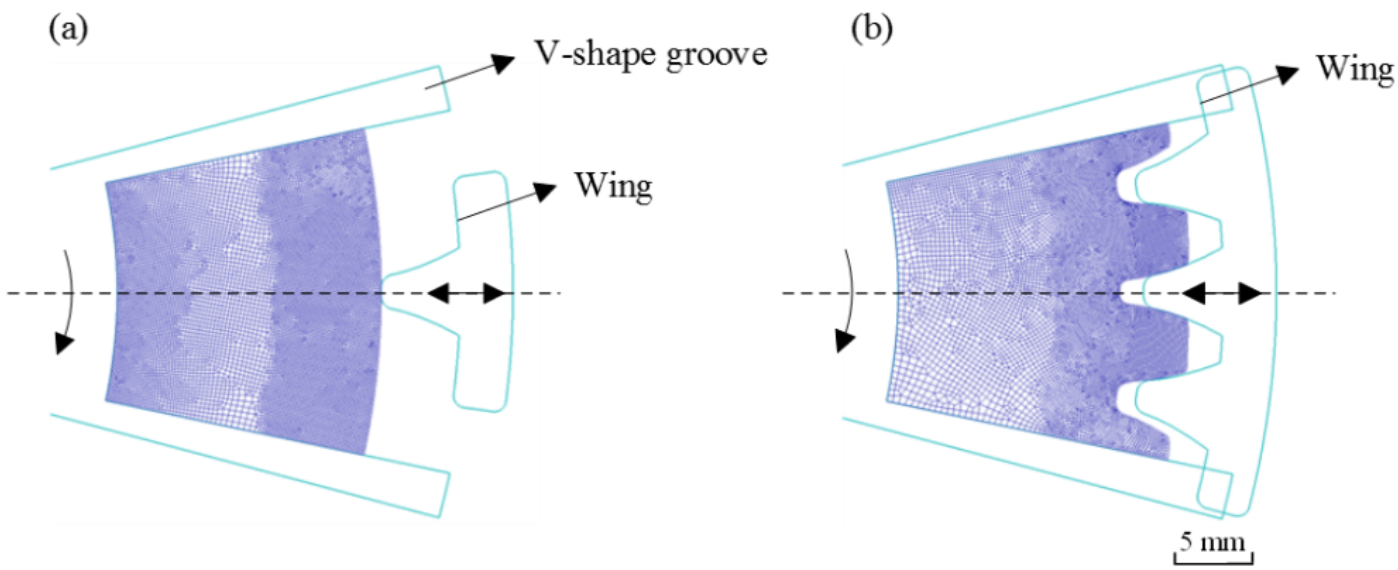

Figure 2

FEM models of two stages: a preforming stage and b finishing stage

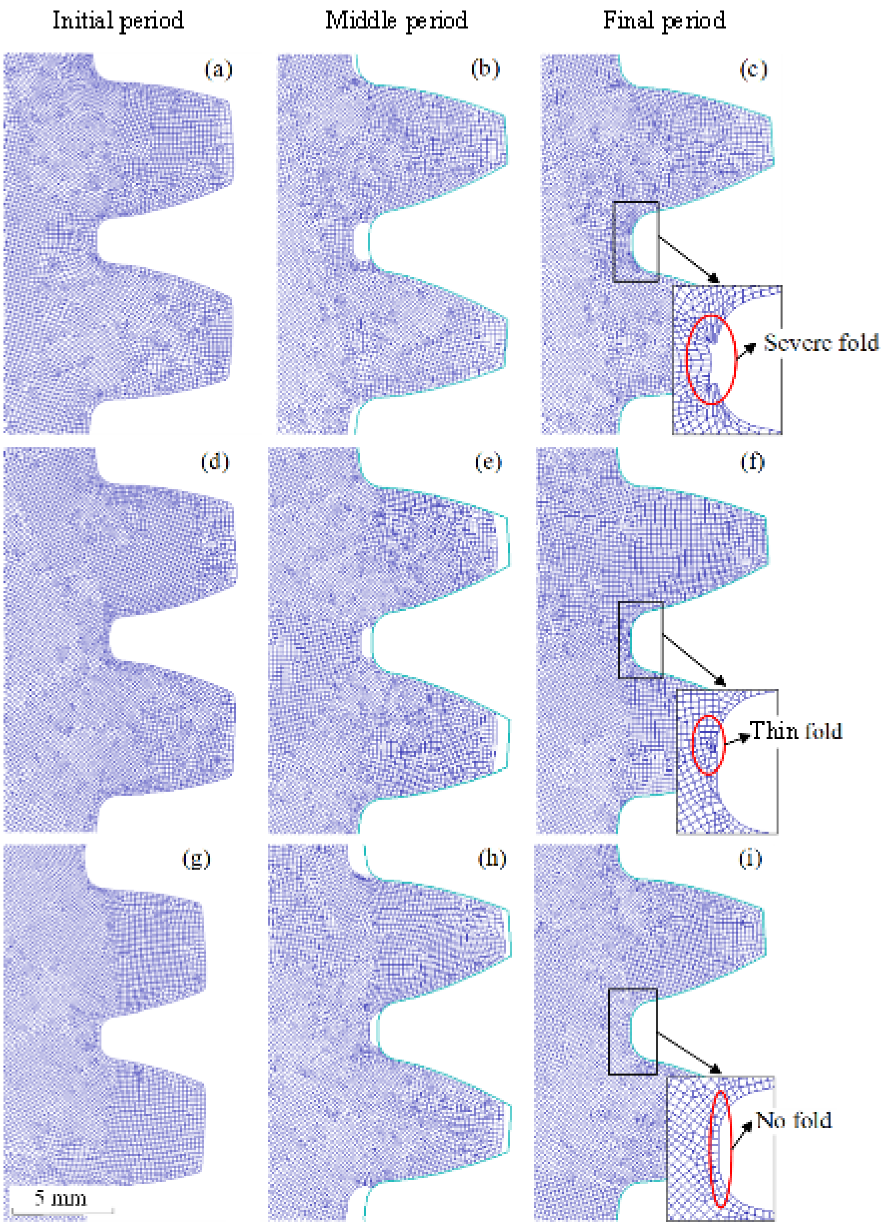

Figure 3

Partial enlarged details of different periods in finishing stage of a-c Scheme 1-1, d-f Scheme 1-2 and g-i Scheme 1-3

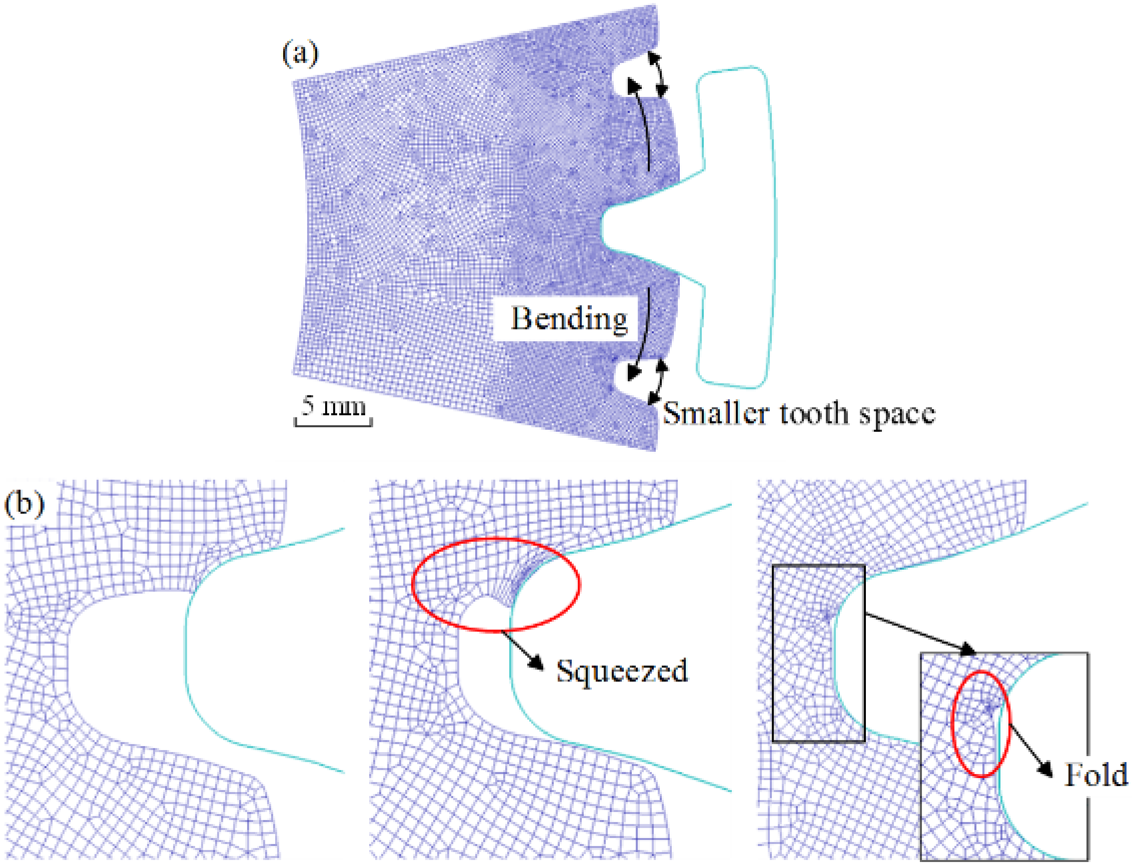

Figure 4

Partial enlarged details of different periods in finishing stage of a-c Scheme 1-1, d-f Scheme 1-2 and g-i Scheme 1-3

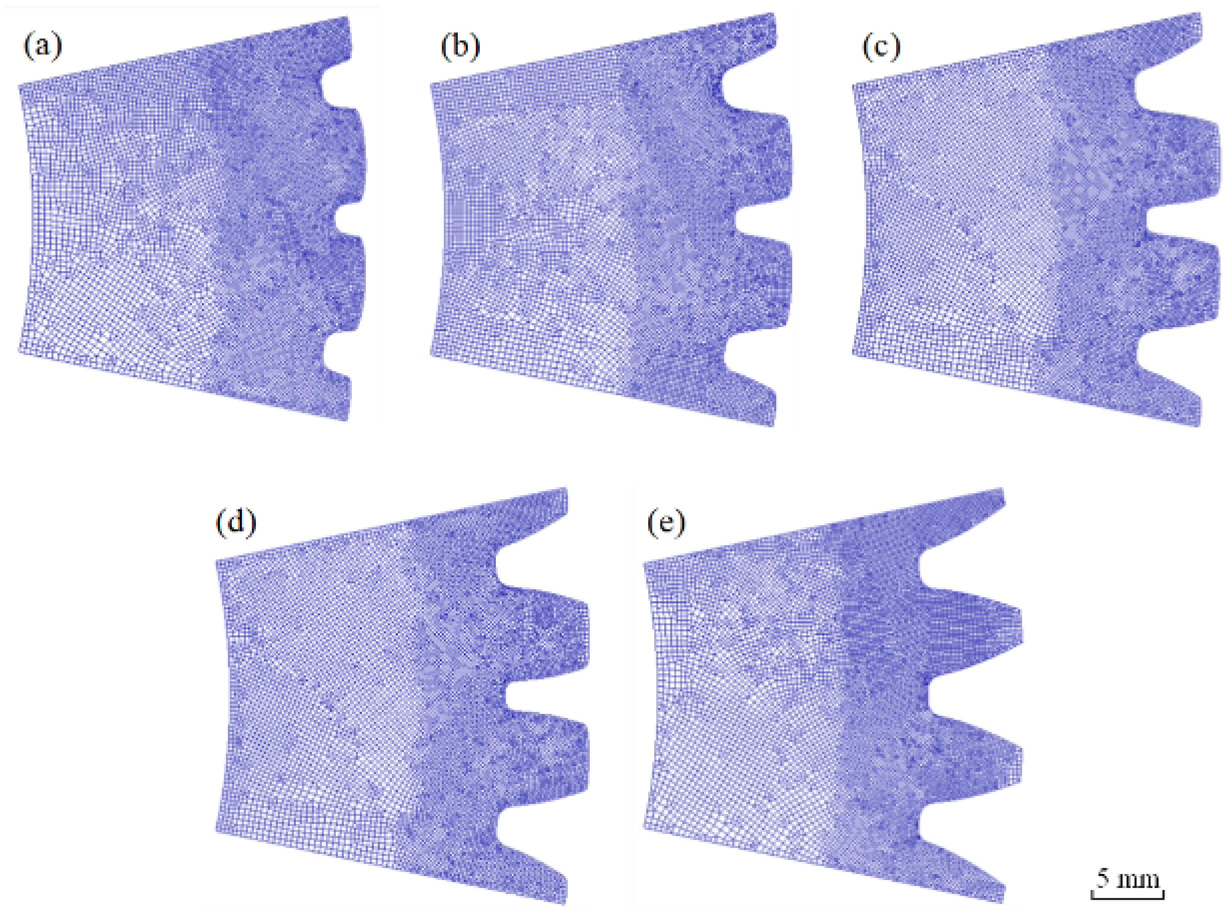

Figure 5

Simulation results of every pass in Scheme 3-2: a pass 1, b pass 2, c pass 3, d pass 4 and e finishing

Figure 6

Experimental setup

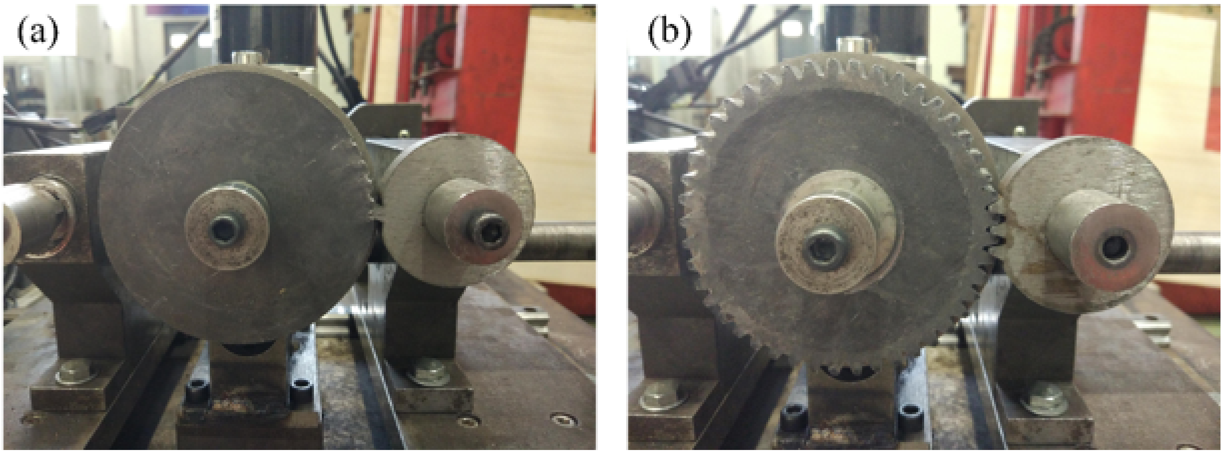

Figure 7

Experimental process of two stages: a preforming stage and b finishing stage

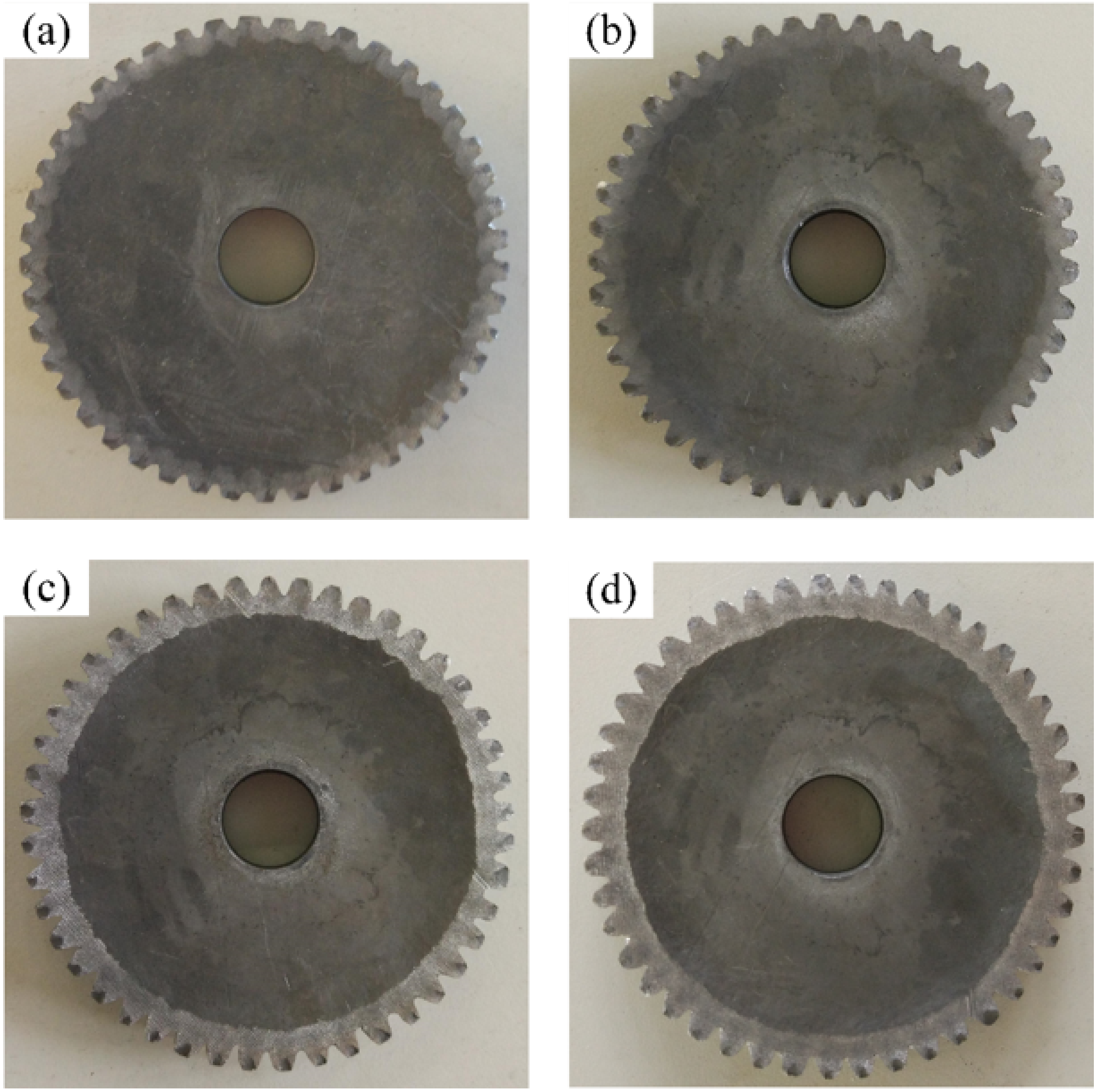

Figure 8

Lead sample's forming results of each pass: a pass 1, b pass 2, c pass 3 and d pass 4

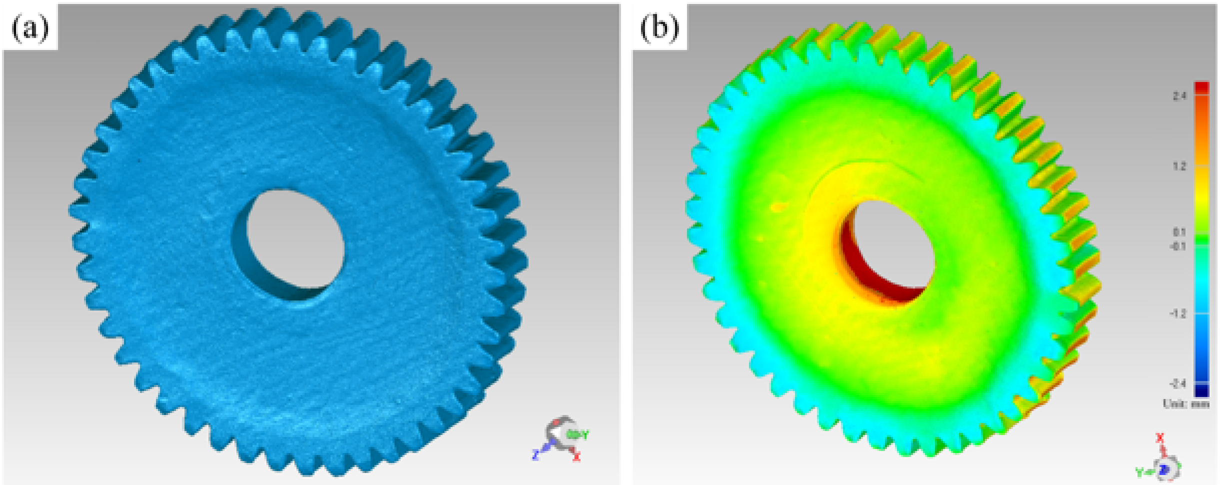

Figure 9

The sample after finishing stage: a 3D solid model and b dimensional deviation nephogram

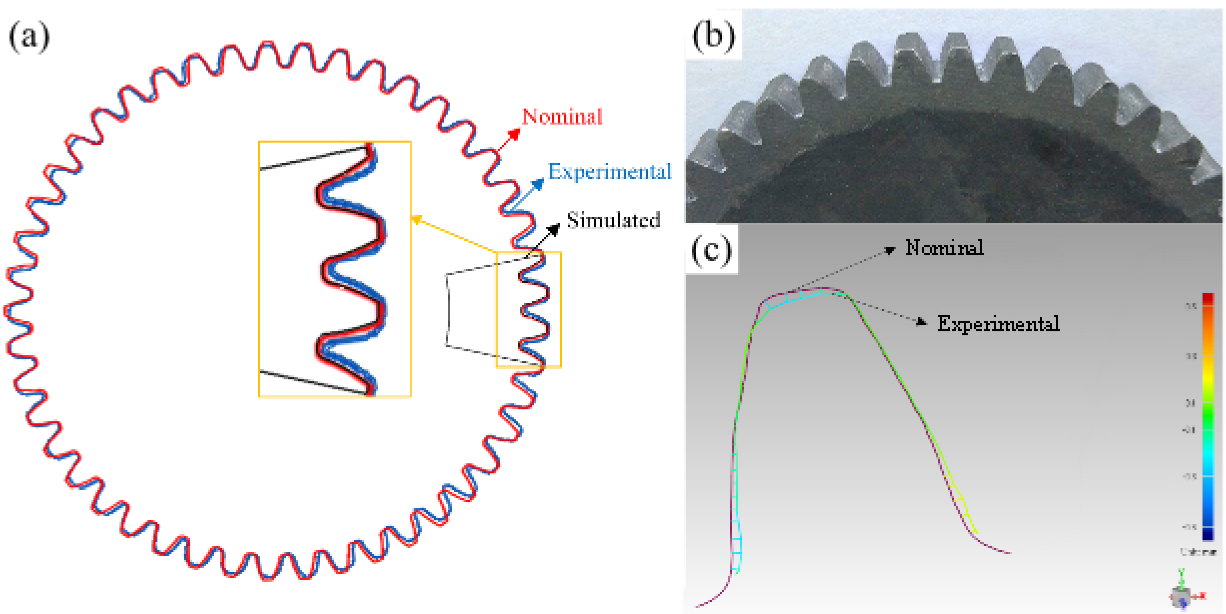

Figure 10

a The complete and detailed tooth profile of the sample obtained from simulations and experiments, b the formed gear in experiments and c the dimensional deviation with a nominal tooth

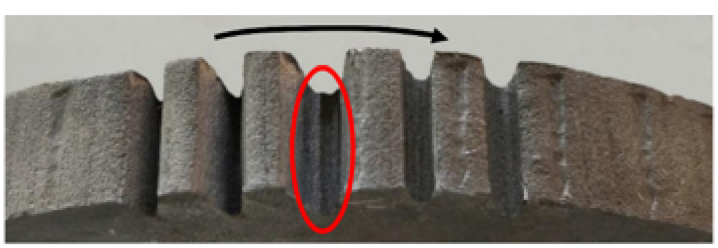

Figure 11

The verification result of fold in the third pass of Scheme 2-4 caused by unreasonable preforming feed distribution