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Forming Flaws Analysis of Lead Screw Cold Roll-Beating Based on Stress-Strain Evolution

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Abstract: Cold roll beating is an advanced precision plastic forming technology. The principle of lead screw cold roll beating was briefly introduced and the dynamic model of single beating process of lead screw cold roll beating is established. Evolutions of the principal stress, hydrostatic pressure and the principal strain in the deformable area are studied. Positions of the defects are further defined and the reasons of these are analyzed according to the stress-strain evolution. And the corresponding measures are put forward to prevent surface defects.

Keywords: Lead screw, Cold roll-beating, Surface defects, Stress-strain.

1. Introduction

The precise plastic forming technology aims at producing near-net-shape products as possible and even the finished parts [1, 2]. High speed cold roll-beating forming technology is a green near-net single-point incremental forming method [3][4] in which the characteristics of metal plastic forming are utilized, the high-speed rotating roller is used to roll-press and beat the rough shaft to compel the work-piece enduring local striking continually and yielding plastic deformation. High speed precise cold roll-beating of lead screw is an advanced precise plastic volume forming technology, in which under the normal temperature, the rotating rigor roller with the specific tooth profile rolls and beats the blank with high speed, owing to the plasticity of metal itself, the surface metal of the blank plastically flows, and forming of work-piece overall by cumulating deformation of continuous tiny region with the relationship of relative motion between the rigor wheel and blank is realized [5, 6].

Compared to the traditional plastic forming, cold roll-beating technology is of lesser load, lower energy-consuming and higher flexibility. At present it has been successfully used for gear and spline shaping [7], while its use for lead-screw forming is still at feasibility study [6, 8]. Studying on the process forming shows that flaws such as ripple texture and flanging always occur on the shaping surface of the lead screw raceways which will always lead to cracking occurred. Studying the stress-strain changing laws in real time will contribute to reveal the flaw forming mechanisms of ripple texture and flanging, etc. [9, 10] and forecasting the occurring positions of
the surface flaws, which will be helpful to take actions to prevent or decrease the flaws to improve the surface forming quality of the lead screw raceways.

In this paper, ABAQUS/Explicit is used to carry out the explicit dynamics simulation analysis of a single beating process in the lead screw cold roll-beating to reveal the evolution of the stress and strain to further forecast the occurring positions of the flaws, reasons for flaw occurring are analyzed the reasonable flaw preventing measures are given.

2. Principle of Lead Screw Cold Roll-Beating

The cold roll-beating process of the lead screw is a complex forming process of high speed, transience, high impact and big deformation [6]. The working principle [8] is shown in the Fig. 1.

In the roll-beating process, the roller of certain shape is mounted on the rotating roll-beating shaft with high speed. The roll-beating shaft moves a pitch per rotating; the roller makes axial and radial feeds with certain velocity while striking the rotating work. At the instance the rollers contacting the work simultaneously, due to the action of the friction force between the roller and the work; the roller rotates on itself with certain angular velocity to ensure rolling between the roller and the work. To avoid interfering, there is a pitch angle $\beta$ between the mounting axis of the roller and the axis of the work. Thus the main motions are: rotation of the beating shaft, rotation of the work, rotation on itself of the roller, the roller’s axial feeding and radial feeding.

3. FE Model of Lead Screw Cold Roll-Beating

Lead screw cold roll-beating is a single-point accumulating forming process. As the raceway’s forming is a repetitive single-beating process, in this paper dynamics simulating of the single beating process is given the great attentions. And only a very small plastic deforming region emerges on the local area of the blank in a single beating, the 1/6 of lead screw circumference is taken as the analysis object. The geometry model is given in the Fig. 2 (a), the axial length of the lead screw blank is taken as 10 mm, and the diameter is 34 mm, the material is 45# steel. While the roller material is W6Mo5Cr4V2Co8, its diameter is 25 mm, thickness is 3 mm, the radius is 1.5 mm and the Revolution diameter is 120 mm.

The element type of the lead screw blank is C3D8R, the global size of the element is 3 mm. As there will no big deformation occurring the central part of the lead screw, grid refinement is taken in the region of 5 mm (thickness) $\times$ 3 mm (width) in the blank’s outer surface contacted with the roller and the size of the element is 0.18 mm. The grid dividing models shown in the Fig. 2 (b). Deformation of the roller is very small relative to the blank, the roller is constrained as rigid body.

As the forming is of local forming, metal flowing is limited, the blank surface contacted with the roller is not constrained, rotation along the Y axis are applied on the other five surfaces, rotating speed of the lead screw blank is 20 rpm and revolution speed of the roller is 1000 rpm. Reverse beating is adopted in the simulation, which means revolution of the roller and feeding of the blank are of the opposite direction. Although in a single beating, rotation of the roller can ensure the metal fiber will not be cut off, the dynamics simulation shows that the angular rotation is extremely small and is about 0.02-0.05 rad, its effect on the strain-stress in the plastic deformation region can be ignored, to shorten the computing time, the rotation of the roller is ignored.
4. Simulation Results and Analysis

Lead screw cold roll-beating is an intermittent local plastic volume forming process, the plastic deformation in a single beating is very small, to simplify the analysis, only the refined element in the surface of the contacting region between the lead screw blank and roller is taken as the research object.

4.1. Stress Evolution

Without considering magnitudes of the principle stress, the stress state can be expressed in form of stress figure, from which it can seen whether the three principle stress exist or not and the directions of the stresses. Considering the magnitudes of the principle stress, hydrostatic pressures determine the effect of the stress state on the plastic deforming quality. To reveal the evolution of the stress in the deforming region, the stress states are analyzed with combination of principle stress diagrams and hydrostatic pressures.

(1) Evolution of principle stress over time

Three moments in the process from roller roll-beating into the deforming region to out of the region are taken out, directions of three principal stresses at different points of the contacting region between the blank surface and roller are given in the Fig. 3, from left to right is the max, middle and min principle stress. From the Fig. 3, in a single roll-beating process, majority of the principle stress diagrams of the surface metal is always 3-D compressing stress diagram, this kind of stress state is most conducive to produce metal plasticity and microscopic failure probability decreases.

(2) Evolution of hydrostatic pressure over time.

The lead screw raceway deforming region is consist of contacting region and deformed region. The region area changing rule can be seen from the Fig. 4. As is it is shown in the Fig. 4, with the progressing of a single beating process, the raceway deforming region changes form a point into ellipse. The direct contacting region (1# Region) between the roller and blank surface first increases and then decrease and is always beneath the raceway deforming region. The raceway’s deformed region (2# Region) is always increasing.

During the roll-beating process, hydrostatic pressures at different regions of the blank surface change continuously. The hydrostatic pressure at top part changes from big to small, i.e. from 2071 MPa to -431 MPa. The hydrostatic pressure at middle part changes from small to big, i.e. from -33 MPa to 2240 MPa. While the hydrostatic pressure at down part is always increasing, i.e. from -33 MPa to 2206 MPa.

The maximum hydrostatic pressure occurs at the central part of the contacting region, in this part the material plasticity is well, whereas the deforming resistance force is bigger, which is helpful for further roll-beating incremental forming. The hydrostatic pressures at the deformed region decrease obviously, which means that number of the compression stress decreases. Low hydrostatic pressure will induce generation of flaws such as cracking etc.

(3) Distribution of the Hydrostatic pressure at the specific moment.

To study the surface hydrostatic pressure distribution while a single beating is finished, the specific moment is selected as 1.92e-3s.

Fig. 3. (a) Principal stress direction of deforming zone at each time: Max, middle and Min principle stress at 1.750e-4s.
Fig. 3. (b) Principal stress direction of deforming zone at each time: Max, middle and Min principle stress at 1.400e-3s.

Definitions and codes of the node paths on the blank surface at the moment are given in the Fig. 5 (a): from top to down, 15 columns of nodes are selected, every column is taken as a path and the paths are coded from 1 to 15, nodes on every path are coded from 1 to 23. Values of the hydrostatic pressure of the nodes at the moment are shown in the Fig. 5 (b) and (c).

From the Fig. 5 (b), the minimum hydrostatic pressures of path 1 and path 2 occur at 11#, 12#, and 13# node, the maximum hydrostatic pressure changing gradient along the path is 70 MPa/mm, which is less than that of the nodes 4#-10#, i.e. 500 MPa/mm. The minimum values of Path 3 and Path 5 occur at 8#, 9#, 15# and 16# node, the gradient of the nodes on the two sides is 1100 MPa/mm, which is bigger than that of the middle nodes 260 MPa/mm. The minimum values of Path 4 occur at 11#, 12# and 13# node, while the local minimum values occur at 8# and 16# node, the maximum changing gradient of 11#-13# node along the path is 100 MPa/mm, which is much smaller than the gradient of 8# and 16# node, i.e. 1100 MPa/mm. The maximum hydrostatic pressure changing gradient along the direction perpendicular to the Path 1-Path 5 is 740 MPa/mm which occurs at 12# node.

Fig. 3. (c) Principal stress direction of deforming zone at each time: Max, middle and Min principle stress at 1.925e-3s.
Fig. 4. Hydrostatic pressure distribution at each time.

(a) Node paths and codes
(b) Path 1 - Path 5
(c) Path 6 - Path 10
(d) Path 11 - Path 15

Fig. 5. Hydrostatic pressure distribution of blank surface.
From the Fig. 5 (c), the minimum values region of the hydrostatic pressure on path 6~10 occurs at 6# and 18# node, the gradient of the region is around 1330 MPa/mm, which is much bigger than that of the middle nodes, i.e. 330 MPa/mm, the gradient along the direction perpendicular to the path is 160 MPa/mm.

From the Fig. 5(d), the minimum values region of the hydrostatic pressure on path 11-15 occurs at 6#-8# and 16#~18# node, the gradient of the region is around 1330 MPa/mm, which is smaller than that of the middle nodes, i.e. 3040 MPa/mm, the maximum gradient along the direction perpendicular to the path is 4150 MPa/mm, which occurs at 12# node.

From above mentioned, the minimum hydrostatic value region occurs at the sides of the raceway at the moment, and the gradients along the node path on the two sides are obviously greater than that of the raceway bottom. Too small hydrostatic pressure and dramatic changing of the hydrostatic pressure mean that the plasticity of the two sides is worse and the flaws are more prone to generate. In the end of the formed region, i.e. region that the roller just rolling out, the gradient of hydrostatic pressure along the direction perpendicular to the path reaches a maximum, so flaw of ripple texture is prone to generate in the region.

4.2. Evolution of the Strain

The compression strain is helpful to inhibit the micro defects, so there should be more strain of the type in a single beating. Here evolution and distribution of the 3-D strain of the deformation region will be studied.

(1) Evolution of the principle strain over time
Directions of the principal stresses at different points of the contacting region at different moment are given in the Fig. 6, from left to right is the maximum, middle and minimum principle strain.

From the Fig. 6, strain in the raceway deforming region is increasing with time, while the directions of there principle strains remain unchanged: the maximum and middle principle strains are of stretching and the minimum is of compressing. Though the strain state is not performing as well as that of 2-D compressing and 1-D stretching, the deforming region is of 3-D compressing stress state in the deforming process, the strain state has little effect on forming quality.

(2) Distribution of strain in specific moment
Considering stretching and compressing directions of strain are different at different positions of the contacting surface in a single beating, according the different direction, the deforming region is divided into three types, which are shown in the Fig. 7-Fig. 9.

(1) Axial stretching, tangential stretching and radial compressing Central part of lead screw raceway, i.e. 1# region, is under a principle strain state of axial stretching, tangential stretching and radial compressing. The axial stretching strain is the maximum, radial compressing strain is the minimum. The strain directions on the left side of the symmetrical surface in the region are given in the Fig. 7(b)-(d).
(2) Axial stretching, tangential compressing and radial stretching. The 2# region is near the position that the roller rolls out of the raceway deforming region, which is under the strain state of axial stretching, tangential compressing and radial compressing. The radial compressing is the maximum principle strain, while the tangential compressing is the minimum. The strain directions on the left side of the symmetrical surface in the region are given in the Fig. 8(b)-(d).

(3) Axial compressing, tangential stretching and radial stretching. Sides of the raceway forming region are defined as 3# region, which is under the strain state of radial stretching, tangential stretching, axial compressing. The radial stretching principle strain is the maximum, while the axial compressing is the minimum. Strain directions on the left side of the symmetrical surfaces in the region are given in the Fig. 9(b)-(d).
From above, the 2# region is the position from where the roller rolls and beats out and is also the position the roller rolling into at the next beating. Form the Fig. 7(b) and 8(d), the beating-in position is of radial compressing strain and the beating-out is of stretching stain. While the second beating occurs, the strain state of the region changes from stretching to compressing, the strain gradient is obviously higher than the surrounding, which may help in generating ripple texture. The radial strain gradient of the 3# region is obvious and is of stretching strain, flaws are prone to generate.

5. Experimental Results

Lead screw cold roll-beating experiments are carried out on CA6140 lathe, the roller material is GCr15, its rotating speed is 1000 rpm, the work material is aluminum, rotation speed of the work is 10 rpm. Part of the formed work is shown in the Fig. 10 (a). From the Fig. 10 (b), there is obvious ripple texture on the raceway surface and flanging on the sides of the raceway.
According to the simulation results, flaw of ripple texture mainly occurs where the intermittent plastic deforming meets, while flanging mainly occurs at the top of the raceway sides, which is consistent with the experiment. Occurring of ripple texture and flanging is mainly due to the uneven gradients of the stress and strain, to improve the formed surface quality, following measures can taken in cold roll-beating.

1. Increasing the revolution speed of the roller or decreasing the circumferential feeding speed of lead screw, i.e. decreasing the feeding per roller.
2. Optimizing section shape of the roller to make the stress-strain gradient on raceway sides changing evenly.

6. Conclusion

In this paper, evolution of stress and strain in the deforming region in a single beating-forming process is studied through simulating a single beating of lead screw cold roll-beating to analyze and forecast the possible flaw occurring and some conclusions can be drawn.

1. In a single beating process, the direct contacting region is always of 3-D compressing stress state, and the hydrostatic pressure of the region is the maximum.
2. The raceway sides are of stress state of 2-D stretching & 1-D compressing or 2-D compressing & 1-D stretching, the hydrostatic pressure of the region is the minimum, the hydrostatic pressure gradient is obviously bigger than that of the raceway bottom.
3. The whole blank surface deforming region is of compressing stress state, the direction of the raceway surface compressing strain is perpendicular to the surface, which assures that the final formed raceway is of residual compressing strain and the overall performance of the lead screw is improved.

Simulations and experiments show that ripple texture mainly occurs where the intermittent plastic deformations meet, the main factor affecting flaws of ripple texture and flanging occurring is the dramatic changing of stress gradient, the unevenness of stress gradient can be weakened through decreasing feeding per roller and optimizing the roller section shape.

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