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Metal Flowing of Involute Spline Cold Roll-beating Forming

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Abstract: The present research on involute spline cold roll-beating forming is mainly about the principles and motion relations of cold roll-beating, the theory of roller design, and the stress and strain field analysis of cold roll-beating, etc. However, the research on law of metal flow in the forming process of involute spline cold roll-beating is rare. According to the principle of involute spline cold roll-beating, the contact model between the rollers and the spline shaft blank in the process of cold roll-beating forming is established, and the theoretical analysis of metal flow in the cold roll-beating deforming region is proceeded. A finite element model of the spline cold roll-beating process is established, the formation mechanism of the involute spline tooth profile in cold roll-beating forming process is studied, and the node flow tracks of the deformation area are analyzed. The experimental research on the metal flow of cold roll-beating spline is conducted, and the metallographic structure variation, grain characteristics and metal flow line of the different tooth profile area are analyzed. The experimental results show that the particle flow directions of the deformable bodies in cold roll-beating deformation area are determined by the minimum moving resistance. There are five types of metal flow rules of the deforming region in the process of cold roll-beating forming. The characteristics of involute spline cold roll-beating forming are given, and the forming mechanism of involute spline cold roll-beating is revealed. This paper researches the law of metal flow in the forming process of involute spline cold roll-beating, which provides theoretical supports for solving the tooth profile forming quality problem.

Key words: involute spline, cold roll-beating forming, rheological rule, simulation

1 Introduction

Cold roll-beating technology exploits the plasticity of metal materials at room temperature; in this case, the material is an involute spline shaft. An involute spline is shaped after workpiece is continuously struck by high-speed rollers. Cold roll-beating is the latest technology in metal forming and is one of the most important processes in advanced manufacturing technology. It is also the latest technical development trend in the machining technology of involute spline shafts[1–2]. In the cold roll-beating process, the involute spline shaft undergoes severe plastic deformation, which not only includes material nonlinearity (stress and strain), but geometric nonlinearity (strain and displacement). At the same time, there exists the larger local load in deforming region during the cold roll-beating forming of an involute spline. Therefore, the mechanism is complicated and the presence of poor stability in quality will generate local deformation and less deformation. For this, it is necessary to study the regularity for revealing the mechanism to solve the problems of quality during the cold roll-beating forming of an involute spline.

YANG, et al[3], systematically studied control of unequal deformation. The formation was developed for in-plane blending by adjusting amount of pushing and shaping movement to change to loading conditions, which obtained the laws of unequal deformation of metal and forming limit. HU, et al[4], conveniently achieved the formation of three-dimensional curved surface of sheet mental, which highly improved flexibility in forming process. LI, et al[5], finished the forming process simulation of the cold roll-beating of involute spline and obtained the stress, strain and the metal flowing law of the forming process. HSU[6] proposed a mathematical model using an upper bound method for forging of spur gear forms and spline to investigate the plastic deformation behavior of billet within the die cavity. YANG, et al[7–9], studied the process principle of cold roll-beating, kinematic relationship and roller structure, and made a process experiment. LIU, et al[10], analyzed the principle and the force of involute spline cold rolling precision forming process and given the rule of the metal flow in the deforming area and the forming mechanics of the microstructure. In the forming process, the inhomogeneity and complexity of deformation degree and stress distribution are verified through experimental data analysis. The largest deformation area located in the transition fillet of the spline is gradually weakened along

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the center line. ABRINIA, et al[11], presented a generalized analytical upper bound method for the study of external shape, pressure, and torque in the single pass rolling of shaped sections. An upper bound on rolling power was established based on the calculated velocity fields. ZHANG, et al[12], analyzed the deformation process of external spline cold rolling and set up the slip-line field of plastically deforming area in process of external spline cold rolling by the graphing method. The research achieved the unit average pressure on contact surface of the rolling process according to the stress filed theory of slip-1ine. These methods provide the basis for the cold roll-beating technology of spline.

Presently, there are no local studies on the metal flow law governing the cold roll-beating forming of a spline. The changes in profile accuracy and dimensions are simply judged by means of experience. Therefore, research on the metal flow law and forming mechanism for cold roll-beating process of the involute spline has theoretical significance and engineering value, which can improve the forming quality of involute spline.

Based on the cold roll-beating forming principle of the spline, a contact model between a rolling machining wheel and a spline shaft blank during the cold roll-beating forming of a spline is established. Simulation analysis of cold roll-beating formation of Involute Spline is made through the theoretical analysis of the metal flow of the deforming region, which give the characteristics of the cold roll-beating forming of a spline.An experimental study of metal flow is also conducted, the mechanism of the cold roll-beating forming of a spline is revealed. All these analyses provide theoretical support to the study of the cold roll-beating forming technology of a complex curved surface.

2 Building a Contact Model of Involute Spline in Cold Roll-beating

The principle of involute spline's cold roll-beating[13–14] is shown in Fig. 1. A pair of roller, which have a certain contour shape, are respectively mounted on the two high-speed rotating shaft (rolling axis), and the two rolling shaft counter rotate synchronously with the angular velocity ω_g. Rollers hit the workpiece once while rolling axis of a turn each. Due to the friction between the workpiece and the rollers, when two rollers contact with the workpiece, rollers rotate with angular velocity ω_r to realize rolling motion between the workpiece and the rollers. In the process of rolling, the workpiece rotate consecutively with the angular speed ω_1 and axial move with the axial feed speed f, wherein $\omega_g/\omega_1=Z$ (involute spline teeth); the uniform involute tooth are formed by continuous striking on the workpiece.

The cold roll-beating process results in local deformation. The spline shaft blank is the deformable body while the roller is the rigid body. Taking the local region of forming as the object of the research, and a cogging of spline is analyzed at a given time because the cold roll-beating of a spline is symmetric. The contact model of a cold roll-beating model of a spline is shown in Fig. 2. In Fig. 2, *OABCD* is the deformable zone and *DCB* is the boundary between the deformable and non-deformable zones. Based on different stress conditions, the flows of the metal are divided into *ACDO* and *ABC* by the boundary line *AC*.

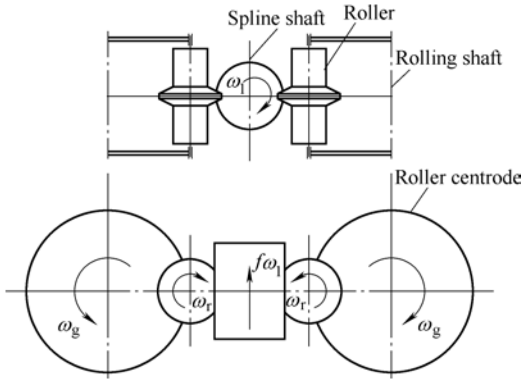


Fig. 1. Principle of involute spline's cold roll-beating

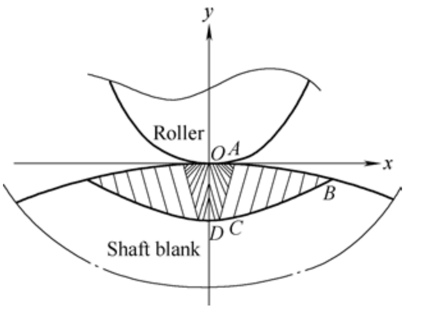


Fig. 2. Model of roller and shaft blank

3 Theoretical Analysis of Metal Flowing of Involute Spline in Cold Roll-beating Forming

From the whole deformable zone, it is zone *AB* where the material point flows. On the one hand, the principle of least resistance (which states that resistance is proportional to the distance) and the principle of volume invariability explain why the metal does not flow to the y direction. On the other hand, the material point located at *ABC* flows to the *AB* boundary line because of internal force influence, thus the material point located at *ACDO* flows to *ABC* along a fixed track.

3.1 Flowing analysis of the *ACDO* region

For the mathematical expressions that follow, f represents flow resistance and I represent flow trends. For any particle in this region, there are trends I_y flowing to y and trends I_x flowing to the least resistance boundary *AB* under pressure. Therefore, any particle in this region has the trends I flowing to the outer boundary (*AB* region) or *ABC* region towards a direction having α angle to x axis.

As shown in Fig. 3, the y coordinates of L and M chosen in the region of *ACDO* are the same while the x coordinates are different. In addition, the x coordinates of M and N are the same while the y coordinates are different. As for L and M, the distance of L from AB is shorter than M in x, so the resistance of L is small in x, $f_{Mx} > f_{Lx}$. According to the least resistance principle, the smaller the resistance, the bigger the flow trends, so $I_{Mx} < I_{Lx}$. Furthermore, because the y coordinates of two points are the same, the y resistance of L and M may be assumed as equal: $f_{My} = f_{Ly}$ and $I_{My} = I_{Ly}$. By principle, $I_M < I_L$ may also be assumed; that is, the flow trends of L are bigger than M and the flow direction of L trends to the AB boundary, while the flow direction of M trends to y.

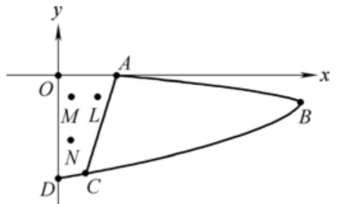


Fig. 3. Particles in *ACDO*

Similarly, the following trends are seen: $I_{Mx} = I_{Nx}$, $I_{My} = I_{Ny}$, $I_M > I_L$. These illustrate that 1) the flow trend of M is bigger than N, 2) the flow direction of N trends to the AB boundary, and 3) the flow direction of M trends to y. Fig. 4 below shows the aforementioned results.

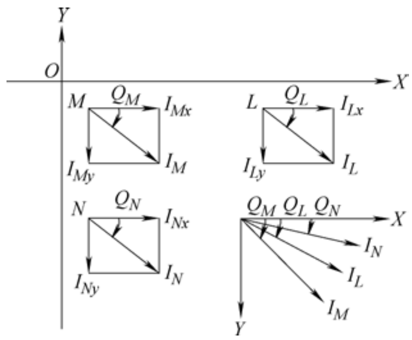


Fig. 4. Particle flow trend

3.2 Rheological analysis of the *ABC* region

The assumptions in section 3.1 can prove that there are trends of flowing into the *ABC* region influenced by different flow directions of some particles in the *ACDO* region, essentially leading the particles in the *ABC* region to flow under the effect of internal power. All the particles in the *ABC* region flow to the *AB* boundary according to the principle of least resistance, because the *BC* edge of the *ABC* region is the region without distortion of the blank, whereas *AB* edge is the boundary line.

3.3 Metal flow path of the forming region

According to the above analysis, there are five kinds of flow paths in the forming zone.

1) The particles close to the contact area *OA*. Under the press of the roller, they flow to the periphery and constantly flow to the region beside the *AB* boundary with the depth of cold roll-beating. This is shown as path 1 in Fig. 5.

2) The particles close to *OD* in the *ACDO* region. Although they flow to the *ABC* region from the x-axis along different angles and flow velocities in the process of cold roll-beating, they do not flow to the *ABC* region according to the trends in the *ACDO* region, even when the cold roll-beating ends. This is shown as path 2 in Fig. 5.

3) The particles belonging entirely to the *ABC* region. According to the incompressible theory, the metal from the *ABC* region will flow to the *AB* boundary that obviously gets little effect from the internal press because metal constantly flows to the *ABC* region in the *ACDO* region. This is shown as path 3 in Fig. 5.

4) Blended particles between the *ACDO* and *ABC* regions. The particles close to the *AC* line in the *ACDO* region will continue flowing by the flow pattern of the *ABC* region because of the larger deformation and after flowing to the *ABC* region under the flowing trend influence of the *ACDO* region. This is shown as path 4 in Fig. 5.

5) The particles on the center line of *OD*. They only flow along the *OD* direction because the left and right sides are symmetrical and the pressure is balanced. This is shown as path 5 in Fig. 5.

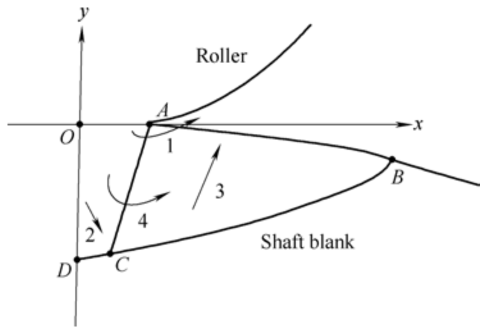


Fig. 5. Metal flow trend in analysis results

4 Finite Element Simulation of Involute Spline Cold Roll-beating Forming

4.1 Finite element model of a involute spline cold roll-beating forming

4.1.1 *Material model*

(1) Shaft blank material model. The blank uses tempered steel 40Cr. Plastic deformation in forming process and noncontinuous features of loads in rolling process are considered, so the selecting material is kinematic hardening model.

(2) Roller material model. The material of roller is W2Mo9Cr4VCo8, super hard high-speed steel containing cobalt, with high hardness, good heat resistance, great wear resistance, good strength and toughness. Because of its high

rigidity and without plastic yielding, the roller is regarded as the rigid body and self-deformation is neglected. The selecting material is rigid material model.

4.1.2 Geometric model

The radius of the roller is 19 mm; the profile is involute. And the basic parameters are shown in Ref. [15].

The blank diameter is 41.7 mm based on the calculation formula. The turning radius of the roller is 36 mm, and the rotation on its own axis is free state. The shaft blank is slender and symmetric. Only a half model of the shaft blank (length 8 mm) is used to reduce computational complexity. The simplified model is shown in Fig. 6.

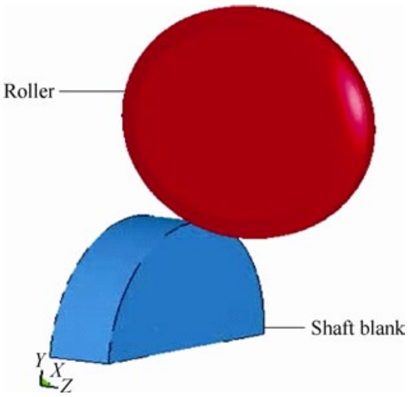


Fig. 6. Geometry model of cold roll-beating

4.1.3 Model of FEM mesh

The shaft blank uses solid 164. The roller is regarded as the rigid body without considering deformation, and it uses a shell element for meshing to improve computing efficiency. The partial thinning mesh and remesh can be used to improve accuracy. As for the non-forming region of shaft blank and roller, without deformation, the free mesh is used to speed calculation. Fig. 7 shows the mesh model.

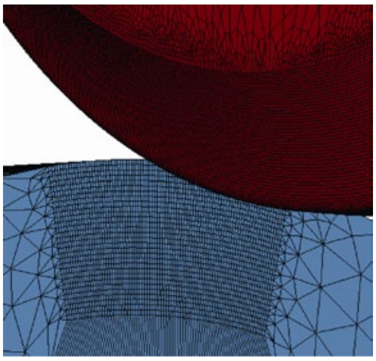


Fig. 7. Local mesh model

4.1.4 Contact, friction, and boundary conditions

(1) Definition of contact body. In the contact of roller and work piece, the plane-plane contact of deformable body and rigid body is used based on the relationship between roller and work piece. In this simulation, the contact interface is prone to be penetrated, so the penalty factor is 1.6 after lots of trial and error.

(2) Definition of friction. The coefficient of kinetic friction is 0.12 and the static friction coefficient is 0.2.

(3) Boundary conditions. Axial symmetry constraint is applied on the symmetrical plane of the shaft blank, and the axial feed speed of the shaft blank is 1.5 mm/s; the three translational freedom of rollers and two rotary freedom paralleling Y and Z direction should be constrained. What's more, the rotational speed of the rollers circled the rolling shaft (X axis) is 2 000 r/min.

4.2 Results of FEM

Fig. 8 shows the process of cold roll-beating. In Fig. 8, the metal flows to the blank of the roller under pressure. The tooth profile of the spline and the convex corner of the addendum are formed in the flow, in which the metal flows along the outer surface of roller up. The whole process is basically accorded with constancy of volume. The extrusion part is equal to the reduction part, forming the tooth profile of the spline together.

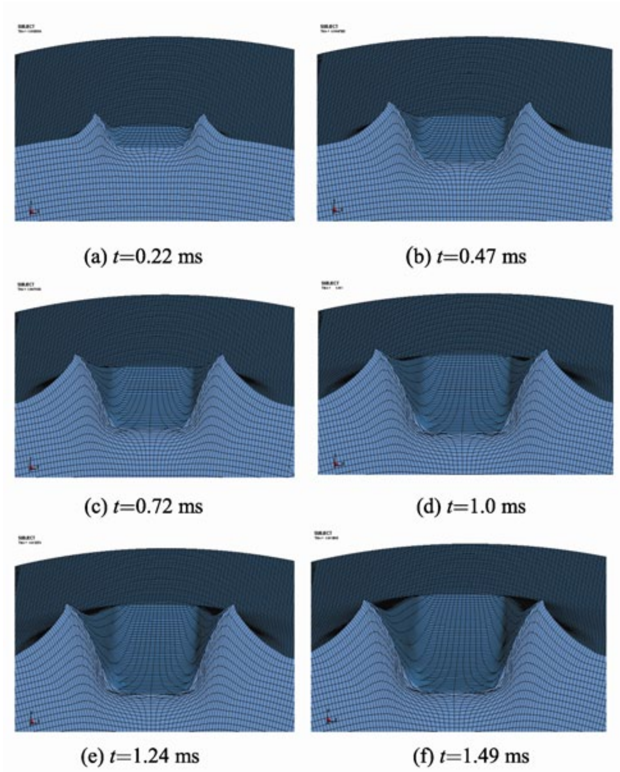


Fig. 8. Process of cold roll-beating

The flow traces of the part nodes in the simulation are shown in Fig. 9. From Fig. 9, the nodes in the contact zone, which close to the perimeter zone, flow to the blank zone (such as 284 019, 284 016, 284 014, etc). Its flow track is formulated as track 1 shown in Fig. 10. The mean flowing direction of the nodes (such as 285 217, 285 172, etc) close to the region of the center line is at a certain oblique angle to the center line, which is approximate to leaner flow; its flow traces can be attributed to track 2 shown in Figure 10. The flow paths of both sides of the nodes far from the deformation region (such as 284 603, 284 576, 284 462, etc) flow out of the blank in a fixed direction as an approximate line, which can be attributed to track 3 shown in Fig. 10. The nodes positioned in the center of the right half cogging zone (such as 299 432 and 285 158, etc) flow to a certain curve track in the forming region, but their nodes cannot flow out of blank zone. The corresponding flow path can be attributed to track 4 shown in Fig. 10. The nodes represented by 284 010 flows up along the center line of cogging, which can be attributed to track 5 shown in Fig. 10.

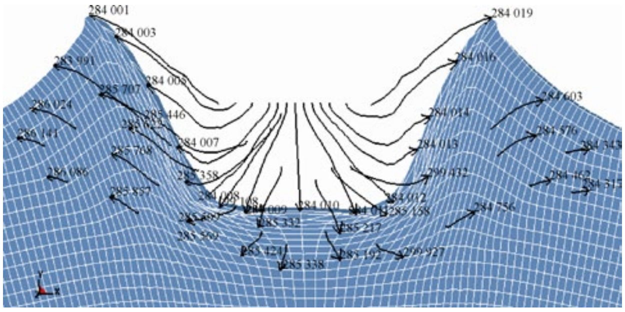


Fig. 9.　Metal flow tracks in simulation result

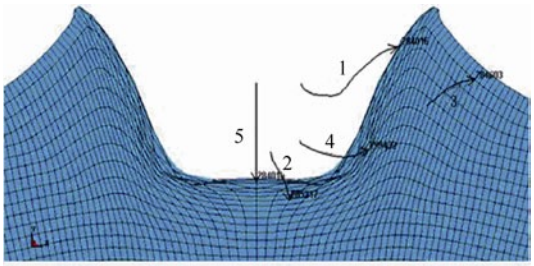


Fig. 10.　The whole flow trend in simulation results

The whole flow trend in the simulation results (Fig. 10) is basically anastomosed with the flow trend in the theoretical analysis (Fig. 5).

5　Experimental Study

Based on the conditions and process parameter of the simulation analysis, the cold roll-beating processing of involute spline is carried on. The experimental study on the metallographic structure and microstructure of the involute spline are conducted, and the flowing law of the metal structure and its change are analyzed.

5.1　Experimental scheme

(1) A section of the spline formed by cold roll-beating is collected as a sample.

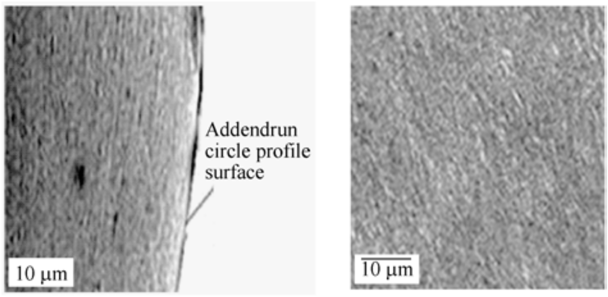
(2) The sample surface is ground and polished to achieve the requirement of a standard metallographic sample. It is then corroded to silver gray by 4% alcohol.

(3) The metal structure is observed using Neophot-1 and JEOL JSM-5610LV.

(4) The sample is transmitted using PIPS691. The microstructure is observed using H-8001 TEM.

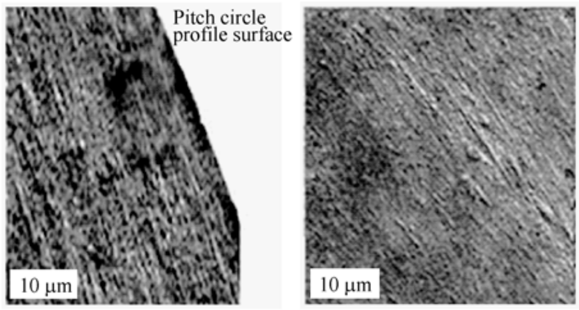
5.2　Experimental results

Fig. 11, Fig.12 and Fig. 13 show the addendum, pitch circle, and dedendum respectively, observed with scanning electron microscope JEOL JSM-5610LV magnified 500 times. Fig. 14 is the microstructure under transmission electron microscope.



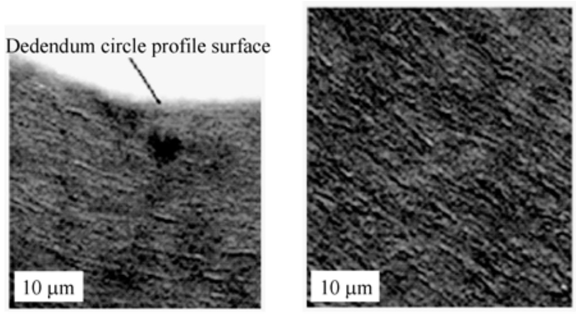
(a) Surface　　(b) Surface normal

Fig. 11.　Experimental results with a step signal



(a) Surface　　(b) Surface normal

Fig. 12.　Structure change of normal pitch circle



(a) Surface　　(b) Surface normal

Fig. 13.　Structure change of normal dedendum

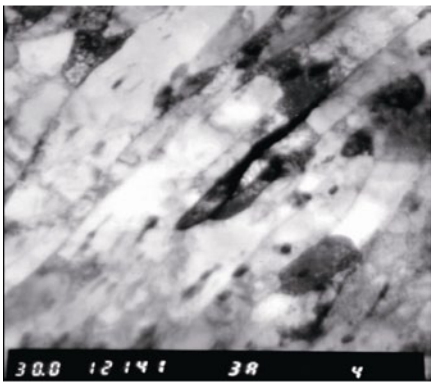


Fig. 14.　Metal microstructure of cold roll-beating

5.3 Analysis of experimental results

When the spline is hit by the roller, the metal will flow to the axial surroundings of the roller under stress. At this time, the equiaxed grain is extended and distorted to the orientation of the metal deformation. When the deformation is big enough and the grain boundary gets blurred (i.e., the grain cannot be distinguished easily), the slip fibrous tissue that is continuously distributed along the surface of the tooth is finally pulled, as shown in Fig. 11(a), Fig. 12(a) and Fig. 13(a). In the process of plastic deformation, the substructure changes as follows: with increasing deformation, the grain is stretched, the misalignment is enhanced rapidly, and the magnitude of sliding is increased continuously; even the original grain and inclusion are crushed continuously and refined, forming the new grain or subgrain. The differences between the new grain and the original grain are not clear and cannot be distinguished, as shown in Fig. 14. The magnitude of refining is also different because the stress from the addendum, pitch circle, and bottom is different in the process of plastic deformation. From Fig. 11(b), Fig. 12(b) and Fig. 13(b), the following conclusions can be made: The grain in the bottom is the most detailed, the grain in the addendum is the roughest, and the grain in the pitch circle is medium.

As explained in section 3 and 4, the stress imposed by roller and the metal flowing of involute spline are different from addendum, pitch circle, and dedendum, which lead to the diversification of the metal structure. The metal in the process will flow to the direction of the least resistance. At the addendum, the stress of the blank imposed by the roller is relatively small, and the resistance power is least when the metal flows to the upper left side. However, the metal flow is not gradual and leads to the convex of the addendum sides, which also results in few elongated metal fibrous tissue that gets scattered along the normal addendum, as shown in Fig. 11(a). Fig. 12(a) shows that the part of metal in the pitch circle is similar to linear flowing. The intensity of the flow lines in the pitch circle is larger than in the addendum because the both sides of the roller simultaneously act on the both sides of the cogging where the stress is bigger than that in the addendum. The stress of the dedendum is the largest, where the metal can only flow down and to both sides, instead of flowing to the outside of the blank. So, the deformation of the dedendum is the largest and the density of elongated fibrous tissue is also the largest, as shown in Fig. 13(a).

In short, fibrous tissue is not cut in the machine process of cold roll-beating; the grain is crushed, refined, and the density of misalignment increased with the development of plastic deformation, resulting in a metal structure that is distributed along the radial tooth surface in a streamlined manner. Owing to the different flowing directions of the metal particles, their every location deformation is also entirely different. The closer it is to the bottom, the more intensive the effect on fibrous tissue becomes. More particularly, the metal fiber is bent intensively along the cogging. The organizational structure and mechanical properties in the metal's interior are changed by cold roll-beating. With increasing deformation, the phenomenon of work hardening appears, resulting in the increased strength and hardness of the metal.

6 Shaping Characteristics of Cold Roll-beating

As stated previously, the shaping characteristics of the spline is obtained through the law of volume constancy.

(1) Roller beating shaft blank forces the mental to flow to the axle center and excircle divided by the interface of a certain circle, leading partial metal protruding to form tooth profile.

(2) The shaft blank undergoes local deformation through high-speed exploding. The internal stress spreads from the surface to the inside under the effect of impact load. The crystal moves with minimum drag. The shift dwindles from the surface to the inside, which significantly improves the quality of the surface.

(3) The roller has rotational freedom, and the contact surface is rolling friction. Due to small resistance of metal in the tangential contact, the metal fiber is not destroyed. Thus, the surface of the spline is smooth and highly polished.

(4) The bottom of tooth of the spline is net-shaped, the other parts are progressive forming. Elastic recovery after each punch has completed before next hit. This leads to a minimal recovery of elasticity and a high precision of the formed part.

7 Conclusions

(1) According to the principle of cold roll-beating, the contact model of a spline between a blank shaft and a roller is built. According to the principle of least resistance, the five flowing laws of metal can be obtained through an analysis of the flow region.

(2) The finite element model of cold roll-beating is built and the forming of a spline is simulated. The analyses state that the flow regions have five flowing laws and their characteristics are obtained.

(3) Results of the experimental study indicate that the metal flows around the roller under pressure to form the tooth profile of the spline as the roller is hitting the shaft blank; in the cold roll-beating process, fibrous tissue is developed with the plastic deformation, and that the metal structure is streamlined along the radial distribution. The grain is refined, and the dislocation density increases. Simultaneously, the deformation degree of metal varies with different positions.

(4) The closer it is to the bottom, the more intensive the effect on fibrous tissue becomes, especially in the bottom of the tooth, where the metal fibers intensively curve along the tooth profile.

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