

The influence of roller motion on profile and hardness of T2 worm

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Abstract. The rolling process of T2 worm is studied by numerical simulation and experiment in this paper. The rolling forming of the worm part is realized by using the two rollers forming method with parallel axes and the radial feed at the same time as rotation. Firstly, the influence of the unidirectional rotation and reciprocating rotation of the roller on the hardness of the teeth, the strain distribution and the streamline distribution of the worm are analyzed. The results show that in numerical simulation, the tooth shape of reciprocating rolling workpiece is symmetrical according to the central axis of the tooth, and the workpiece has no axis displacement. The hardness distribution of both sides of the tooth of the reciprocating rolling workpiece is more uniform than that of the unidirectional rolling workpiece, and the streamline distribution is more uniform and symmetrical. The strain variation in the numerical simulation is consistent with the experimental variation of hardness and streamlines. It shows that the reciprocating rolling has substantial help to the strength and hardness of the lifting worm. Then, the analysis of the teeth of the simulated and experimental parts show that the maximum difference of the gear parameters between the analogy and the experimental parts is 1.46%, and the accuracy of the numerical simulation is higher.

1. Introduction

Turbine and worm are the core transmission parts of the equipment manufacturing industry. They carry complex torque and play a key role in the normal operation of the equipment ^[1-2]. Early worm processing methods were mainly turning, milling and grinding ^[3-4]. Later, with the development of the industry, there was a whirlwind milling. In recent years, more and more attention has been paid to the plastic forming process of shaft hole parts with complex characteristics. Compared to the traditional cutting process, the precision of parts, good mechanical performance, high productivity and high utilization ratio of material are high, and it is a kind of efficient and accurate volume forming technology, which has been done by domestic and foreign scholars and enterprises. Quantity study.

From the 80s of the last century, some research institutions and enterprises in China have studied the plastic forming process of the spline shaft parts. The literature 5 on the patent of the plastic forming technology of the spline shaft in CNABS China Patent digest database has been carried out. It is found that the number of patents on the plastic processing of the spline shaft has broken through 100 pieces in 2005. It developed rapidly in 2014 to 578. The cold extrusion process of the involute spline was studied by the team of associate professor Xu Hong of Jilin University studied, a foundation for the cold extrusion forming process of the spline parts of automotive was laid ^[6-7]. The qualification of tooth graduation for cold rolling formation of spline was studied theoretically by Professor Li Yongtang of Taiyuan University of Science and Technology ^[8-10]. Numerical simulation and experimental studies on the rolling process of the worm shaft and thread axis wedge rolling were carried out by the team of



Professor Hu Zhenghuan of Beijing University of Science and Technology. The results show that if process parameters are proper, worm shaft can be rolled successfully using the technique of cross wedge rolling and cross rolling^[11-13]. The theoretical analysis, process simulation analysis and equipment development of spline shaft rolling forming were studied by the team of Professor Zhao Shengdun of Xi'an Jiao Tong University^[14-19]. The effect of thread type, friction parameter and working hardening on tooth height, tooth top and tooth root in roll forming process of external thread was studied by finite element analysis and experiments in literature 20-21. The effect of friction types on the forming process is studied in literature 22. The roll forming process of micro bolts was studied by numerically simulation and experiments in literature 23. The precision forming of the worm shaft was studied by numerical simulation and experiments using the rack dies. It is found that the worm shaft has a higher hardness and straightness and better profile of the tooth surface using the plate dies than using the wheel dies in literature 24. The finite element analysis and experimental study of 2618 aluminium alloy toothed shaft in the cross-wedge rolling processing were carried out in literature 25. In this paper, the effect of rolling wheel movement on the tooth shape and hardness of the workpiece was studied in the rolling process of T2 worm parts by the numerical simulation and experiments. And the flow line analysis of the tooth shape of the worm was analyzed. At the same time, the distribution of hardness and the distribution of the flow line were well explained by the strain distribution in the Forge numerical simulation.

2. Rolling test die and equipment for worm rolling

The cold rolling of worm part (as shown in Figure 1), which number of threads of is 2 and axial pitch is 6.285mm, is studied in this paper. The material of the worm is T2 pure copper. Billets with diameter of 25mm and length of 200mm were used in this experiment. Both ends of the billet can be rolled to worm shape. According to the mechanical design manual and considering the size limit of the roller die for the spindle of the NC rolling mill, a rolling die with a diameter of 192mm and a thread number of 16 was designed (as shown in Figure 2). The material of die was Cr12MoV. The dual roller with parallel axis structure, and a rolling equipment Z28K-25 NC rolling machine, which maximum rolling force is 250KN and maximum spindle speed is 110 r/min, made by Qingdao Shengjian Machinery Factory, was used in this study.

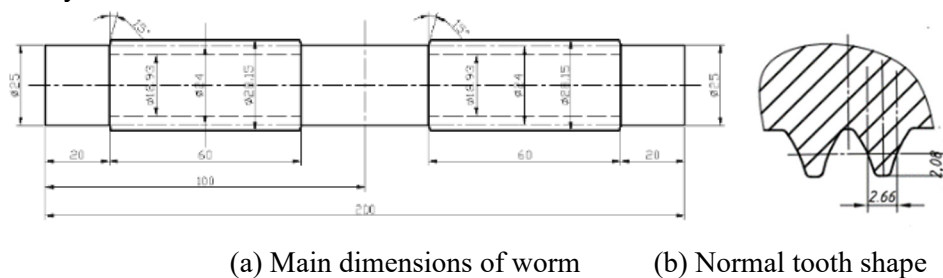


Figure 1. Worm part



Figure 2. Roller wheel

The process parameters: spindle speed of 4 r/min, radial feed of the rolling wheel of 2mm, feed speed of 0.1mm/s, and total rolling time of 20s were applied in the experiment. In the process of experiment, two rolling wheels with positive and negative rotation was used in one end of the billet, and two wheels

with one way rotation was used in another end of the billet. The experimental process is shown in Figure 3, and the experimental parts are shown in Figure 4.

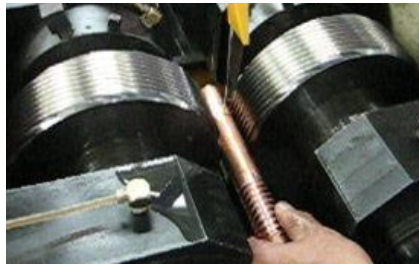


Figure 3. Rolling forming process of worm Figure 4. Worm experimental part

3. The influence of rolling wheel moving mode on the tooth shape of T2 worm

A commercial software ForgeTM was used to simulate the rolling of the worm. As shown in Figure 5, there were two sleeves at each ends to support the billet without limitation on the flow of metal during the forming process. The simulation parameters are as follows: the rolling speed: 4r/min, the feed speed of the rolling wheel: 0.1mm/s, and the rolling time: 20s.

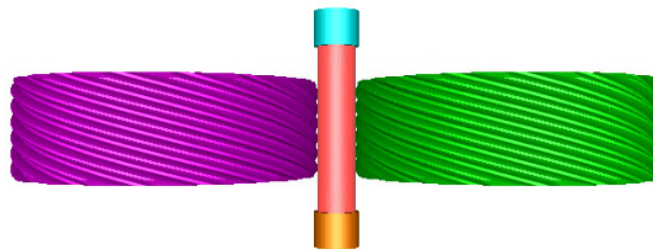
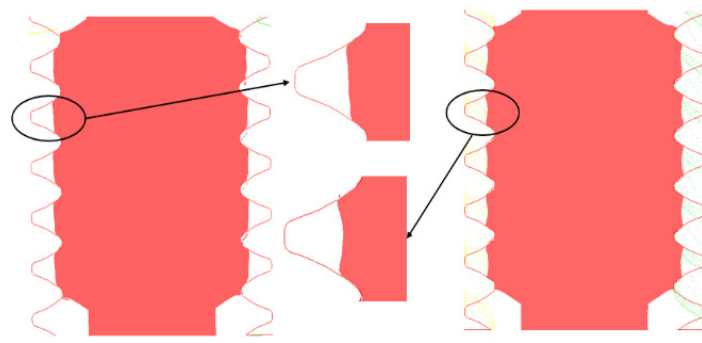


Figure 5. Finite element model

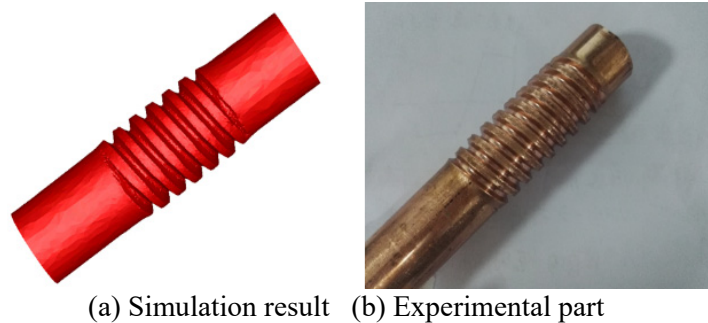
Figure 6 shows the comparison of the worm shafts tooth profile after different rolling process, Figure 6 (a) shows the parts after rolling of two wheels with one way rotation, and Figure 6 (b) shows the part after rolling of two wheels with positive and negative rotation. It can be seen from Figure 6 (a) that the upper side of inner tooth is not symmetrical with the lower side, and the tooth height of the upper side is larger than the lower side. The main reason is the one-way rotation of the rolling wheel which drive the workpiece to rotate in one way, and the direction of the spiral line of the workpiece is always vertical downward. Therefore, when the tooth shape is formed, the material flows down under the rolling wheel, resulting in the axial displacement, which causes more material flow to the upper side. The asymmetrical tooth shape was formed. As shown in Figure 6 (b), the tooth profile is symmetrical with the middle axis of the tooth, and the tooth heights of upper and lower side are larger than the middle side. With the feeding and the positive and negative rotation of the rolling wheel, the material at each side of the tooth is squeezed alternately, forming a symmetrical distribution of the tooth profile. Therefore, rolling of worm with positive and negative rotation have the advantage of smaller axial displacement and more uniform distribution of tooth profile.



(a) in unidirectional rotation of the roller wheel (b) in reciprocating rotation of the roller wheel

Figure 6. Tooth profiles of the worm in the motion of two rolling wheels

Figure 7 shows the comparison between the finite element simulation results of the worm gear rolling and the experimental results. It can be seen that the results of the finite element simulation are in agreement with the experimental results. The helical tooth was well formed with uniform profile, and without error tooth.



(a) Simulation result (b) Experimental part

Figure 7. Simulation result and experimental part of T2 worm

In the spiral tooth part of the worm part, 5 parallel cross sections are selected along the axis with interval of tooth distance. The outer diameter and inner diameter of the spiral teeth in different cross sections are measured both from FEM and experiment. As shown in Table 1, the maximum difference between the FEM and experiment is 1.46% in the outer diameter, while the maximum difference in the inner diameter is 1.42%.

Table 1. Comparison between the simulation results parameters and experimental results of tooth profile

Section position	Simulation result /mm		Experimental part /mm		Difference value/%	
	External diameter	Internal diameter	External diameter	Internal diameter	External diameter	Internal diameter
1	26.24	21.69	26.60	22.0	1.37	1.42
2	26.67	21.83	26.30	21.7	1.39	0.59
3	27.06	21.25	26.70	21.3	1.38	0.24
4	26.69	21.81	26.30	21.9	1.46	0.09
5	27.08	21.73	26.80	21.4	1.03	0.33

4. The influence of rolling wheel motion on the hardness of T2 worm

Microhardness was tested in this study. The seven different testing points of a tooth shape were chose according to Figure 8, which named tooth top, a, b, c, d, e and tooth root. The testing force is 300gf (2.942N) with holding time of 20 seconds.

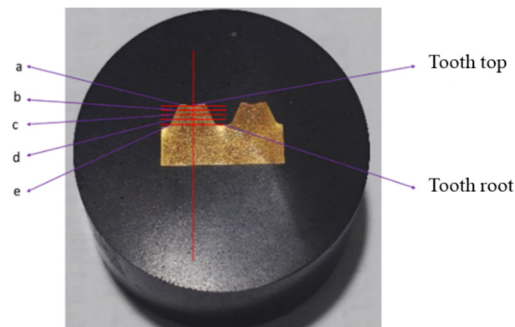


Figure 8. Hardness test point

The hardness of the measuring points of the rolling workpieces during the unidirectional rolling and the reciprocating rolling is shown in Table 2. The hardness is higher, and the hardness of the left side higher than right side during the unidirectional rolling. The hardness difference between the left and right sides from point a to point e is 4, 6.7, 5, 5.9 and 3.4 during the unidirectional rolling. The difference between the hardness of the measuring points on the left and right sides of the forming parts is smaller, from point a to point e is 0.5, 1.2, 0.4, 0.5 and 1.6 during the unidirectional rolling. Therefore, the hardness distribution on both sides of the tooth profile is uniform in the reciprocating rolling.

Table 2. Hardness Distribution

The hardness /HV	Workpiece in unidirectional rolling		Workpiece in reciprocating rolling	
	Left	Right	Left	Right
a	119.6	115.6	114.7	114.2
b	122.0	115.3	117.0	115.8
c	122.0	117.0	119.3	118.9
d	127.3	121.4	119.6	119.1
e	130.3	126.9	124.7	123.1
Tooth top	113.4		101.5	
Tooth root	132.6		128.1	

The equivalent strain distribution of the forming parts during the unidirectional rolling and the reciprocating rolling in the simulation is shown in Figure 9. The strain of the two rolling methods is gradually increasing from the position of the tooth top to the root. The dates of the equivalent strain is shown in Table 3.

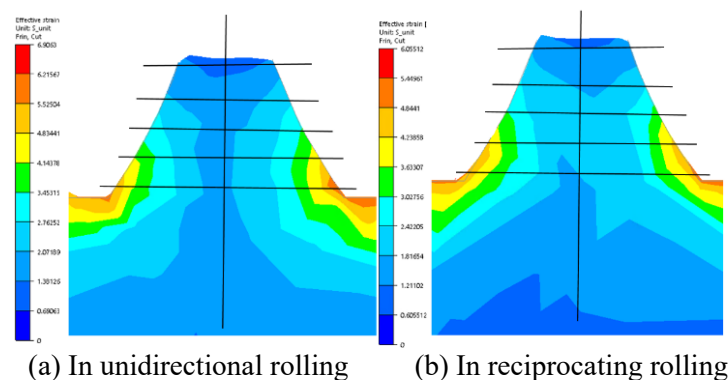


Figure 9. Distribution of equivalent strain

Table 3. Equivalent Strain Data

Equivalent Strain	Workpiece in unidirectional rolling		Workpiece in reciprocating rolling	
	Left	Right	Left	Right

a	1.8410	1.9066	1.5836	1.5916
b	2.9279	2.8047	2.7869	2.8753
c	3.4458	3.1239	3.2168	3.4120
d	4.2138	3.4754	3.7468	3.9739
e	5.5322	4.7613	4.8180	4.9173
Tooth top	1.7518		1.5328	
Tooth root	6.4137		5.2499	

The relationship between the hardness and the equivalent strain obtained by the simulation is shown in Figure 10. The hardness and the equivalent strain increase from the top of the tooth to the tooth root in the two forming methods, and the left equivalent strain in the unidirectional rolling was greatest, which is consistent with the trend of hardness distribution, and the difference of the left and right equivalent strain values in the reciprocating rolling is small. The metallographic specimen shown in Figure 11, and the micro-structure of the cross section of the workpiece after reciprocating rolling shown in Figure 12, and the micro-structure of the cross section of the workpiece after unidirectional rolling shown in Figure 13. As can be seen from Figures 12 and 13, the distribution of metal streamlines on both sides of the tooth root is uniform and almost symmetrical.

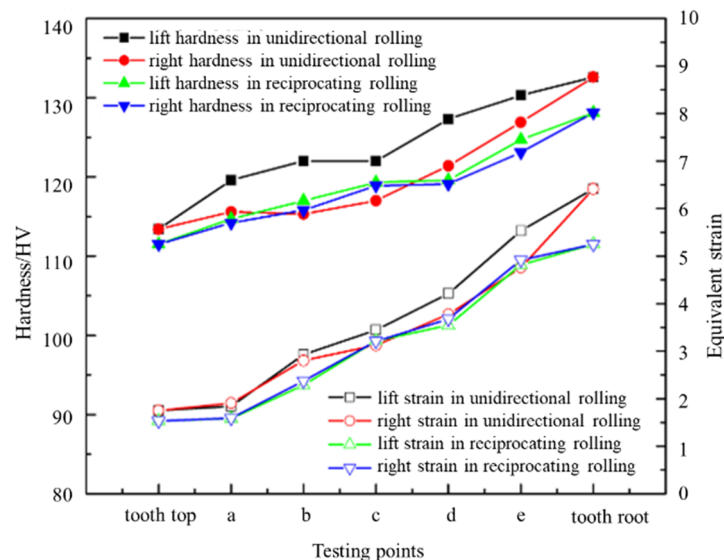
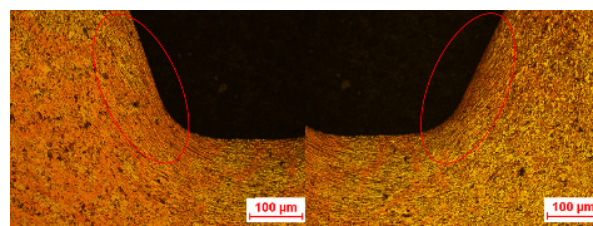


Figure 10. Hardness and strain curve

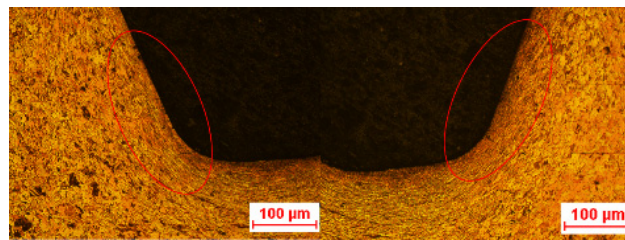


Figure 11. Metallographic specimen of tooth



(a) Left Side of the tooth (b) Right side of the tooth

Figure 12. Microstructure after reciprocate rolling



(a) Left Side of the tooth (b) Right side of the tooth

Figure 13. Microstructure after unidirectional rolling

5. Conclusion

(1) A roller wheel with thread number of 16 was designed, and the rolling forming experiments of T2 worm parts in unidirectional and reciprocating rotation of the roller wheel and at different rotational speeds were carried out by numerical control rolling mill.

(2) The tooth profile of the workpiece in the unidirectional rotation and reciprocating rotation of the roller wheel was compared and analyzed by numerical simulation. It is showed that the tooth profile of the workpiece was not symmetrical with the central axis of the tooth and the workpiece had obvious axial displacement in the forming processing of the unidirectional rotation of the roller wheel. And the tooth profile of the workpiece was evenly distributed and there was no axial displacement in the forming processing of the reciprocating rotation of the roller wheel. The experimental results of gear top height and tooth bottom height in the reciprocating rolling workpiece were consistent with the simulation results.

(3) The hardness distribution, strain distribution and flow line distribution of the workpiece in reciprocating rolling and rolling forming were analyzed by the numerical simulation and experiments. It is showed that the hardness distribution on both sides of the tooth shape in the reciprocating rolling workpiece is more uniform than in the unidirectional rolling, and the strain variation in the simulation and the hardness show the same trend. At the same time, through the metallographic analysis of the tooth profile of the worm, it is showed that the flow line distribution of the workpiece is more uniform and symmetrical, and the streamline of the unidirectional rolling workpiece is not obvious, and the distribution of the hardness is also verified.

Acknowledgments

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