Influences of Friction Condition and End Shape of Billet on Convex at Root of Spline by Rolling with Round Dies

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The rolling process is widely used to manufacture high-performance splined shaft components. However, there is a convex at root on free end of spline formed by rolling with round dies. However, the analysis and representation of this forming problem are difficulty due to the complexity of motion and multiplicity of processing parameters. This paper concentrates on the corner filling problem, and a physical analog experiment was designed to investigate the problem. The physical experimental results indicated that the designed experiment can reflect the formation of convex during spline rolling process. The finite element analysis of the physical analog experiment process was carried out to study the influences of friction condition and end shape of billet on convex at root of rolled spline. The results indicated that the height of convex will be reduced with increasing friction condition; the height of convex can be reduced by optimizing the end shape of billet. The results of present study provide a basis for optimizing and controlling the forming quality on free end during spline rolling process.

Keywords: Spline, Rolling, Convex at root, Friction condition, End shape

1 Introduction

The spline parts are the key load-transfer and torque-transfer component in vehicle and machinery industries. Plastic deformation bring refine grain and high strength for parts [1, 2], and it benefits the improvement of service performance of parts. The complex profiles such as thread and spline also can be maunfactured by the plastic deformation[3]. The rolling process is a efficient plastic forming process with low force [4, 5]. The cold rolling process which can provide a high-performance and high-precision spline with saving material and time, has been widely used in manufacture of spline shaft [6, 7]. However, the rolling process is a complicated plastic deformation process and characterized by local loading and multi-axis motion. Thus, some problems about forming quality, such as the convex at root on free end of rolled spline, are prone to occurrence.

In spline rolling processes, rotation of workpiece is driven by friction moment at initial rolling stage and driven by engagement motion at form-tooth stage [8]. The rotatory condition at initial stage of spline was studied, the motional parameters of rolling die can be determined by the rotatory condition and geometry of die [9]. The speed-control of workpiece can guarantee the forming quality declared by Neugebauer et al. [6, 10], and the speed depends on changing rolling circle. Zhang et al. [11] studied the motion characteristic in spline rolling process, and provided a basis for determining the rolling circle. Slip-line field during spline rolling modeled by Zhang et al. [7, 8] indicated that the deformation concentrates on the outer layer of workpiece. The experiment [12] and finite element (FE) analysis [13] also presented that the deformation in spline rolling process occurs in superficial zone. Generally, if the length of rolled spline section is greater than 20mm, then the axial deformation can be neglected in rolling process [14]. However, there is a slight convex at root on free end of rolled spline, and it only effects the small range around the end cross section [15]. Up to now, the relevant literature doesn't pay attention on the convex although it has an influence on the quality of end for rolled spline.

Thus, in the present study, corner filling problem about the convex at root on free end of rolled spline was studied systematically. A physical analog experiment was designed to investigate the problem, and finite element analysis (FEA) of the physical analog experiment process was carried out to study the influences of friction condition and end shape of billet on convex at root of rolled spline. The orthogonal experiment design was adopted to explore the influences of geometrical parameters of end on the convex. The results provide an approach for determining the shape of billet for spline rolling process.

2 Methods

2.1 Physical analog experiment

The spline rolling process is a complicated plastic deformation process and characterized by local loading and multi-axis motion. The small deformation zone and multi-axis rotation are liable to cause severe distortion for mesh in FEA. The 3D FEA for whole workpiece also needs long CPU time. The analysis and representation of the convex in rolling process are difficulty.

Thus, in order to simplify analysis and reduce time, a physical analog experiment was designed according to the forming and tooth characteristics, as shown in Fig. 1, where the shape of upper die was simplified from a spline with module m=2mm and pressure angle $\alpha = 37.5^\circ$.

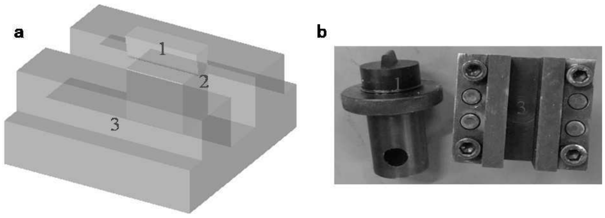

Fig. 1 Physical analog experiment; 1-upper die, 2-billet, 3-lower die: (a) sketch of forming process; (b) experimental dies

The physical analog experiment can reflect the deformation inhomogeneity and the convex at root on free end. The experiment used the dies shown in Fig. 1b indicates that the designed experiment can reflect the formation of convex during spline rolling process. The FEA also indicates the physical analog experiment can reflect the formation of convex during spline rolling process, as shown in Fig. 2.

Experiment Numerical simulation

a

b

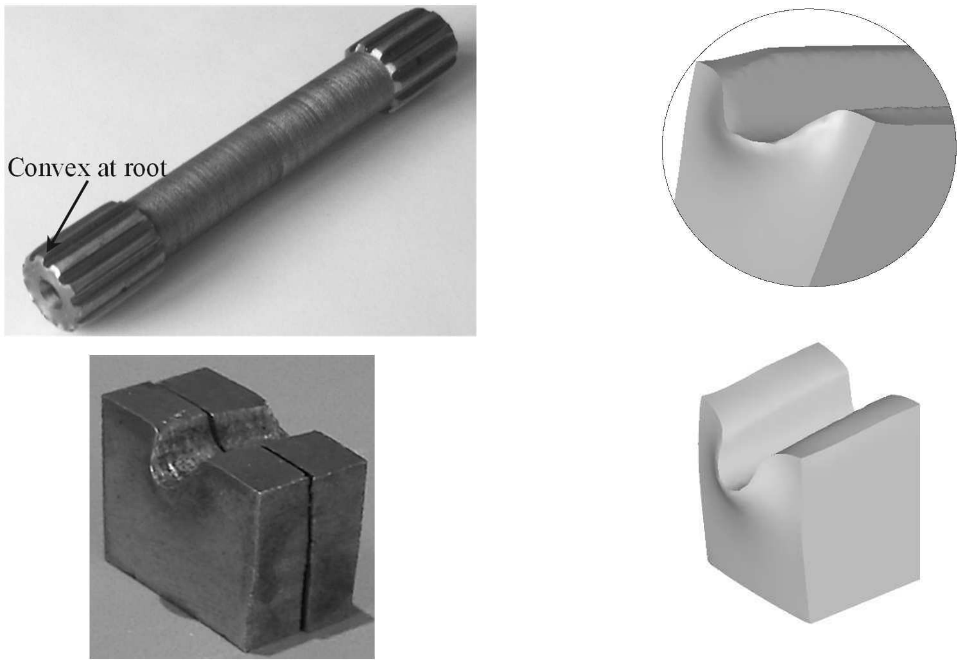

Fig. 2 *Convex at root in rolling process and physical analog experiment: (a) rolling process [15]; (b) physical analog experiment.*

2.2 Finite element model

The FE model of physical analog experiment process was developed under code DEFORM. Only one-fourth problem of process was modeled due to the symmetries of geometry and boundary conditions. The tetrahedron elements were used to mesh billet/workpiece. Two symmetry planes were set, and the constraints of lower die were replaced by a displacement constraint along normal direction, and the end of billet is free, as shown in Fig. 3. Only contact pair of upper die and billet was adopted, and Tresca friction model was employed to describe the friction between the contact pair. AISI 1045 was used in FE model because it is also used in experiment. The metal flow behavior was obtained from tension test in our group. Von Mises criteria was adopted to describe the metal yielding.

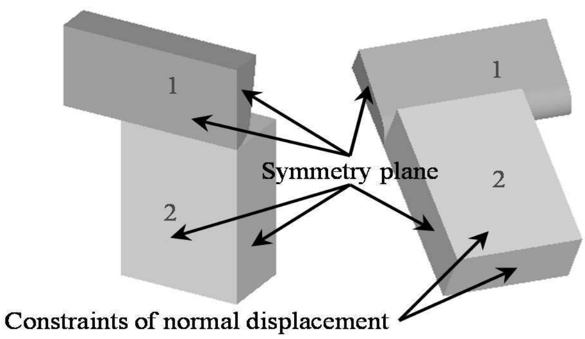

Fig. 3 *FE model of one-fourth problem; 1-upper die, 2-billet*

In order to evaluate the convex at root on free end, the height (h_c) of convex was defined as follows:

$$h_c = \frac{l_c - l_0}{2}, \tag{1}$$

Where:

l_0... Length of billet/workpiece before forming [mm],

l_c ...Maximal length of billet/workpiece before forming and after forming [mm] , as shown in Fig. 4.

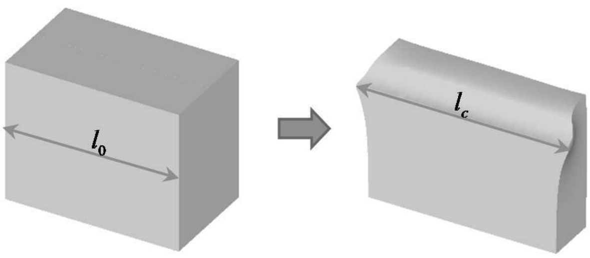

Fig. 4 *Length of billet/workpiece before and after forming*

Comparing with the experiment results (Fig. 2b) indicates that the developed FE model can describe the deformation and formation of convex at root in physical analog experiment. The experimental h_c in Fig. 2b is about 1.375mm, and numerical result is 1.53mm under the frictional condition determined by classic ring compression test [16]. The predicted error is about 11%, and thus the numerical results in this paper can be considered to be valid.

3 Results and discussion

3.1 Influence of friction condition

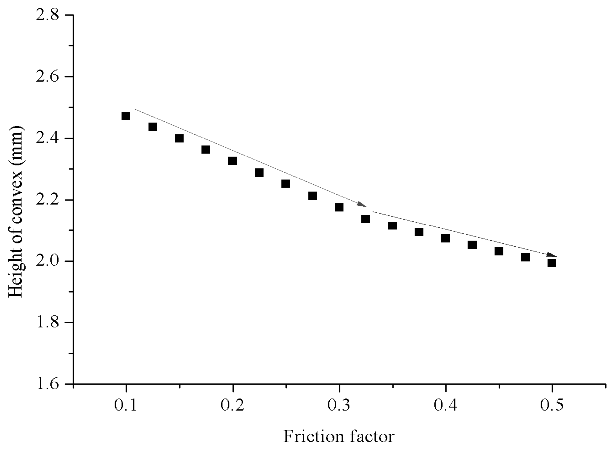

Fig. 5 *Variation of height of convex with friction factor*

The height of convex decreases with increasing friction factor, as shown Fig. 5. The axial metal flow causes convex due to free on the end. However, the friction adds resistance to axial flow, and then the height of convex will decrease when friction condition increase.

It can be found from Fig. 5 that the influence of friction on the height will reduce after the friction factor is greater than 0.3. The great friction will bring some forming problems. And the friction factor is about 0.3 in cold bulk forming of AISI 1045 according to ring compression test [16]. The Lubricating condition of m=0.3 is easy to implement in industry. Thus, the friction factor 0.3 was adopted in below discussion.

3.2 Influences of end shape of billet

The convex caused by axial metal flow, and the axial flow only occur in a small range around the end cross section. Thus, to reduce the material around the end of billet can reduce the axial metal flow. To add a restriction, such as a bar, on the free end, will add resistance to axial flow. If the axial metal flow reduce, then the height of convex would decrease. Thus, the following end shape of billet was adopted to reduce convex: (i) chamfer D×45° pattern, as shown in Fig. 6a; (ii) bar restriction pattern, as shown in Fig. 6b; (iii) hybrid pattern, as shown in Fig. 6c.

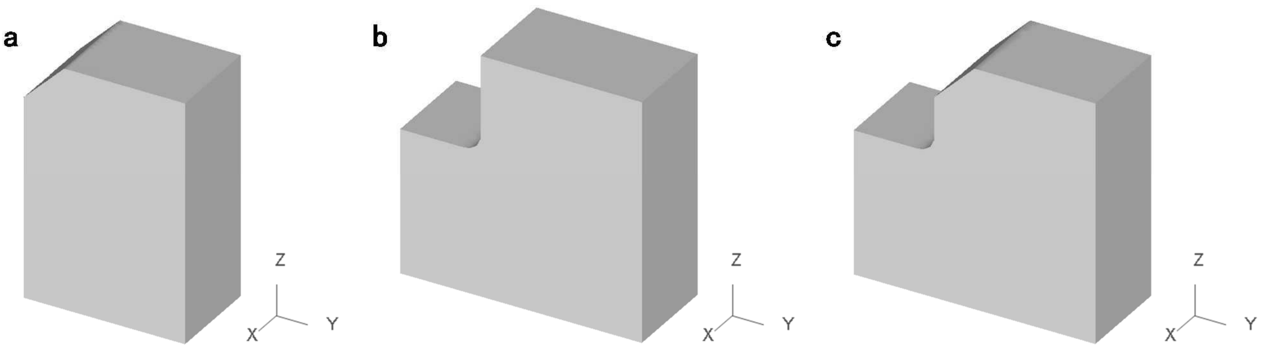

Fig. 6 *End shape of billet: (a) chamfer pattern; (b) bar restriction pattern; (c) hybrid pattern*

Comparing with shape shown in Fig. 4, the heights of convex under chamfer pattern and hybrid pattern decrease sharply, as shown in Fig. 7. The height of convex under bar restriction pattern does not decrease. Because the bar have a little influence on the height of convex according to the study in next section, especially for a smaller height (or diameter) of the bar.

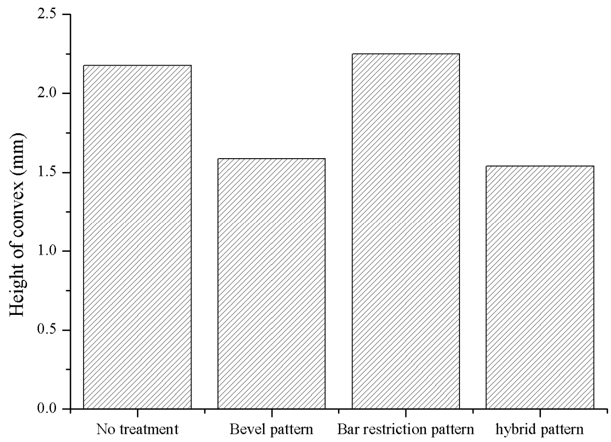

Fig. 7 *Height of convex under different end shapes*

However, the height under hybrid pattern is less than that under chamfer pattern although the difference is only 0.047mm. Thus, the bar restriction works. The bar restriction will work better if the height (or diameter) of bar is close to formed root of spline. However the ratio (R) of height (or diameter) of bar to height (or diameter) of formed root is only 0.75 in this section.

3.3 Influences of geometrical parameters of billet

The previous discussion indicates that the hybrid pattern should be chosen as end shape of billet for spline rolling. The virtualizing orthogonal experiment design was adopted to study the influence of geometrical parameters of hybrid pattern on the convex. The height of convex was chosen as the experimental index. The hybrid pattern is characterized by chamfer D×45° and bar, so the length (D) of straight-side of chamfer and the ratio (R) of height (or diameter) of bar to height (or diameter) of formed root were chosen as the variables. Thus, an orthogonal experiment design array $L_9(3^4)$ [17] was adopted, where the coupling effect of variables D and R is considered. The experiment design array and height of convex are listed in Table 1, where results were obtained from FEA.

***Tab. 1** Orthogonal experiment design array and results*

No.	A (D)	B (R)	(A×B)1	(A×B)2	Height of convex
1	1(2.0)	1(0.750)	1	1	1.73
2	1(2.0)	2(0.875)	2	2	1.77
3	1(2.0)	3(1.000)	3	3	1.75
4	2(2.5)	1(0.750)	2	3	1.54
5	2(2.5)	2(0.875)	3	1	1.56
6	2(2.5)	3(1.000)	1	2	1.51
7	3(3.0)	1(0.750)	3	2	1.34
8	3(3.0)	2(0.875)	1	3	1.30
9	3(3.0)	3(1.000)	2	1	0.84

It can be found from Fig. 8 that the geometrical parameters of end shape of initial billet have a little coupling effect. Range analysis of data listed in Table 1 indicates that the order of experimental factor on experiment h_c index is A>B>A×B. The prime factor influencing convex is the chamfer. The value of range analysis for factor B is almost equal to that for factor A×B, but the influence of bar should not be ignored. Table 1 and Fig. 8 indicate that combing the best geometrical parameters of chamfer and bar can make height of convex decrease sharply.

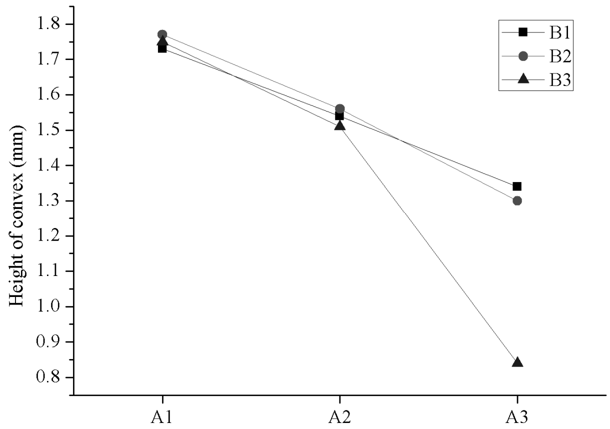

***Fig. 8** Coupling effect of geometrical parameters*

The variance analysis was also implemented for the data listed in Table 1. The contribution ratio ρ_I [18] is adopted to evaluate the influence of factor I on the height of convex. The total variation is SS_T, and the variation of factor I is SS_T, and then the contribution ratio ρ_I of factor I is defined as following:

$$\rho_I = \frac{SS_I}{SS_T} \times 100\% \,, \tag{1}$$

Table 2 describes the results of variance analysis. The factor having largest influence is factor A, i.e. chamfer, and its contribution ratio is close to 80%. The contribution ratio of coupling effect is greater than the 10%, but the contribution ratio of bar (factor B) is less than 10%.

***Tab. 2** Variance analysis of height of convex.*

Source	Variation SS	Degree of freedom f	Variance V	Variance ratio F	Contribution ratio ρ (%)
A (D)	0.5355	2	0.2677	11.1200	77.3878
B (R)	0.0602	2	0.0301	1.2492	8.6936
(A×B)	0.0963	4	0.0241	1.0000	13.9187

It can be found from Table 2 that the variance of coupling effect is smallest. Thus the (A×B) can be chosen as error, and then the variance ratio F can be calculated. The significance test also indicates that the length of chamfer has a significance influence on height of convex under significance level α=0.025, where $F_{0.025}(2,4)$=10.65 obtained from distribution table of F in the book [17]. Although the influence of geometrical parameter about bar on convex is less than influence of geometrical parameter about chamfer, the chamfer combing with suitable bar will make height of convex decrease more.

4 Conclusion

The corner filling problem about the convex at root on free end of rolled spline has been study by designed physical analog experiment. Results of experiment and FEA indicated that physical analog experiment can reflect the formation of convex during spline rolling process. The results in the present study indicated that: the height of convex decrease with increasing friction factor; chamfering side of initial billet can reduce convex notable, and the bar with suitable geometrical parameter also can reduce the convex; suitable chamfer combining bar can reduce convex sharply.

Acknowledgement

The authors would like to gratefully acknowledge the supports of the National Natural Science Foundation of China (Grant Nos. 51675415 and 51335009).

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DOI: 10.21062/ujep/72.2018/a/1213-2489/MT/18/1/165