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Research on continuous multi-point forming method for rotary surface

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ABSTRACT

In order to realize high efficient and flexible manufacturing for 3-D surface, continuous multi-point forming (CMPF) is researched. Firstly, principle of CMPF is described, and its characteristics are analyzed by comparing with the conventional spinning methods. Secondly, FEA model of CMPF for disc-shape surface is established, forming load is analyzed theoretically, equivalent stress and plastic strain distributions of disc-shape surface are analyzed. Thirdly, wrinkling is analyzed through simulation results. Fourthly, forming process of tube-shape surface is studied. Finally, CMPF equipment is developed, and experiments are carried out. Results indicate: For disc-shape surface, equivalent stress in regions of center fixture and flexible roller exceeds yield stress; the maximum plastic strain is generated in center region; plastic strain in region of flexible roller takes the second place; shell elements in wrinkling region generate tangent direction compress deformation. For tube-shape surface, maximum value of equivalent stress appears in region of flexible roller; plastic strain field presents annular distribution, its maximum value appears in marginal region. Measure results of curvature radius of disc-shape surface and tube-shape surface almost accord with simulation results. Simulation results of stress field, strain field and wrinkling almost accord with practical situation.

1. Introduction

Multi-point forming is a flexible manufacturing method for 3-D surface. Its basic idea is to divide an entire die into many punches which can be arranged and adjusted precisely. These punches constitute a “configurable multi-point die”. 3-D surface can be formed by the “configurable multi-point dies”. The concept of multi-point forming was put forward in Japan initially. Nakajima (1969) gave the concept of adjustable discrete surface tooling firstly. He made a die by using wires and fabricated a simple equipment. The surface of the die can be variable by adjusting the height of each wire manually; different surface sheet metal can be formed by the dies. Nakajima’s work is the first attempt and provides other researchers with a new idea. Nishioka (1973) trial-produced a universal press machine based on the adjustable discrete tooling principle. The universal press machine was composed of an upper flexible die and a lower flexible die, which were controlled by computer. The die was made up of many punches. The punch of upper flexible die was driven by hydraulic cylinder, and the punch of lower flexible die was driven by gear reducer motor. He discussed surface quality and springback of formed surface part. Nishioka’s work realized the automatization of multi-point forming, and promoted the development of multi-point forming. After 1990, researchers in Tokyo University and Tokyo Industry University also researched multi-point forming deeply. In USA, Walczyk and Hardt (1998) and Webb and Hardt (1991) did an extensive research on multi-point forming. They proposed a closed loop shape control system for variable configuration discrete element die, and made an experimental equipment controlled by computer. Deep drawing experiment was carried out by the equipment, and forming accuracy was measured by the closed loop shape control system. That the concept of closed loop shape control system was put forward is a big progress for multi-point forming. In Germany, Finckenstein and Kleiner (1991) described the development of a flexible, numerically controlled tool system for deep drawing and stretching. They pointed out that the tool system consists of a matrix of 1089 rods, which form the drawing die by adjusting them individually. The shape of workpiece was constructed with a CAD-system; the control data for the tool adjustment was generated automatically out of the workpiece geometry by a special software. Their work shows that a surface construction software and a automatic control software are necessary for flexible drawing tool (multi-point forming). In India, Rao and Dhande (2002) draped the discrete surface tool elements with a flexible sheet of rubber-like material to provide a continuous surface, and named it flexible surface tooling. Computational simulation was carried out on the flexible surface tooling, and it was indicated that the flexible surface tooling is an option for sheet forming process in general and for processes like composite layup in particular. In

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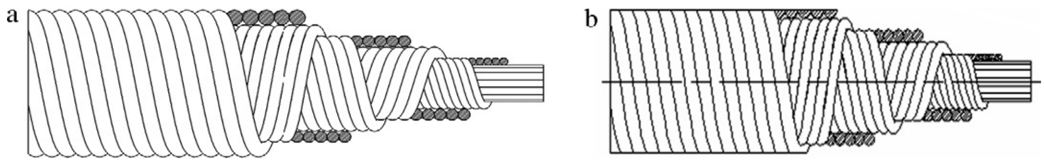

Fig. 1. Schematic diagram of the flexible roller.

China, Li and Liu (1999) studied basic theory and practical technology of multi-point forming deeply. For basic theory, they proposed four basic methods for multi-point forming, and proposed a repeating forming method which can control springback effectively. For practical technology, they developed the first multi-point forming practical prototype. Their work lays a solid foundation for practicality of multi-point forming. At present, multi-point forming has been applied in many domains, such as the forming of aircraft's skin, the forming of human skull repair body, the forming of high-speed train head's cover surface, and the forming of submarine's hull in China. The developmental trend of multi-point forming is high precision, large-scale working surface, and continuous forming. Li et al. (2007) proposed a new method which is called continuous multi-point forming (CMPF). It is the combination of multi-point forming and continuous forming (rolling or spinning). They developed an experimental equipment and carried out some experiments. The experimental results show that 3-D surface can be formed by a continuous local forming method.

Rotary surfaces are applied in industries of aviation, chemistry, machine and automobile, and also play a very important role in scientific research and industry. In the last two decades or so, spinning has gradually matured as rotary surface forming process for the production of engineering components in small to medium batch quantities. Wong et al. (2003) reviewed the principle and the development of spinning. He indicated that spinning has a great potential in the development for manufacturing complex shapes, which are being required in increasing numbers by global manufacturing industries. Music et al. (2010) surveyed most academic work on the analysis and application of the mechanics of spinning. They aimed to provide insight into the mechanics of the process and act as a guide for researchers. They indicated that existing work reveals several gaps in current knowledge of spinning mechanics, and that the study on novel process configurations in spinning show great potential for innovation in spinning exists. The spinning process has the potential to be more flexible, to manufacture a wider range of shapes, and to form more challenging materials.

Conventional method for rotary surface—spinning—adopts rotary wheel as forming tool to manufacture workpieces. The classification of spinning into conventional spinning, shear spinning and tube spinning is widely accepted. During spinning process, rotary wheel contacts sheet metal in a small region which can be considered as a point region. Sheet metal can be formed by the point contact forming method, but manufacturing efficiency is low. During forming process of rotary surface, if there is no die to support the sheet metal, lower precision of the point contact forming method will be exposed. In order to enhance the forming efficiency, the best way is to increase the area of forming region. Therefore, a bendable flexible roller is adopted to replace the rotary wheel in order to realize above idea; meanwhile, integrating with multi-point adjusting technology, a new forming method which is called CMPF for rotary surface comes into being.

2. Principle and characteristics of continuous multi-point forming for rotary surface

Adopting flexible roller as forming tool, and combining multi-point adjusting technology to make sheet metal continuous formed, this method is continuous multi-point forming. Through this method, rotary movement of sheet metal can be realized, and then rotary surface part can be formed. Flexible roller contacts sheet metal directly and makes it generate deformation, so the flexible roller must have three characteristics: first, it can bend along its axis; second, it has certain rigidity along its radial direction; third, it can rotate along it axis. Steel wire flexible shaft was adopted as the flexible roller. It is made from many steel wires which enwind several steel core wires. In order to make the surface of flexible roller smooth, the surface of flexible roller is grinded. Fig. 1 shows schematic diagram of the flexible roller. Diameter of the flexible roller is 19 mm; its minimum bendable radius is 280 mm; its maximum torque is 76 Nm. After grinding, diameter of the flexible roller becomes to 17 mm. In order to adjust the bendable form of flexible roller, and keep the bendable form after adjusting, adjusting element must be used. Each adjusting element controls a part of flexible roller. When all adjusting elements are arranged together, the whole flexible roller can be controlled by them. Fig. 2 shows the structure of adjusting element. It consists of adjusting body, pin and holder. There is a thread hole inside the adjusting body, so the adjusting body can move up and down through screw drive method. The holder holds the flexible roller. When the flexible roller bends, the holder can swing along an axis which is determined by the pin. The dimension of the adjusting element is $90 \times 30 \times 15$ mm. Fig. 3 shows that the flexible roller is adjusted by the adjusting elements. Movement of the adjusting element can be controlled manually or automatically.

Fig. 2. Structure of adjusting element.

Fig. 4 shows schematic diagram of continuous multi-point forming for rotary surface. Forming process is shown as follow: first, flexible roller is adjusted by adjusting elements to obtain desired curvature; second, sheet metal is clamped by center fixture, and relative position between sheet metal and flexible roller is adjusted; third, upper flexible roller moves down to contact sheet metal and make it local plastic formed; finally, flexible roller rotates and drives sheet metal and center fixture rotate, then rotary surface is formed. When manufacturing another shape rotary surface, the

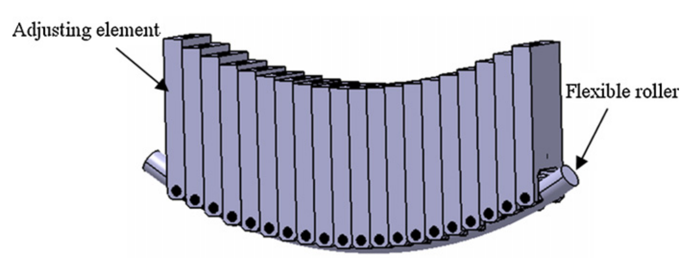

Fig. 3. Flexible roller is adjusted by adjusting elements.

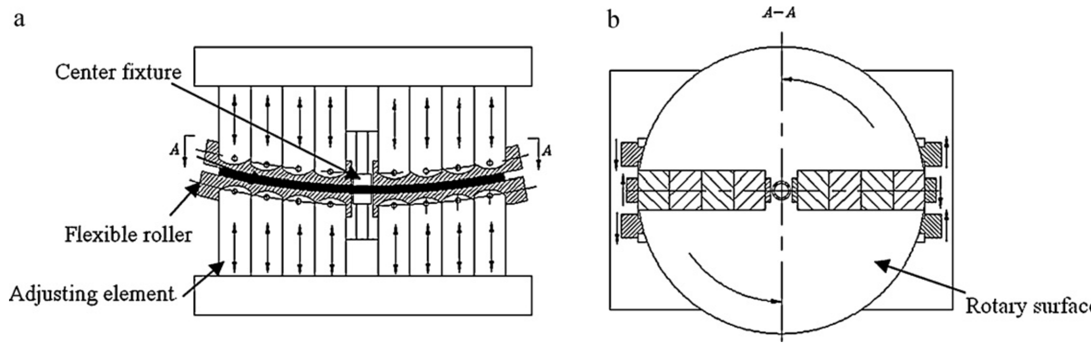

Fig. 4. Schematic diagram of continuous multi-point forming for rotary surface.

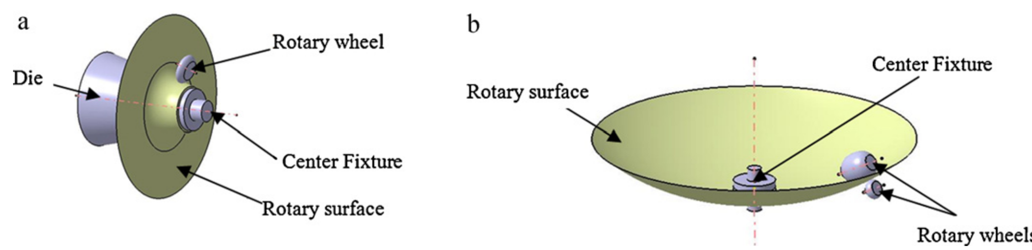

Fig. 5. Schematic diagram of conventional spinning.

flexible roller needs to be adjusted again according to the shape of desired rotary surface by controlling displacement of the adjusting elements. Rotary directions of flexible rollers and rotary surface are shown in Fig. 4.

Conventional spinning method for rotary surface is shown in Fig. 5. Die is not used in Fig. 5(a), while it is used in Fig. 5(b). For Fig. 5(a), sheet metal is clamped by center fixture which is rotated by hydraulic motor. Two rotary wheels are rotated by motor along each axis. The rotary wheels can be adjusted along upper, lower, left and right directions, and can swing along the axis which is perpendicular to each rotary axis. The method is widely used in forming disc-shape head. Li (2006) simulated the process of disc-shape head formed by the method shown in Fig. 5(a). His work provided dependable basis for confirming the energetics parameter and structure optimization of spinner body. For Fig. 5(b), sheet metal is clamped on die by center fixture. The die and the center fixture rotate together, and make the sheet metal rotate. Certain movement track is designed for rotary wheel, which makes the sheet metal generate deformation, and makes shape of the sheet metal accord with the shape of the die. Sheet metal is formed by acting force between rotary wheel and sheet metal in above methods. Contact region between rotary wheel and sheet metal is small, it can be considered as a point region. Forming track of conventional method for rotary surface is shown in Fig. 6, while forming track of continuous multi-point forming is shown in Fig. 7. As we can see, forming region of conventional method is the active region of rotary wheel, forming region of continuous multi-point forming is the active region of flexible roller, the latter is several times or several decuple bigger than the former. For conventional spinning, the forming region is a point region; it accumulates gradually along a definite track, and forms a desired rotary surface part at last. For continuous multi-point forming, the forming region is a line region; it accumulates gradually along a definite track to form a desired part. Because the area of forming region increases, the deformation of sheet metal is much more homogeneous, forming effect and efficiency are also improved. Different shape parts can be formed by adjusting the curvature of flexible roller, so the flexible manufacturing feature is not changed when the forming region increases in continuous multi-point forming.

3. Numerical simulation of forming process

3.1. Establishment of finite element model

Disc-shape part is a basic and typical rotary surface part. In order to research forming process of rotary surface deeply, numerical simulation is needed to introduce. For forming disc-shape part, two group flexible rollers (shown in Fig. 4) or one group flexible rollers (shown in Fig. 8) both can be used. Through experiments, it was found that using two group flexible rollers costs much adjusting time, so using one group flexible roller to form the sheet metal is often adopted. In simulation process, one group flexible roller is adopted, which accords with real situation. Material is steel 1008 (ASTM), whose attribute is shown in Table 1. Technical parameters are shown in Table 2. Finite element model is shown in Fig. 8.

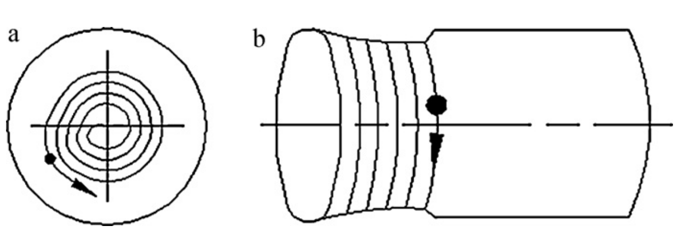

Fig. 6. Forming track of conventional manufacturing method.

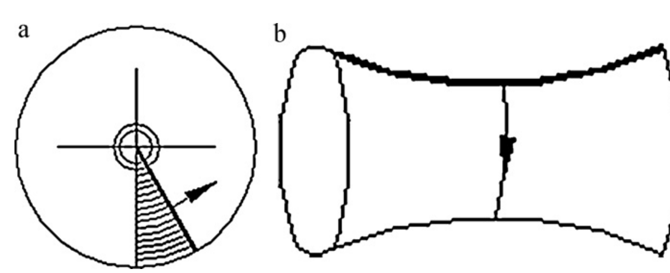

Fig. 7. Forming track of continuous multi-point forming.

Table 1
Material parameters.

Material	Density/kg/m^3	Elastic modulus/GPa	Poisson's ratio	Yield stress/MPa	Tangent modulus/MPa	*r*
Steel 1008	7845	207	0.29	207	20.2	1.41

Table 2
Technical parameters.

Curvature of flexible roller/mm	Diameter of flexible roller/mm	Space between two lower rollers/mm	Diameter of sheet metal/mm	Thickness of sheet metal/mm	Press displacement of upper flexible roller/mm	Press/kN
600	17	41	280	0.5, 2	0.5	1.7

CMPF is a complex plastic forming process, which is characterized by large deformation, geometric non-linear, material non-linear and contact non-linear, so explicit dynamical analytical software ANSYS/LS-DYNA is used to simulate the process of CMPF. Shell 163 element and transversely anisotropic elastic plastic material model are used for sheet metal. Shell 163 element and rigid body material model are used for flexible roller. Shell 163 is a 4-node element with both bending and membrane capabilities, both in-plane and normal loads are permitted, it has 12 degrees of freedom at each node: translations, accelerations, and velocities in the nodal *x*, *y*, and *z* directions and rotations about the nodal *x*, *y*, and *z*-axes. Belytschko–Wong–Chiang formulation is adopted for shell 163 element; it generally gives correct results for warping, so it is fit for the analysis of sheet metal forming. Flexible roller rotates along a bended axis; in order to simulate the rotation of the flexible roller, it must be divided into many segments. The segment is cylindrical shape, and rotates along its axis. The real rotary speed of flexible roller is 2.19 rad/s. If the real rotary speed is used in simulation, the calculated time is too long and the simulated results cannot be obtained probably, so the simulation rotary speed needs to be increased. If the simulation rotary speed is too large, the reliability of simulation is weak, so the simulation rotary speed is defined as 21.9 rad/s by many attempts. Contact mode between flexible roller and sheet metal is automatic surface to surface mode. Penalty function contact algorithm is adopted. Static friction factor is 0.3, and dynamic friction factor is 0.2.

3.2. Analysis of forming Load

When rotary surface is formed, the force that the rotary surface bears comes from two aspects. One is the force which is exerted by center fixture; the other is the force which is exerted by flexible roller. Fig. 9 shows force condition of CMPF for rotary surface. Center region of sheet metal bears press from center fixture; when the sheet metal is rotated by center fixture and flexible roller, it also bears torque. In the forming region, the sheet metal bears the force which is exerted by flexible rollers. Based on static analysis and elastic–plastic mechanics, the force exerted by flexible rollers can be divided into transversal load and longitudinal load. In order to study the transversal load and the longitudinal load, local transversal bending and local longitudinal bending are defined. Local transversal bending starts with that flexible rollers contact sheet metal, and ends with that the whole flexible rollers contact sheet metal neither more nor less than, that is, there is no press displacement along normal direction of sheet metal. Local longitudinal bending starts with that the whole flexible rollers contact sheet metal neither more nor less than, then every part of upper flexible roller generates certain press displacement along normal direction of sheet metal.

The following analysis is based on Euler–Bernouli plane section hypothesis and single direction stress hypothesis. Stress and strain curves of stretching and pressing are the same, they are $\sigma = f(\varepsilon)$. Material of sheet metal is considered as ideal elastic–plastic material, yield stress is σ_s. The sheet metal in Fig. 9 is taken as research object. Sheet metal generates transversal bending deformation by transversal load P_t. Space between two support points is $b = 2R_t \sin \alpha$

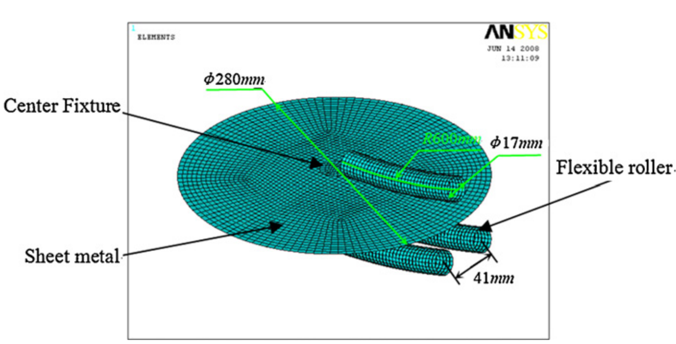

Fig. 8. FEA model of disc-shape surface.

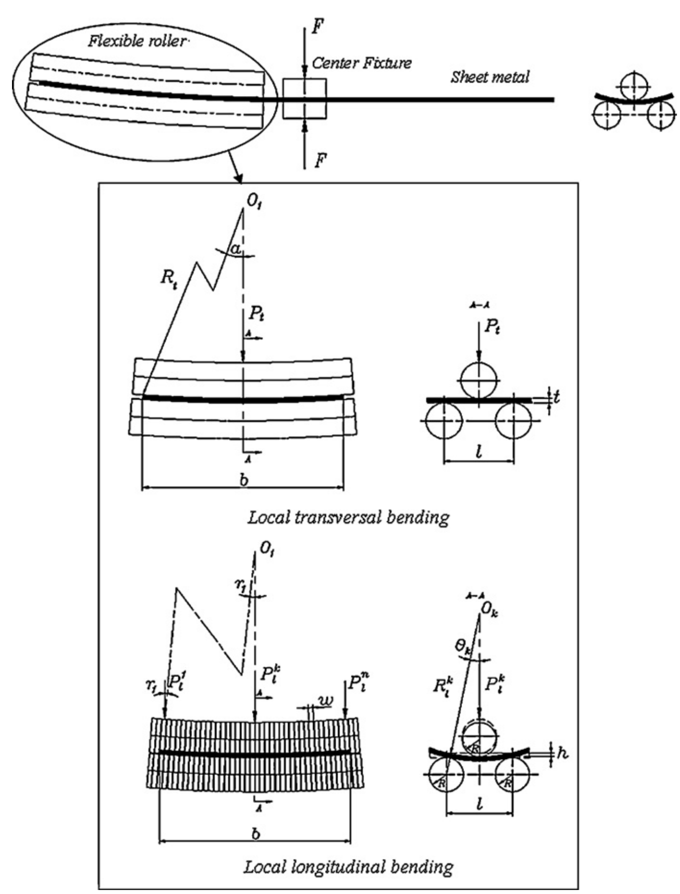

Fig. 9. Schematic diagram of force condition of CMPF for rotary surface.

$\alpha = 90B/R_t\pi$. R_t is transversal curvature radius of sheet metal upper surface. B is width of sheet metal. L is space between two lower flexible rollers. In this case, center section of sheet metal bears maximum bending moment, which is

$$M_{\max}^t = \frac{1}{4}P_t b = 2\int_0^{t/2} \sigma lzdz = 2\int_0^{t/2} f(\varepsilon)lzdz \qquad (1)$$

In formula (1), t is thickness of sheet metal, σ is stress of section, z is distance between any point of section and neutral axis. When sheet metal generates plastic deformation, formula (1) turns to

$$\frac{1}{4}P_t b = 2\int_0^{t/2} \sigma_s lzdz = \frac{1}{4}\sigma_s lt^2 \qquad (2)$$

Then

$$P_t = \frac{\sigma_s lt^2}{2R_t \sin\alpha} \qquad (3)$$

P_t is the transversal load. Formula (3) has some constraint conditions. B/R_t is not close to zero. When R_t is confirmed, B cannot be close to zero, because if the width of sheet metal is very narrow, its deformation no longer belongs to bending deformation, the transversal bending can be neglected. When B is confirmed, R_t cannot be close to infinite, because if the transversal radius is infinite, the transversal bending also can be neglected.

After transversal bending, if the flexible rollers rotate directly, the sheet metal only generates transversal bending deformation. In order to make sheet metal generate double direction bending deformation, the sheet metal must generate both transversal bending deformation and longitudinal bending deformation. Because the flexible roller is bendable and it only can generate press displacement along erect direction, so the press displacement of every part of flexible roller along normal direction of sheet metal is different, the deformation of each part of sheet metal along its normal direction is also different. In order to study longitudinal load, the flexible roller is divided into many short segments shown in Fig. 9. These short segments constitute the shape of flexible roller; each segment manufactures the sheet metal whose width is the same as the width of segment.

The longitudinal load P_l can be divided into many loads of segment, that is, $P_l = {P_l}^1 + {P_l}^2 + \ldots + {P_l}^n$. The k segment is taken as research object. Because the bending moment caused by external load is equal to the bending moment caused by internal force, so the equation is

$$M_l^k = \frac{1}{4}P_l^k \cos\gamma_k(l - 2R\sin\theta_k) = 2\int_0^{t/2} \sigma wzdz = 2\int_0^{t/2} f(\varepsilon)wzdz \qquad (4)$$

where R is the radius of flexible roller; w is the width of segment, it is equal to the diameter of steel wire generally. From geometrical relationship in Fig. 9, the following equations can be obtained.

$$\sin\theta_k = \frac{l}{2(R_l^k + t + R)} \qquad (5)$$

$$R_l^k = \frac{4(h\cos\gamma_k)^2 + l^2 - 8h(R+t)\cos\gamma_k}{8h\cos\gamma_k} \qquad (6)$$

where $h\cos\gamma_k$ is the press displacement of k segment along normal direction of sheet metal; h is the press displacement of the whole flexible roller along erect direction. When sheet metal generates plastic deformation, formula (4) turns to

$$\frac{1}{4}P_l^k \cos\gamma_k(l - 2R\sin\theta_k) = 2\int_0^{t/2} \sigma_s wzdz = \frac{1}{4}\sigma_s wt^2 \qquad (7)$$

Then

$$P_l^k = \frac{\sigma_s wt^2}{\cos\gamma_k(l - 2R\sin\theta_k)} \qquad (8)$$

Each segment make the sheet metal generate plastic deformation, so the longitudinal load P_l can be expressed as:

$$P_l = \sum_{k=1}^{n} P_l^k = \sum_{k=1}^{n} \frac{\sigma_s wt^2}{\cos\gamma_k(l - 2R\sin\theta_k)} \qquad (9)$$

So the total load can be expressed as:

$$P = P_t + P_l = \frac{\sigma_s lt^2}{2R_t\sin\alpha} + \sum_{k=1}^{n} \frac{\sigma_s wt^2}{\cos\gamma_k(l - 2R\sin\theta_k)} \qquad (10)$$

From above description, in order to make sheet metal generate double direction bending deformation, it must bears transversal load and longitudinal load of flexible rollers; in order to make sheet metal rotate, it must bears press and torque of center fixture. Theoretically, when a disc-shape sheet metal rotates, the velocity of sheet metal will vary from center to edge. The velocity of edge is maximum, and the velocity of center is minimum. During forming process, the velocity of sheet metal is related to the rotate speed of flexible roller, so the rotate speed of flexible roller should be vary from center to edge theoretically, but the flexible roller is an entire body, the rotate speed of flexible roller is the same from center to edge actually. In order to make the disc-shape sheet metal formed, the center fixture must exert enough force on the center region of sheet metal to prevent it from moving, and there must be slip between flexible roller and sheet metal.

3.3. Analysis of stress and strain fields

Changing rule of stress and strain of sheet metal is not obtained by experiment merely, so finite element analysis method is needed to research stress and strain fields. Disc-shape surface with 2 mm thickness is taken as research object, and its stress and strain fields are analyzed.

Fig. 10(a) and (b) shows equivalent stress and plastic strain fields of disc-shape surface at the beginning of forming. Equivalent stress in regions of center fixture and flexible roller exceeds yield stress; its maximum value is 213 Mpa. Equivalent stress in the other

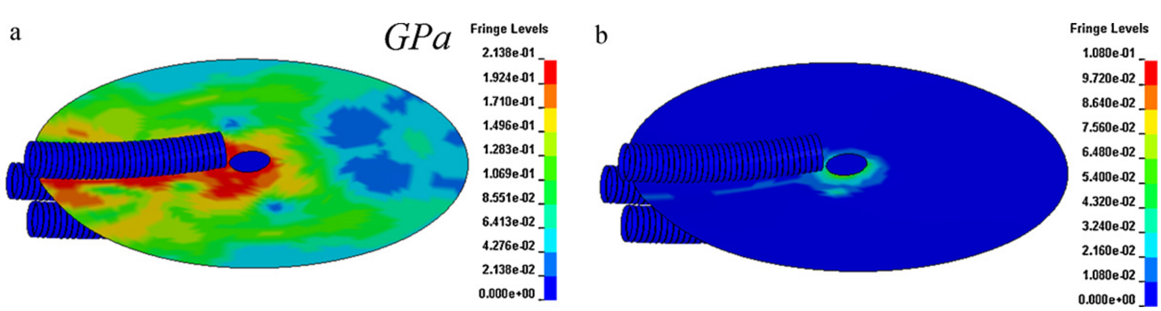

Fig. 10. Stress and strain fields at the beginning of forming process.

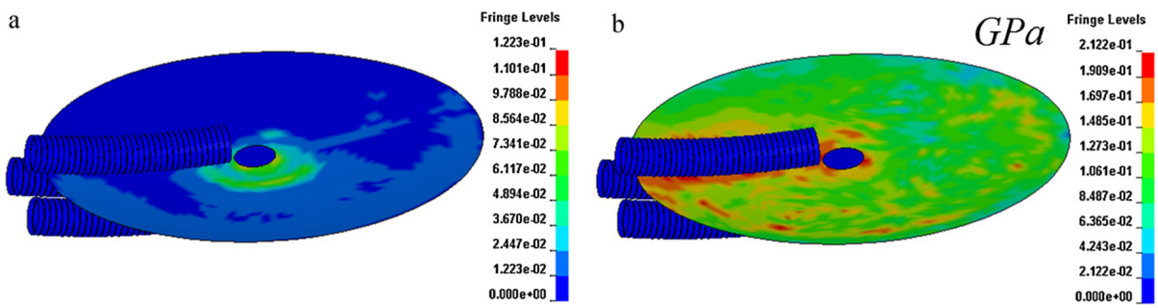

Fig. 11. Stress and strain fields at the time of rotating half circle in forming process.

regions does not arrive at yield stress. The reason is that center fixture provides enough press to prevent sheet metal from shifting when it rotates; sheet metal generates local plastic deformation in region of flexible roller; other regions are at free state, and do not bear any exterior loads, but equivalent stress in these regions is influenced by the regions of center fixture and flexible roller, however, its value is smaller than yield stress generally. Plastic strain in center region of sheet metal is the biggest, its value is 0.07; plastic strain in region of flexible roller takes the second place, its value is 0.03; other regions do not generate plastic deformation. The reason is that equivalent stress in regions of center fixture and flexible roller exceeds yield stress, while equivalent stress of other regions does not arrive at yield stress. Plastic deformation mechanism in region of center fixture is different from region of flexible roller; the former is thickness direction compress deformation which is generated by the press of center fixture, the center fixture also exerts torque on the sheet metal; while the latter is bending deformation which is generated by the press of flexible roller, the bending deformation involves transversal bending deformation and longitudinal bending deformation. The press which is exerted by center fixture is bigger than flexible roller, so plastic strain in region of center fixture is bigger than region of flexible roller.

Fig. 11(a) and (b) shows equivalent stress and plastic strain fields of disc-shape surface when it rotates half circle. Equivalent stress distribution of Fig. 11(a) is similar to Fig. 10(a). The reason is that when sheet metal passes through active region of flexible roller, equivalent stress exceeds yield stress; when sheet metal leaves active region of flexible roller, equivalent stress is released and diminishes. Fig. 11(b) shows that half region of sheet metal generates plastic deformation, but the other half region generates plastic deformation scarcely. The reason is that plastic deformation is kept when sheet metal passes through active region of flexible roller, but no plastic deformation is generated when sheet metal does not pass through active region of flexible roller.

Fig. 12(a) and (b) show equivalent stress and plastic strain fields of disc-shape surface when it rotates one circle. Situation of Fig. 12(a) is similar to Fig. 10(a) and Fig. 11(a). The reason is that the equivalent stress in active regions of center fixture and flexible roller is bigger than the equivalent stress in other regions of sheet metal. Fig. 12(b) shows that almost each part of the sheet metal generates plastic deformation when it rotates one circle; disc-shape surface is formed basically. The reason is that all parts of sheet metal pass through active region of flexible roller.

The equivalent stress in Fig. 10(a), Fig. 11(a) and Fig. 12(a) is uneven. The reason is that the sheet metal generates continuous local deformation; the forming region and the non-forming region impact each other; the same part of sheet metal will experience forming and springback again and again. The above reasons result in the patchy equivalent stress distribution.

3.4. Analysis of forming limits

Wrinkling is a principal defect during forming process of continuous multi-point forming; it severely impacts forming quality of workpiece. From mechanical standpoint, wrinkling is caused by tangential compress stress when it makes material generate plastic compression instability. From standpoint of energy, wrinkling is generated when the energy released by tangential compress stress equals to the energy needed by wrinkling. From standpoint of forming techniques, the weaker the restriction is exerted in thickness direction of sheet metal, the easier the wrinkling is generated. Presently, wrinkling of continuous multi-point forming is predicted by numerical simulation method generally.

Fig. 13 shows a typical simulation result of wrinkling of 0.5 mm thickness rotary surface. Wrinkling is generated on the edge of rotary surface. Deformation state of shell elements in different regions can be obtained according to simulation result of principal strain which is shown in Fig. 14. Shell elements in different regions are analyzed. Value of principal strain is as follow: $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$.

In wrinkling region, $\varepsilon_1 > 0$, it is along normal direction of shell middle surface, $\varepsilon_2 > 0$, it is along tangential direction of shell middle surface, $\varepsilon_3 < 0$, it is along tangential direction of shell middle surface, and is perpendicular to the direction of ε_2. In this principal strain state, shell element generates tangential compress deformation, when tangential compress stress arrives at wrinkling critical value, wrinkling is generated. In non-wrinkling region, $\varepsilon_1 > 0$, it is along tangential direction of shell middle surface, $\varepsilon_2 > 0$, it is along tangential direction of shell middle surface, and is perpendicular

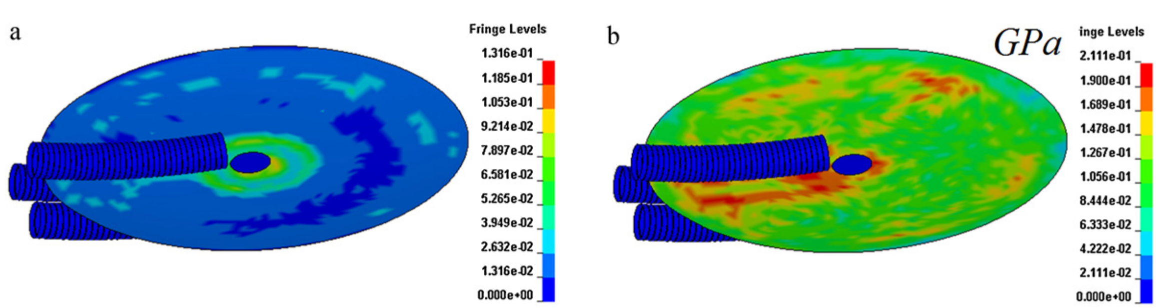

Fig. 12. Stress and strain fields at the time of rotating one circle in forming process.

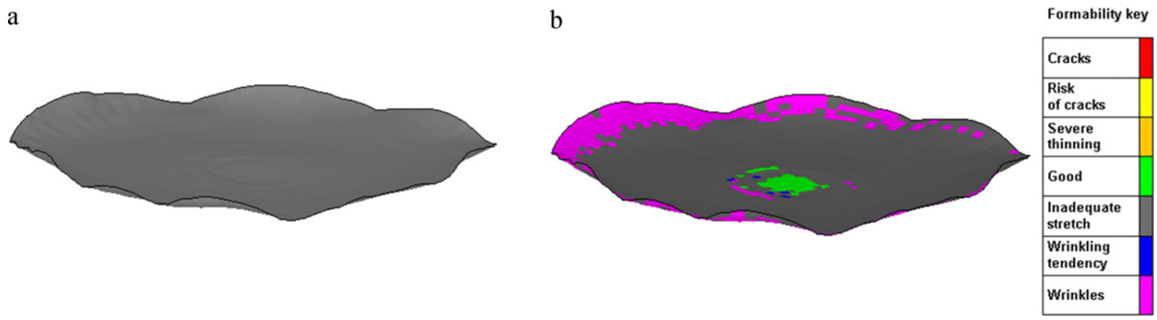

Fig. 13. Wrinkling simulation result of disc-shape surface.

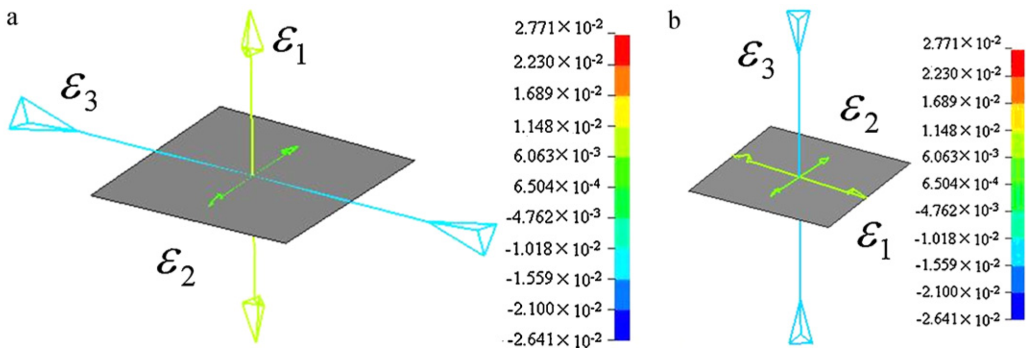

Fig. 14. Simulation results of principal strain vectors of shell element middle surface.

to the direction of ε_1, $\varepsilon_3 < 0$, it is along normal direction of shell middle surface. In this principal strain state, shell element generates stretching deformation along ε_1 direction and ε_2 direction, so tangential direction compression instability is not generated, and wrinkling is not generated.

The disc-shape surfaces with the thickness of 0.5 mm, 1 mm, 1.5 mm and 2 mm are taken as research object, the experimental equipment which will be described in next section is used to manufacture these sheet metals. Experimental result of wrinkling is shown in Fig. 15. For the disc-shape surface with 0.5 mm thickness, its wrinkles disappear after 10 circles spinning. For the disc-shape surface with 1 mm thickness, its wrinkles disappear after 3 circles spinning. For the disc-shape surface with 1.5 mm thickness, its wrinkles disappear after 2 circles spinning. For the disc-shape surface with 2 mm thickness, there is no wrinkle on it after 1 circle spinning. When the thickness of sheet metal is thicker, the critical compression stress is bigger, so the wrinkles are not easy to be generated. For the thin sheet metal, the wrinkling is severe and is not easy to be eliminated, so more spinning times are needed to eliminate the wrinkles. After 1 circle spinning, the wrinkles are generated. When next circle spinning starts, these wrinkles bear the force from flexible rollers along their thickness direction again, and generate reverse deformation, so that the size of wrinkles minishes. When the size of wrinkles minishes, the neighboring wrinkles exert tangential compression stress on the region which is between the neighboring wrinkles, so the region generate new wrinkle, but the size of the wrinkle is small. Along with the increase of spinning times, the size of wrinkles minishes, but the number of wrinkles increases. When the spinning times reaches certain extent, the size of wrinkles is close to infinitesimal, the exterior form is that the wrinkles disappear. In Fig. 15, the zone above the red line is non-wrinkling or wrinkling vanished condition, the zone below the red line is wrinkling condition.

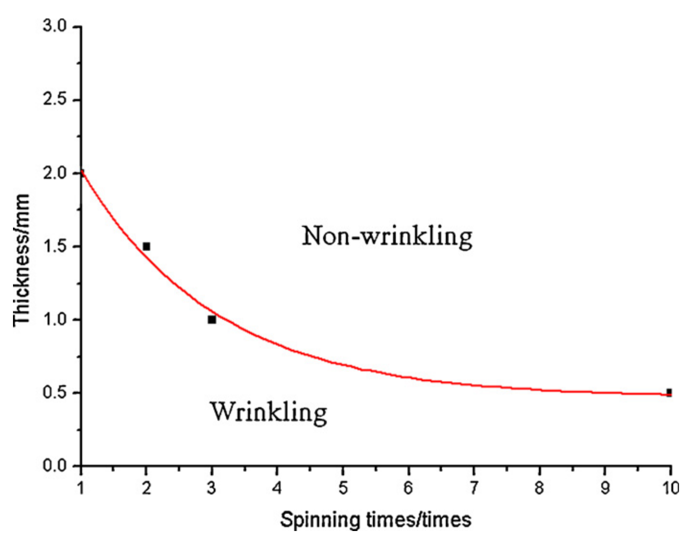

Fig. 15. Non-wrinkling critical graph.

Table 3
Technical parameters.

Curvature radius of flexible rollers/mm	Diameter of flexible rollers/mm	Span between two lower flexible rollers/mm	Diameter of cylinder/mm	Length of cylinder/mm	Thickness of sheet metal/mm	Displacement of upper flexible roller/mm
300	17	41	300	300	2	0.5

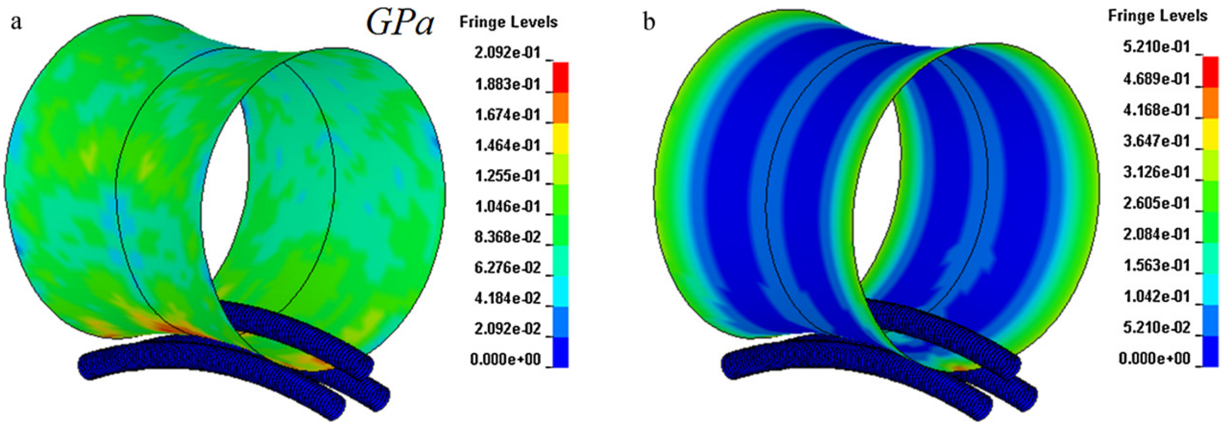

Fig. 16. Stress and strain fields of tube-shape surface.

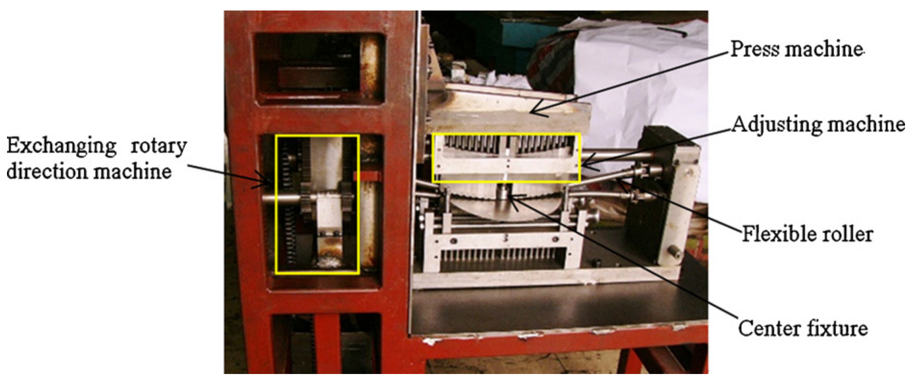

Fig. 17. Continuous multi-point forming device.

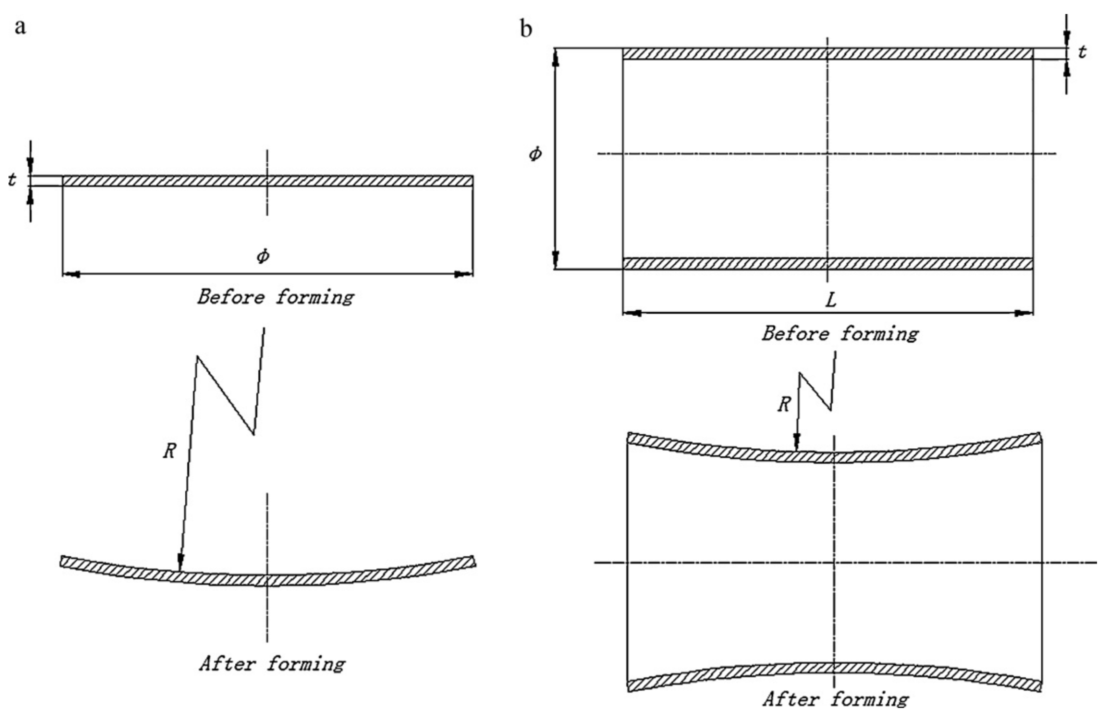

Fig. 18. Schematic diagram of technical parameters of disc-shape surface and tube-shape surface.

3.5. Numerical simulation of tube-shape surface

Besides disc-shape surface, tube-shape surface is also researched. Material is steel 1008; its parameters are shown in Table 1. Technical parameters are shown in Table 3. When forming tube-shape surface, center fixture is not used. Fig. 16 shows stress and strain fields of tube-shape surface. Maximum value of equivalent stress appears in region of flexible roller, it exceeds yield stress; value of equivalent stress in other regions is smaller than yield stress. The reason is that load is exerted in region of flexible roller; equivalent stress in other regions is released. Plastic strain field presents annular distribution. Maximum value of plastic strain appears in marginal region. Owing to initial position relation between flexible roller and sheet metal, the biggest deformation in marginal region is generated when upper flexible roller moves down. When flexible roller rotates, the deformation is continuously generated. During the forming process, the diameter of mid-section of tube-shape surface increases little; the diameters of ends of tube-shape surface increase largely.

4. Forming equipment and experimental results

Continuous multi-point forming equipment is developed for rotary surface through above principle analysis and numerical analysis. Fig. 17 shows the continuous multi-point forming equipment, it consists of press machine, adjusting machine, center fixture, exchanging rotary direction machine and flexible roller. By the equipment, two kinds of part are manufactured. One is disc-shape surface whose geometrical parameter is $\Phi = 280$, $t = 2$ mm (shown in Fig. 18(a)) and material is steel 1008. The other one is tube-shape surface whose geometrical parameter is $\Phi = 300$, $L = 300$ mm, $t = 2$ mm (shown in Fig. 18(b)) and material is steel 1008. Fig. 19 shows the experimental results, wrinkling almost disappears when sheet metal rotates about two circles. Shape and deformation of experimental results almost accord with numerical simulation results. Average curvature of experimental results is measured by three-point measure method; this method is based on a dial indicator, whose measure error is 0.01 mm. Average curvature of simulation results is measured by three-point measure function of postprocessor. Fig. 20 shows the measure method, there are 13 measure points on each measure line. Curvature of each point is measured first on same line, then average value of these points is calculated to obtain average curvature of the line. Fig. 21 shows compared results of experimental value and simulation value. These values are the measure values of curvature radius of disc-shape surface and tube-shape surface. For disc-shape surface, whether the experimental value or the simulation value, they are both between 590 mm and 630 mm; experimental value and simulation value are fitted respectively, fitting results are almost same, they are between 605 mm and 615 mm; the fitting results almost accord with flexible roller's curvature radius which is 600 mm. For tube-shape surface, experimental result and simulation result are between 280 mm and 340 mm; their fitting results are between

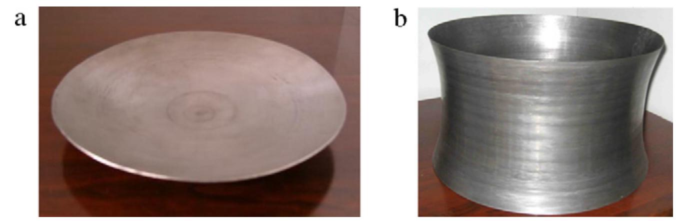

Fig. 19. Experimental results.

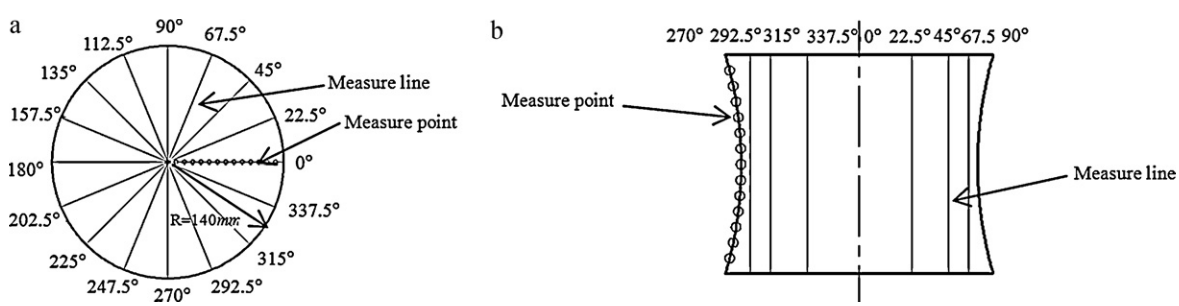

Fig. 20. Measure lines and measure points of experimental result and simulation result.

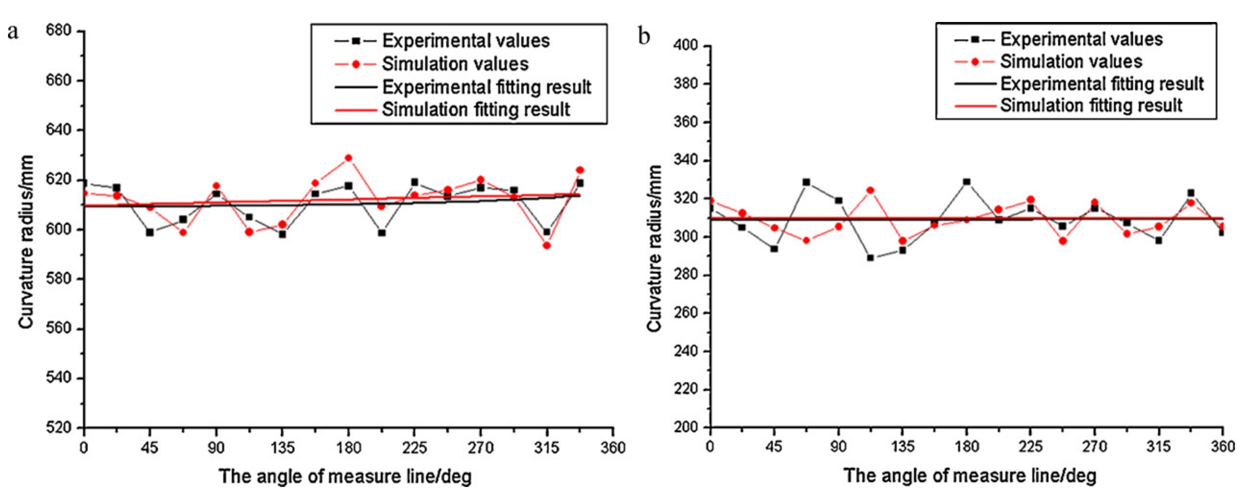

Fig. 21. Compare of average curvature radius between experimental result and simulation result.

305 mm and 310 mm, and almost accord with flexible roller's curvature radius which is 300 mm.

5. Conclusions

(1) Principle and characteristic of continuous multi-point forming are described. The principle is that flexible roller is adopted as forming tool to realize 3-D surface forming for sheet metal. The characteristic is that line forming replaces point forming, so the forming area is increased and the forming efficiency is enhanced.
(2) Forming load is analyzed theoretically. Center region of sheet metal bears press and torque from center fixture. In forming region, sheet metal bears the load from flexible rollers. The load consists of transversal load and longitudinal load.
(3) For disc-shape surface, stress and strain field distributions are analyzed. Equivalent stress in regions of center fixture and flexible roller exceeds yield stress. Plastic strain in region of center fixture has maximum value; plastic strain in region of flexible roller takes the second place.
(4) Wrinkling is analyzed. Shell element in wrinkling region generates tangential direction compress deformation. When tangential direction compress stress arrives at critical stress of wrinkling, wrinkling is generated.
(5) For tube-shape surface, maximum value of equivalent stress appears in region of flexible roller; plastic strain field presents annular distribution, its maximum value appears in marginal region.
(6) Experimental equipment is developed. Experimental results almost accord with simulation results, and they almost accord with technical parameter.

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