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# Deformation characteristics of mechanical expanding of thin-walled cylindrical parts①

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**Abstract:** Mechanical expanding is one of the finishing processes in cylindrical part forming. The distribution of stress and strain shows clearly regional features. FEA simulation and experiments show that the deformation process can be divided into three phases called as rounding phase, expanding phase and unloading phase in turn, in which the main types of deformation are wall bending, circumference elongating and thickness reducing, and spring back respectively. And the longitudinal section can be divided into three portions: expanding region, transition region and rigid region. The plastic deformation occurs regionally in suspended portion. A regional convex in transitional portion is inevitable.

**Key words:** mechanical expanding; deformation characteristic; numerical simulation

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## 1 INTRODUCTION

Mechanical pipe-expanding is an advanced plastic working technology of metals. The plastic deformation is caused in cylindrical blank to produce excellent cylindrical parts by using wedge-shaped die. It has been used in fields of aviation and space flight, nonferrous metal industry and mechanical manufacturing industry. Although the purpose of application of mechanical expanding varies in the type of cylindrical blank and the usage of products, its main function is to improve accuracy of shape and mechanical properties of finished products. In R&D of manufacturing process of large diameter longitudinal submerged arc-welding line pipe, the expanding process has been significantly concerned because it has so much benefit for product precision and for residual stress relieving[1-10]. Spinning is known as a special metal forming process, which can be used to form large thin-walled cylinder. In that case, the mechanical expanding must be taken to reshape the cylinder after spinning for improving accuracy of finished product[11]. The strength of spun cylinder can be increased by 3% after expanding.

In mechanical expanding, owing to the unsymmetric shape in cross-section of cylindrical blank and sectorial structure of dies, the deformation shows some regional features and special regularities. By elasto-plastic finite element method and experiments, the deformation process of cylindrical blank in mechanical expanding is analyzed systematically so that the deforming characteristics and the deforming regularities in its cross section and longitudinal section are presented in this paper.

## 2 FEM MODEL

### 2.1 Model of material

A thin-walled, cylindrical elasto-plastic deformable body is made from some engineering material. The mechanical properties of the material are listed in Table 1. The stress—strain curve is expressed by an analytical expression, a simplified elasto-plastic form with a uniform strain-hardening rate, with yield strength $\sigma_s = 475$ MPa, tensile strength $\sigma_b = 600$ MPa, elastic modulus $E = 2.1 \times 10^5$ MPa and plastic modulus $E_s = 375$ MPa.

**Table 1** Mechanical properties of material

| Yield strength/MPa | Tensile strength/MPa | Specific elongation/% | Impact energy/J(-20 ℃) | Average energy/J(-20 ℃) |
|---|---|---|---|---|
| 470 - 515 | 555 - 610 | 38.0 - 41.0 | 140 - 200 | 143 - 194 |

### 2.2 Model of mechanics

Practically speaking, the shape error of cross section of cylindrical parts is expressed by ellipticity or roundness. For this reason, the shape of the cross section of cylindrical blank is always assumed a standard ellipse section in FEM simulation.

Fig. 1 gives the mechanical model of three di-

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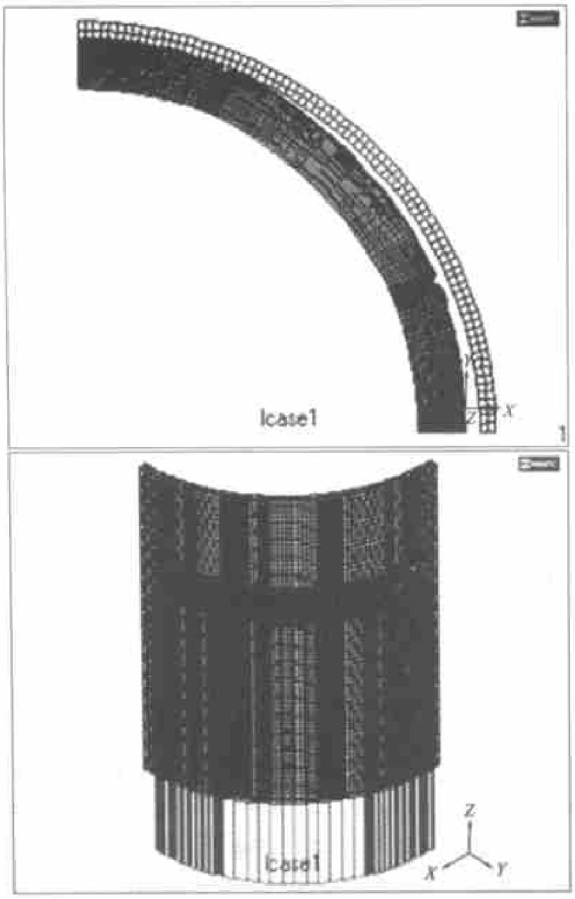


**Fig. 1** 3-D model of FEA

mensions for expanding process simulation. The cylinder is considered as an elasto-plastic deformable body.

Fig. 2 shows the experimental device and samples. The die assembly, composing of octagonal pyramid and eight dies around it, is positioned in the cylindrical blank. During the simulation, each die is treated as a rigid body, so that only sectorial dies are shown in Fig. 1. Because of the symmetry of assembly, a quarter that is taken from the assembly will be used for the simulation. Taking an example, the cylindrical blank with an ellipticity of 3% is 406 mm in normal diameter outside, 8 mm in normal wall thickness and 345 mm in length. The sectorial dies are of the outside diameter of 430 mm, the round corner radius of 5 mm in cross section and 24 mm at the rear end in longitudinal section, and the sectorial-angle of 45°. The length for expanding is 225 mm. The hexahedron type of element with eight nodes is adopted in the simulation. The analyzed body is meshed into 11 200 elements with a total of 17 253 nodes. Friction type of Stick-Slip is assumed. The friction coefficient is 0.075.

Numerical simulation to many practical engineering problems shows that the accuracy of the FEA solution is influenced by many factors such as the accuracy of mechanical model assumed, the type of element adopted, as well as the number of elements and nodes. Therefore, the other two mechanical models, shown in Fig. 3, are adopted and the most of the results are derived from them. It should be pointed out that the numerical results based on the 2-D model only show the characteristics of cross section located at the expanding deforming region, and those based on the axisymmetric model only show the approximate characteristics of longitudinal section at the expanding deforming region and transitional deforming region.

**Fig. 2** Experimental device and samples

In numerical simulations, cylindrical blanks are elasto-plastic deformable bodies, dies are rigid bodies, and other conditions are the same as those in the model shown in Fig. 1. For the model of two-dimension shown in Fig. 3(a), the die has

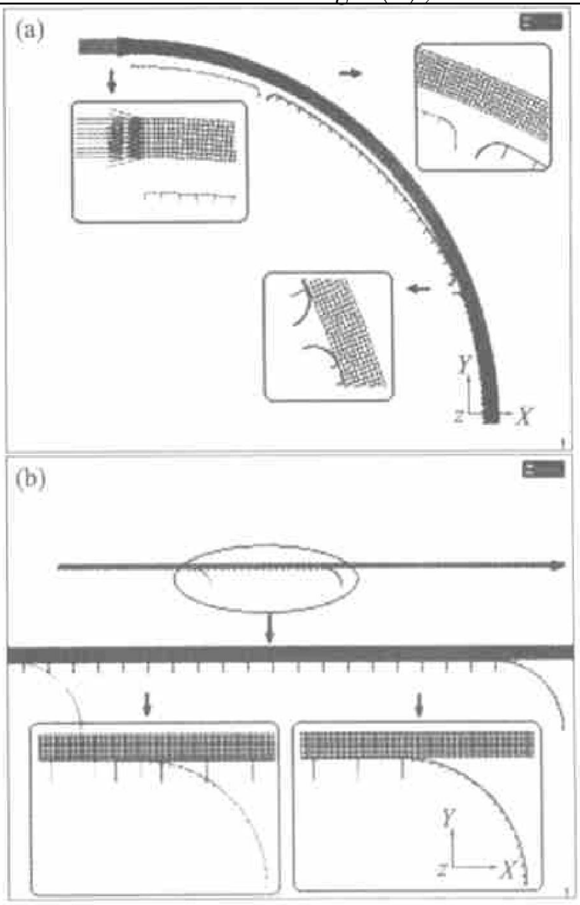


**Fig. 3** Models of FEA
(a) —2-D model; (b) —Axisymmetric model

three types of sectorial angle corresponding to three simulated examples, that is, 45°, 36° and 30° respectively. A type of plane strain quadrangle element is used for it. For the model shown in Fig. 3(b), the profile of the rear end of the die is designed respectively to be a straight corner and a round corner for two simulated examples. The axisymmetric quadrangle elements are used.

## 3 DEFORMATION CHARACTERISTICS

### 3.1 Dimensional characteristics

The dies stay close together so that there is a circular gap between inner surface of the cylinder and working surfaces of dies before the expanding. When the dies move outward in their radial direction, the gap will disappear and a contact condition between the cylinder and the die will be first established at the location of minimum radius of the blank. Then, the working surfaces of all dies will get into a full contact condition with the inner surface of cylinder; meanwhile circumradius of the dies will get large. During this process, the elasto-plastic deformation will take place in the blank.

The parameters of mechanical expanding in experiments and simulations are as follows. Expanding rate is 1.5%, spring-back ratio is 0.25%, and minimum die radial displacement is 6.6 mm. In simulation, the increment step is taken as 0.1 mm.

According to the results of the simulation, the deformation process of mechanical expanding of the cylindrical blank with ellipticity falls into three phases, which are rounding phase, expanding phase and unloading phase. Fig. 4 shows the distribution of equivalent strain at different moments of expanding process.

Generally, for a cylinder whose normal outer diameter is between 330 mm and 1 420 mm with a wall thickness between 12 mm and 40 mm, if its ellipticity is less than 3% there will be no plastic deformation in it during rounding phase, as shown in Fig. 4(a). This conclusion has been proved by theoretical analysis[12]. In the phase of expanding, the plastic deformation occurs mainly on the suspended part without supporting of die and has many distinct regional deformation characteristics. With local contact between the dies and the cylinder, these characteristics can be summarized as follows.

1) In the rounding phase, the plastic deformation doesn't firstly occur at the inner diameter along the long axis of the cylinder's ellipse cross-section or at the outer diameter along its short axis, where the maximum tangential stress theoretically occurs. It occurs only near the sides of the short axis, just on the outer surface located at the dies end and in the vicinity of the gap between two dies.

2) The regional plastic deformation in cylin-

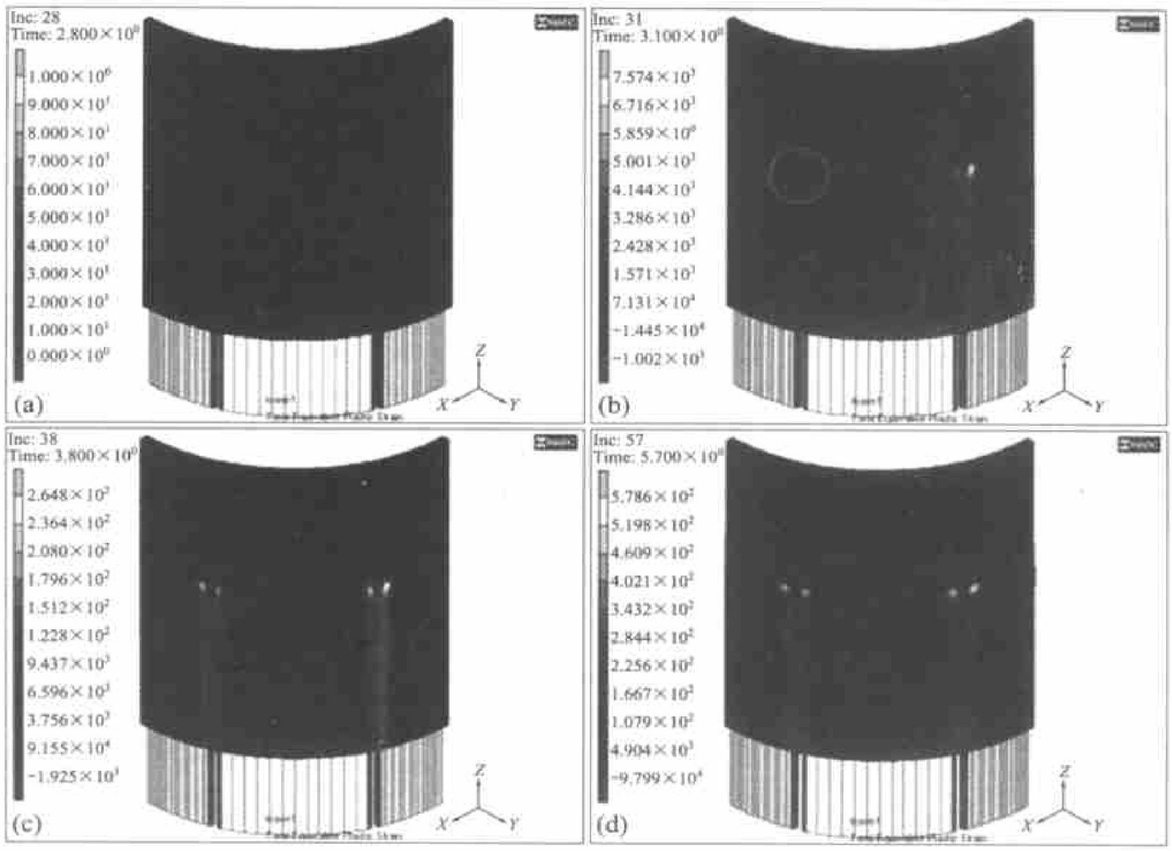


**Fig. 4** Distribution of equivalent strain

(a) —Just before finish of rounding phase; (b) —At beginning of expending phase;
(c) —During process of expending phase; (d) —At end of expanding phase

drical blank extends from the rear end of the die to the other end so that a deformation zone can be formed along the longitudinal direction of the suspended part, as shown in Fig. 4(b). However, in this zone the regional deformation mainly occurs in the outside of the cylinder. It can only appear in the inside of it near the rear end of die. Then, the plastic deformation will occur on the outside of the suspended part located at the rear end of dies and in the side of the long axis. But most of the cylinder won't get into plastic deformation.

3) With increasing deformation extent, the deformation zone, that is on the outside of the suspended part corresponding with the rear end of dies and in the side of the long axis, gets larger continuously, and then it extends toward the other end of the die so that another plastic deformation zone will be formed along the longitudinal direction of the suspended part, as shown in Fig. 4(c).

4) At the end of expanding process, the plastic deformation exists along the expanded length direction, as shown in Fig. 4(d). But it is really regional, and the extents of the deformation at different regions are nonidentical.

5) At unloading phase, the deformation of cylinder is mainly spring back.

### 3.2 Characteristics of cross section

The uneven deformation on cross section of cylinder finally results in an irregular figure on the suspended part, as shown in Fig. 5(a). After unloading, the shape of the cross section of finished product is still an ellipse, as shown in Fig. 5(b), whose long axis is in accordance with that of the cylindrical blank.

Based on the results of simulation, such a conclusion can be drawn that the unequal wall thickness of the finished product on cross section will be inevitable, as shown in Fig. 5(c). Whatever the expanding parameters are, the distribution form of the wall thickness is the same. However, the wall thickness reduction at a certain location changes with deformation conditions.

### 3.3 Characteristics of longitudinal section

There is a conical section in the cylinder called as transitional portion after every expanding near the rear end of the die. After second action, there will be a local convex, as shown in Fig. 5(d), in the transitional portion on the longitudinal section. The convex located around the point of tangency of generatrix of cylinder with the die rear end.

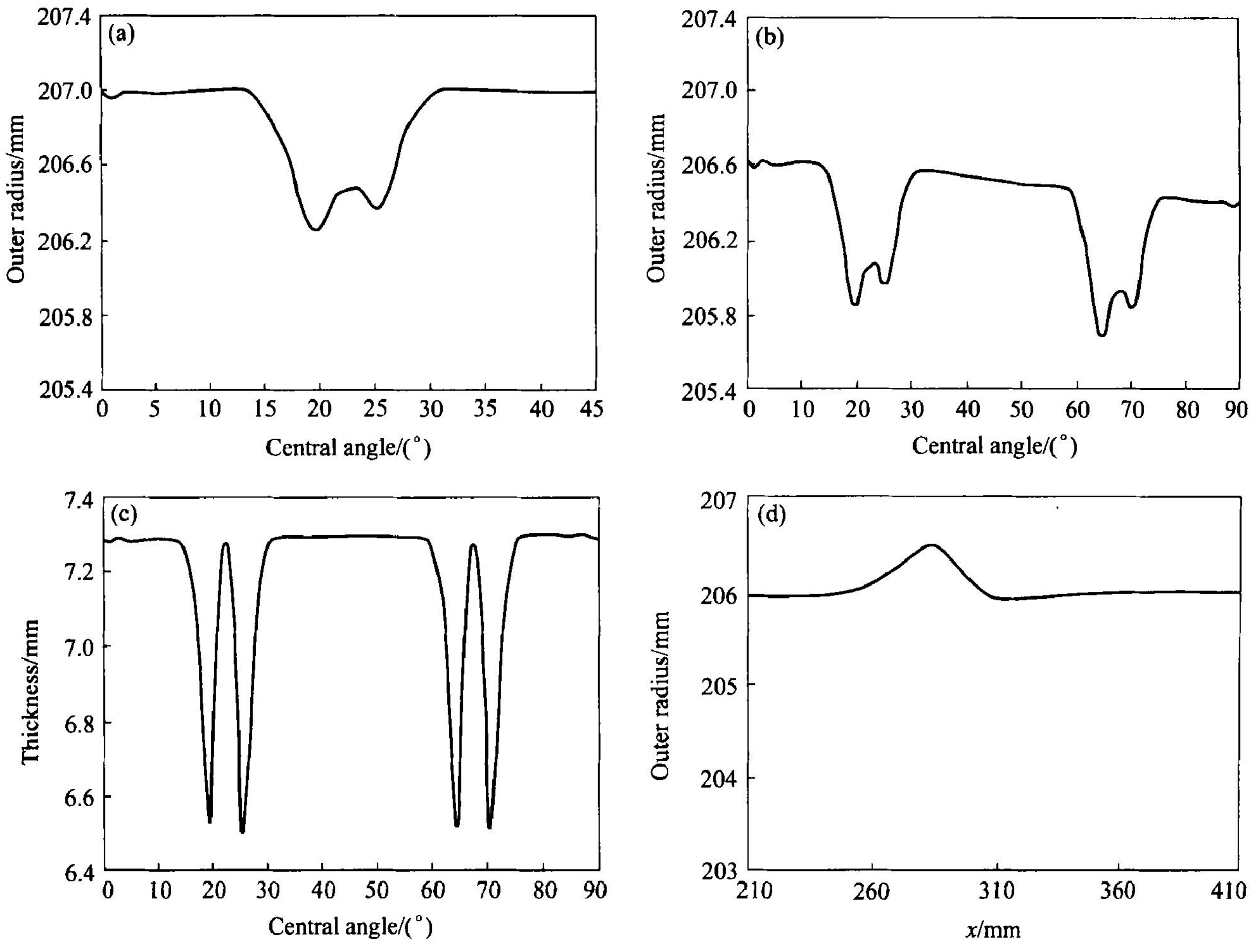


**Fig. 5** Deformation characteristics
(a) —Outer radius at end of expanding; (b) —Outer radius after unloading;
(c) —Wall thickness of finished product; (d) —Convex transitional region

It is necessary to notice that Fig. 5(d) is derived from the results of simulation about the axisymmetric model. A similar phenomenon can be found in the simulation about the problem shown in Fig. 1. The model size of the cylinder shown in Fig. 5(d) is with outer diameter of 406 mm, wall thickness of 7.3 mm and length of 1 000 mm. The mechanical model of the cylinder is meshed into 8 768 elements with a total nodes of 9 873. The die length is 300 mm, and the round corner radius at the rear end is 14.6 mm. The expanding rate is 1.5%, the spring-back ratio is 0.25%, the minimum radial displacement is 3.5 mm, and the overlap length of the die is equal to the wall thickness. The frictional coefficient is 0.075. The expanding process experiences two steps from one end to the other. The process route is as follows. Loading the first section and unloading it when the displacement gets over. Then loading the second section and unloading it when expanding finished.

Owing to the fact that it isn't easy to measure the generatrix linearity of the finished cylinder, we didn't pay much attention to the measurement of it in our experiments. Fig. 6 shows a convex on the longitudinal section of 330 mm × 7.3 mm × 1 000 mm cylinder. Although the convex can be seen clearly in this picture, it is really difficult to recognize the regional concaves clearly at two ends of the convex, even though they have been observed from the results of the simulation. In Fig. 6, the highness of the convex is visibly larger than the simulation results because it is related not only to a large angle at the end of die, but also to the precision of position control of the hydraulic press used in the experiments. The press is provided without the function of position control. Consequentially, the position error of slide affects negatively the generatrix linearity of the finished cylinder.

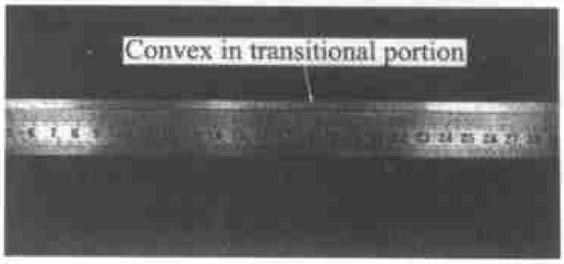


**Fig. 6** Convex in transitional portion

Fig. 7 shows the distribution of axial stress in the transitional region. Based on Fig. 7 and other results of simulation, it is reasonable to divide the longitudinal section of the cylinder into three regions, i.e. expanding deforming region, transitional deforming region and rigid region. Among them, the expanding deforming region is exactly

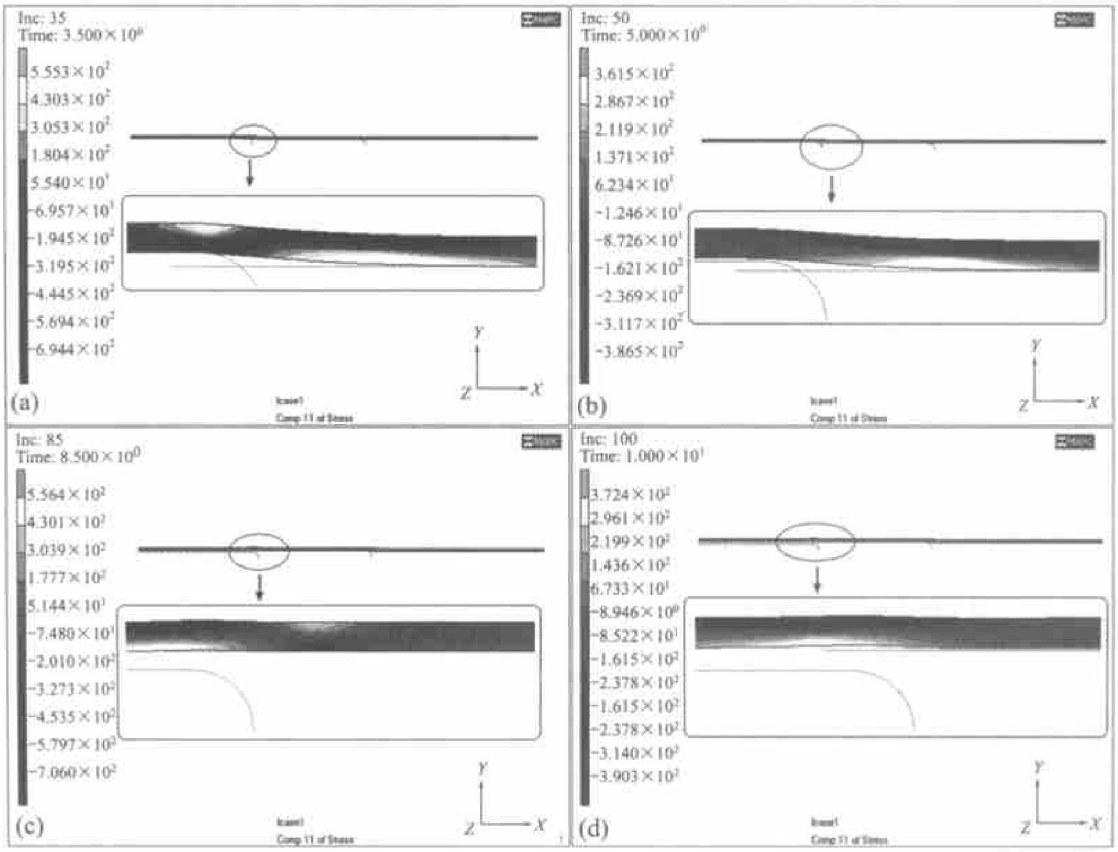


**Fig. 7** Distribution of axial stress in transitional region

(a) —At end of expanding for first section; (b) —At end of unloading for first section;
(c) —At end of expanding for second section; (d) —At end of unloading for second section

the portion to contact with straight part of die and it is a uniform deforming region. For the reason that there will be the largest $\sigma_\theta$ and the largest absolute value of $\sigma_r$ on the inner surface of the cylinder, the Tresca yield criterion ($\sigma_\theta - \sigma_r = \sigma_s$) is satisfied firstly, so the plastic deformation occurs firstly. The deformation will be extended from inside to outside. That's why there may be a slight change in deformation, decreasing from inside to outside of the wall.

The transitional deforming region, having uneven plastic deformation, is just on the transitional portion. The bend of cylinder wall is a major pattern of plastic deformation in this region. In expanded section, the material is longitudinally compressed inside and elongated outside. However, the situation in the non-expanded range is just opposite. After unloading, the stress characteristics of the expanded section will almost disappear. When the next segment of cylinder is expanded, the bend of the cylinder wall is also a major pattern of plastic deformation in pre-existed transitional portion. However, the direction of bending is just opposite to the foregoing statement. At the end of second expanding, former compressive stress region and former tension stress region change to each other. After unloading, there are only one tension stress region and one compressive stress region in pre-existed transitional portion. The undeformed part is called rigid region. The rigid region may influence expanding force, but its effect is related to the relative thickness of the wall[13].

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