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# Research of Metal Flow Behavior during Extrusion with Active Friction

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**Using numerical simulation and experiment, the metal flow behavior mechanical mechanisms in the extrusion process with active friction were investigated. The characteristic variables, second invariant of the stress deviator $J_2$ and the Lode's coefficient μ were employed to partition the deformation region. It is shown that no metal flow interface occurred at the container bottom in the extrusion with active friction and the dead zone disappeared completely. The strain types of the material in the plastic deformation area decreased from three types into a single type of tension, and the homogeneity of metal deformation as well as metal flow was greatly improved. It was also indicted that the active friction was beneficial to the extrusion process and the promotion of product quality. After contrasting the result of experiment and the simulation, the displacement and the load were well correlated on both values and trends.**

**Keywords** active friction, extrusion, numerical simulation

## 1. Introduction

It is difficult to control accurately the bulk forming processes used to make complicated parts because during the process, the degrees of deformation, the states of stress and the formability of materials vary greatly (Ref 1, 2). There are many kinds of bulk forming, however, from the viewpoint of plastic working mechanics, the whole plastic process in forming complicated parts can be abstracted and decomposed into several fundamental forming modes such as extrusion, upsetting and so on, according to the deformation steps and regions. The theory basis for the precise forming of complicated parts can be drawn from the research on metal flow behavior of the limited typical forming procedures.

Extrusion is one of the widest used and the most basic processes of plastic forming, and the metal flow in extrusion is affected by many factors, such as friction, die shape (Ref 3), billet temperature (Ref 4) and so on. Among these factors, friction is the key boundary condition to determine the property of the extruded products (Ref 5-7). For example, during extrusion, friction inhibits flow, makes the process prone to flow defects, and increases energy consumption. To decrease or completely eliminate the retarding effects caused by friction, backward extrusion and the hydrostatic extrusion have been proposed. However, they introduce other problems which are hard to overcome. Fortunately, from numerous studies researchers have found that, friction can be a positive factor for the extrusion process by changing its direction. Theoretical investigations about the application of extrusion with active friction are based on work of Russian scientists. Hereby it concerns to use the friction between billet and container for promoting metal flow in the indirect extruding process. If the vectors of frictional force and the direction of material flow have the same orientation, friction takes over an active role. The use of active frictional forces between container and billet was introduced by Berezhnoi and Moroz (Ref 8). Based on backward extrusion, the ISA method (Ref 9) was put forward by Müller, which makes friction an active factor. By optimizing and improving the extrusion conditions, the ISA method can enhance the productivity by 8-10% compared with traditional backward extrusion and increase the homogeneity and mechanical property of the extruded products.

Although some research has been done on extrusion with active friction, the mechanism of metal flow in this kind of extrusion process has not been studied thoroughly and the process is seldom used in manufacturing practice. In this paper, some simple equipment is designed for extrusion with active friction, which can make the friction between billet and container an active factor for the process, change the metal flow behavior and aid the avoidance of flow defects. In addition, numerical simulation is applied to study the metal flow behavior during extrusion with active friction. The second invariant of the stress deviator $J_2$ and the Lode's coefficient μ are used to partition the deformation region (Ref 10), and then the mechanism of metal flow during extrusion process with active friction is investigated.

## 2. Extrusion Process and Numerical Simulation

### 2.1 Analysis of Extrusion Process

Figure 1 is a schematic diagram of extrusion with active friction. In order to reduce the normally retarding effect of friction, the direction of friction between billet and container is reversed to change the friction into a positive condition for metal flow. That is, the extrusion force $F_E = F_R + F_C$, where $F_R$ represents the force from the punch, $F_C$ represents the

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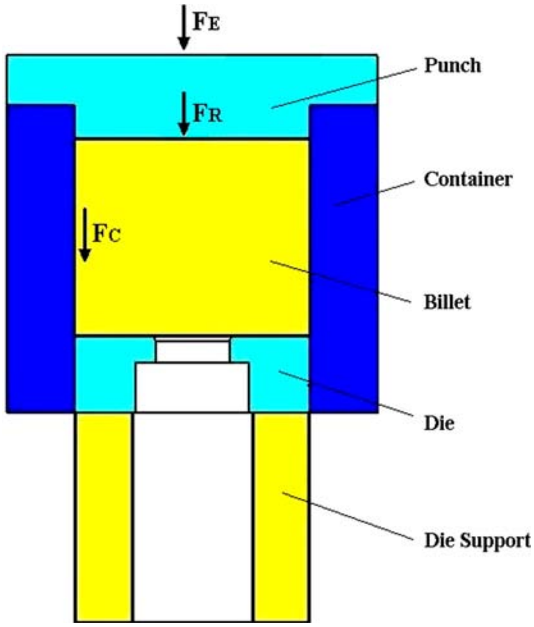


**Fig. 1** Schematic diagram of extrusion with active friction

assistant friction. The metal flow speed rate of the outer billet will be increased and close to the rate of the billet axis due to the effect of $F_C$, so the uneven metal flow across the billet section will be reduced.

The tooling design in Fig. 1 is simple as it enables punch and container to move downwards at the same speed, the normal connection between die and container is eliminated, together with the guide assembly between punch and container.

### *2.2 Finite Element Model*

DEFORM$^{TM}$-2D was used to simulate the extrusion process. Due to the symmetrical characteristics, axisymmetric model is selected in the simulation. The nodes along the symmetric plane are restricted radially and the speed along the normal direction is zero, as shown in Fig. 2.

The diameter of billet was 50 mm and the height was 50 mm. In this article, the extrusion process was simulated by using rigid-plastic finite element model. The billet was considered as plastic bodies. The punch, the container and the die were considered as rigid bodies. The original mesh of billet was 2000 four-nodal elements. The speed of punch was 1 mm/s, and the speed of container was 0 and 1 mm/s respectively for comparison. When the speed of container was 0, the process corresponds to the extrusion without active friction. The extrusion temperature was 435 °C and the extrusion ratio was 9.8.

The coefficient of friction between billet and container was 0.3, which was determined by the relationship between inner diameter and height of hot ring compression ((Ref 11), and the hot ring compression experiment was done at 435 °C. Aluminum alloy 7050 billet was used in the experiments. The chemical compositions of 7050 aluminum alloy used for the experiment is presented in Table 1.

The hot compression experiment of 7050 aluminum alloy was carried out under the temperature of 435 °C and the stress-stain curves with different strain rate are presented in Fig. 3.

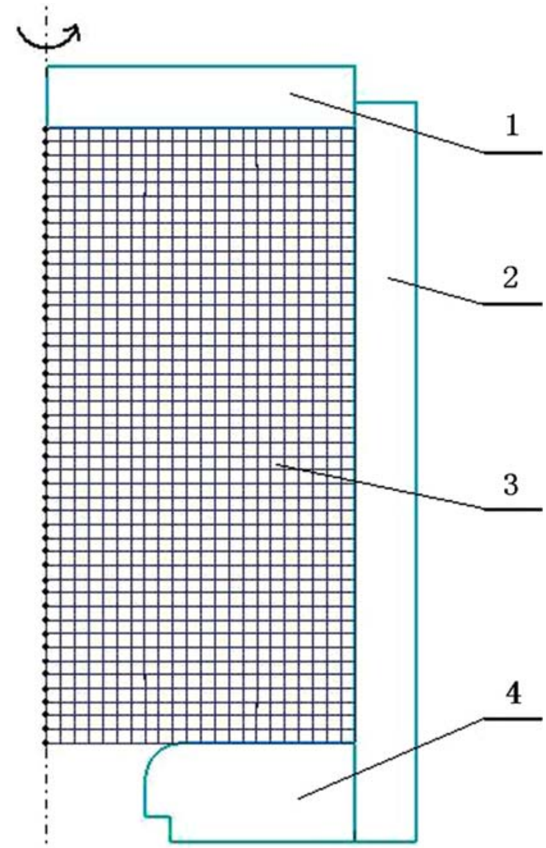


**Fig. 2** Finite element model (1. punch; 2. container; 3. billet; and 4. die)

**Table 1 Nominal compostion of the AA7050 (wt.%)**

| Alloy | |
|---|---|
| Cu | 2.0-2.6 |
| Zn | 5.7-6.7 |
| Mg | 1.9-2.6 |
| Fe | 0.15 |
| Si | 0.12 |
| Mn | 0.10 |
| Cr | 0.04 |
| Ti | 0.06 |
| Al | Rest |

From the Fig. 3, it can be seen that with the increasing of strain rate, the flow stress is enhanced distinctly.

## 3. Simulation of Metal Flow Behavior

Figure 4 shows the comparison the deformation of mesh grids with or without active friction. It can be seen in Fig. 4(a) that for extruding without active friction, the deformation and flow of metal is uneven and the grids near the bottom of the container are distorted significantly. While in the extrusion with active friction, as shown in Fig. 4(b), the grids near the bottom of the container are almost in the shape of parallelogram. This indicates that the deformation and flow of the metal is homogeneous. Therefore, it is easier for the metal to flow out of the die aperture without the formation of dead zone.

Figure 5 shows the velocity field with and without active friction at the bottom of the die. It can be seen from Fig. 5(a) that without active friction, there is an obvious metal flow interface at the bottom of the die. Some metal moves toward the die aperture, whilst the other toward the container and a dead zone is formed. In extrusion with active friction, as shown in Fig. 5(b), the metal near the container flows to the die aperture, and no metal flow interface is observed in the plastic deformation zone. Which not only decreases the generation of dead metal zone, but also improves the extrusion product quality.

The load and displacement curves with and without active friction were shown in Fig. 6. It can be seen that, during the extrusion without active friction, the load value at the beginning stage is the highest and with the extrusion processing going on the value decreases obviously. However, during the extrusion with active friction, the load value keeps fairly steady in the whole processing.

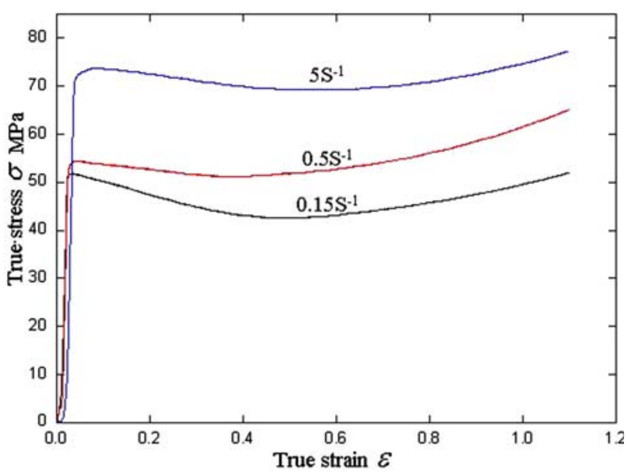


**Fig. 3** True stress-strain curves of AA7050 at the temperature of 435 °C with different strain rates

## 4. Deformation Division and Stress/Strain Analysis

The stress distribution in the deformed grids can be obtained by the post-process module of the numerical simulation software, which is convenient for the further analysis.

### 4.1 Method of Deformation Division

The stress tensor of any point in the deformed object is usually described as six independent stress components acting on perpendicular planes or three principal stresses. In different coordinate system, the magnitude and direction of the stress components are different, but the stress tensor invariant and deviator invariant will not change with the coordinate system, so the deviator invariant can serve a very important role in plastic forming (Ref 12).

In extrusion, the metal in some regions of a billet cannot satisfy the plastic deformation condition and the plastic deformation cannot occur due to the friction. For the convenience, the Von-Mises yield criterion can be described as (Ref 13):

$$J_2 = \frac{1}{3}\sigma_S^2 \qquad \text{(Eq 1)}$$

where, $J_2$ is the second invariant of stress deviator, $\sigma_s$ is the flow stress of the work piece, which is a constant value. Using the invariant $J_2$, the division of stress field with or without active friction can be shown in Fig. 7. The regions marked with shadow represent the areas where a plastic deformation occurs.

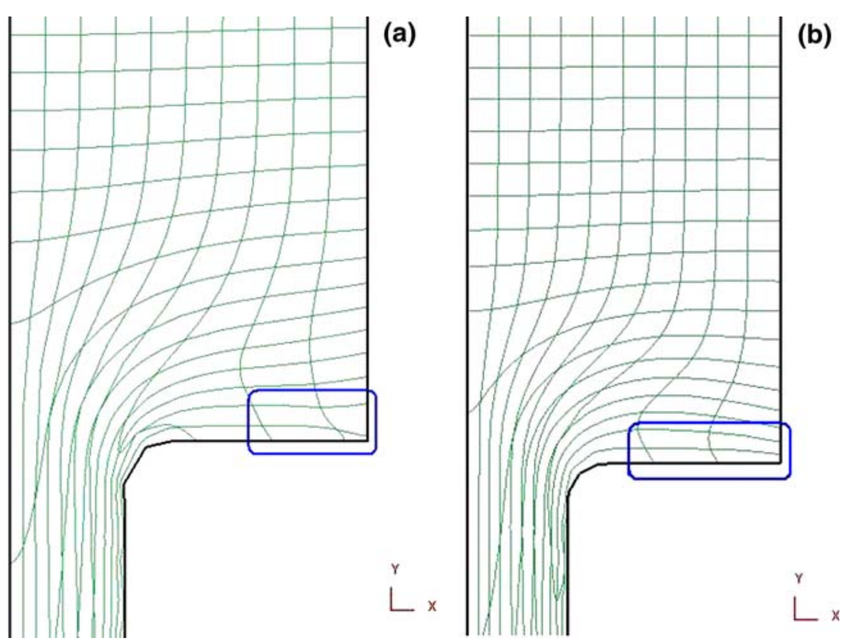


**Fig. 4** Deformation of the mesh grids (a) without and (b) with active friction

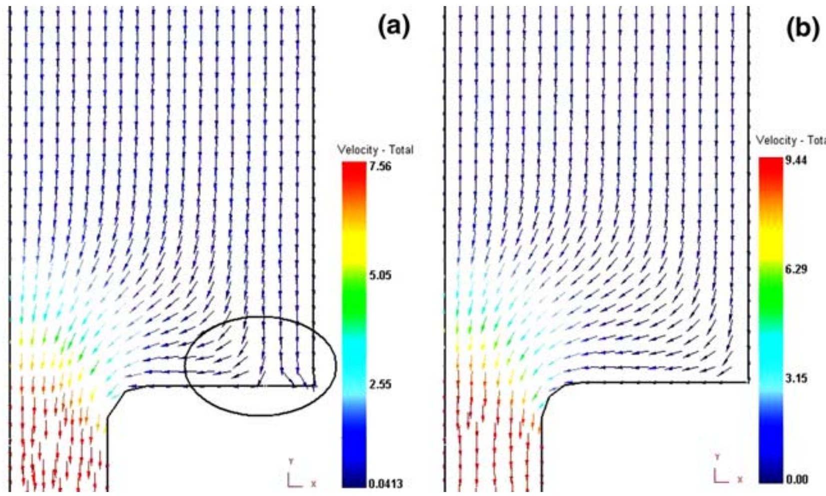


**Fig. 5** Distribution of the velocity field (a) without and (b) with active friction

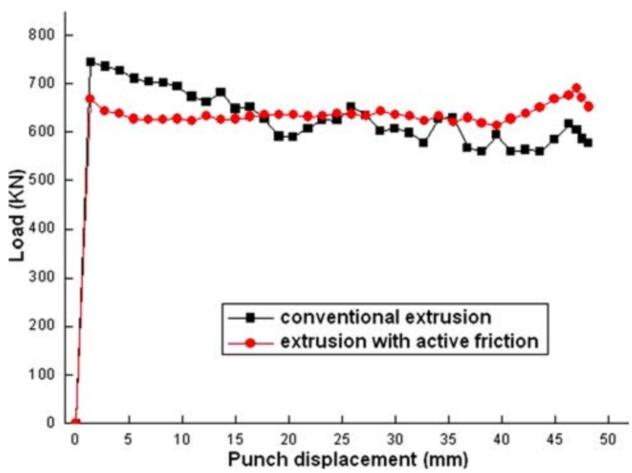


**Fig. 6** The curve of load and displacement

Figure 7(a) shows that without active friction, the region of the work piece in the upper part of the container and in the lower-corner of the container, does not deform plastically. In the extrusion with active friction, as shown in Fig. 7(b), the plastic region is larger, and there is no dead zone. So it can be assumed that the active friction increases the amount of plastic deformation of the metal at the bottom corner of the container.

### 4.2 Types of Deformation

Lode's parameter $\mu$ is used to represent the stress situation regularly, since it can reflect the relative magnitude of the second principal stress, and is also relative with the type of strain state. For example when $-1 \leq \mu < 0$, it is tensile strain state, when $\mu = 0$, it is plane strain state and when $0 < \mu \leq 1$, it is compress strain state. That is, the type of strain state and the degree of complicacy can be determined by the Lode's parameter (Ref 13-15). When through the analysis of the Lode's parameter, some measures can be taken to change the stress situation, and then change the plastic deformation condition to improve the forming property of the billet.

Based on the rigid-plastic division, the strain of the material in the plastic area during extrusion process can be classified into different types using the visual display of the Lode's coefficient, as shown in Fig. 8.

It can be seen from Fig. 8(a) that without active friction, Lode's coefficient in most of the region near the die is negative, i.e., the strain in the material is tensile. The region where Lode's coefficient equals to zero belongs to plane strain; while in a region in the corner of the container, Lode's coefficient is positive, i.e. the strain type is compressive. In the extrusion with active friction, the strain in the plastic region is everywhere tensile, as shown in Fig. 8(b). So compared to the extrusion without active friction, the metal flow in the container is more homogeneous.

### 4.3 Stress and Strain Analysis

According to the plastic working mechanics, metal flows in the direction of the maximum principal stress gradient. In addition, if the order of the principal stress does not change, the deviation of principal stress and the increment of principal strain have a relationship correspondence (Ref 16, 17). Figure 7 shows the stress and strain distribution of typical points in the plastic region, where the positive arrows represent tension stress and negative arrows represent compression stress respectively.

Figure 9 indicates that the stress state of each point in the plastic region is three-dimensional compression, in both types of extrusion, and the direction of maximum principal stress $\sigma_{max}$ always points to the die aperture. However, its direction varies obviously in different positions in the plastic region. Take the material near the billet axis for example, during the extrusion without active friction, the direction of the maximum principal stress differs more from the direction of the axis with the increasing of distance from the die aperture. However for a given position, in extrusion with active friction, the deflection angle between the maximum principal stress and the direction of axis is less than for extrusion without active friction.

Figure 9(a) also shows that in the plastic region of extrusion without active friction, the increment of maximum principal strain of the material being the extension strain state almost

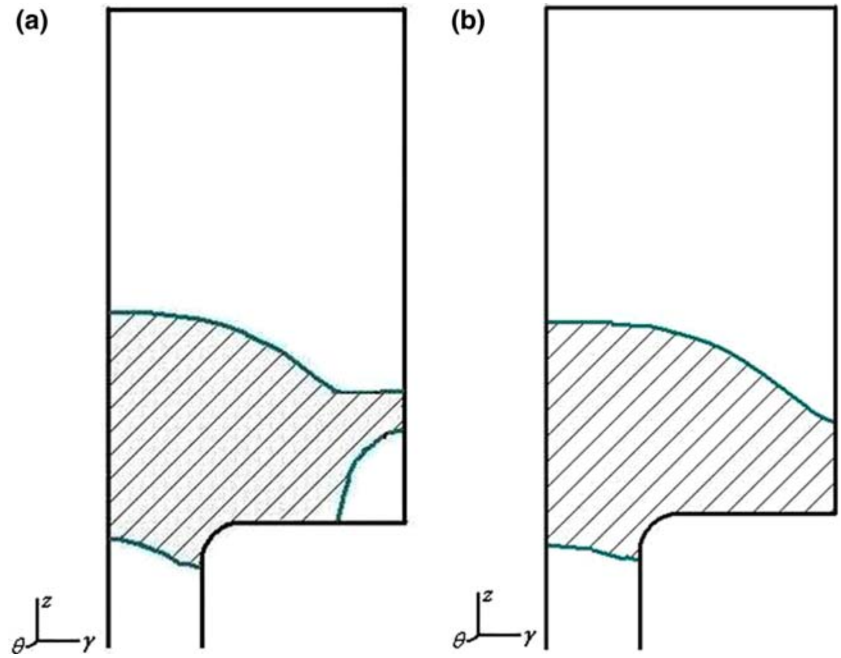


**Fig. 7** Division of rigid and plastic region (a) without and (b) with active friction

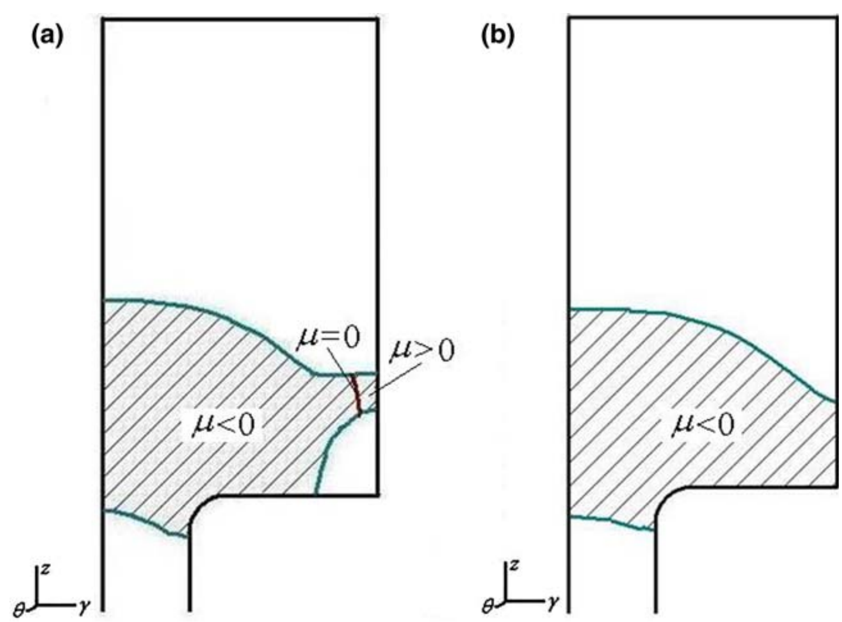


**Fig. 8** Division of Lode's coefficient (a) without and (b) with active friction

always be an elongation change towards the die aperture and the other two increments of principal strain turn to be a shortening tendency. It makes the metal in that region to be easier extruded. However, the material being the compression strain state exhibits not only a radial elongation tendency but also a circumferential elongation tendency. That is to say, metal in that region can be divided into two portions, one portion flows outlet the die aperture and the other portion stays in the container. For the extrusion with active friction, as shown in Fig. 9(b), the strain state in the plastic region is all of the extension strain, the increment of maximum principal strain exhibits an elongation tendency, and the other two increments of principal strain present a shortening tendency.

## 5. Experiment Research

### 5.1 Experiment Setup

The extrusion was performed on the hydraulic press with nominal pressure of 3150 kN. The diameter of billet was 50 mm and the height was 50 mm. The billet was split into two

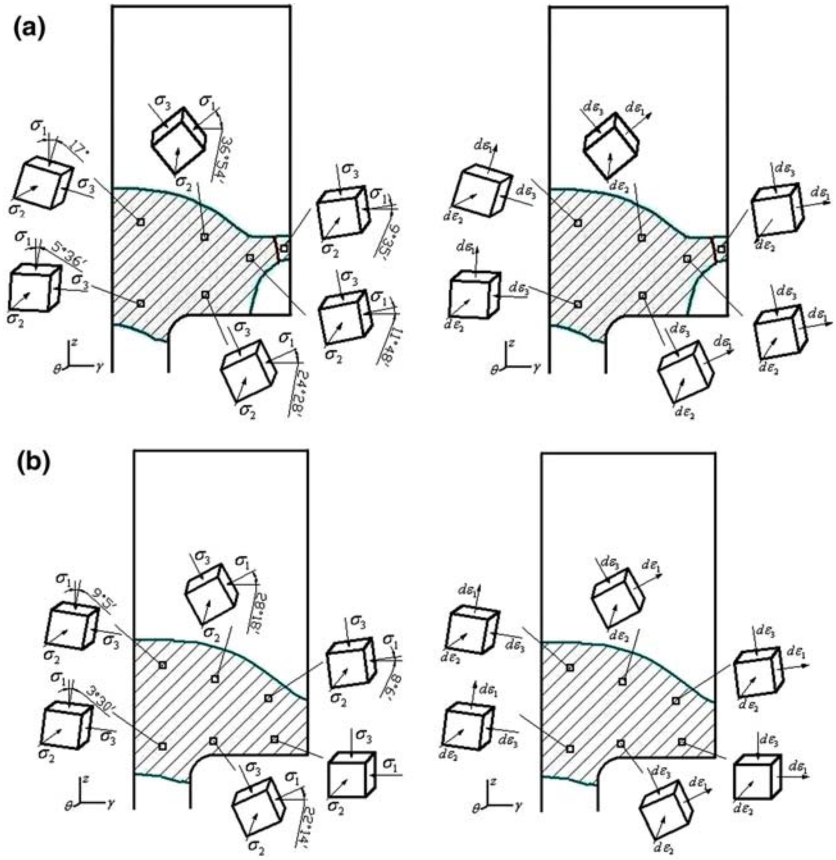

**Fig. 9** Vector distribution of stress and strain state (a) without and (b) with active friction

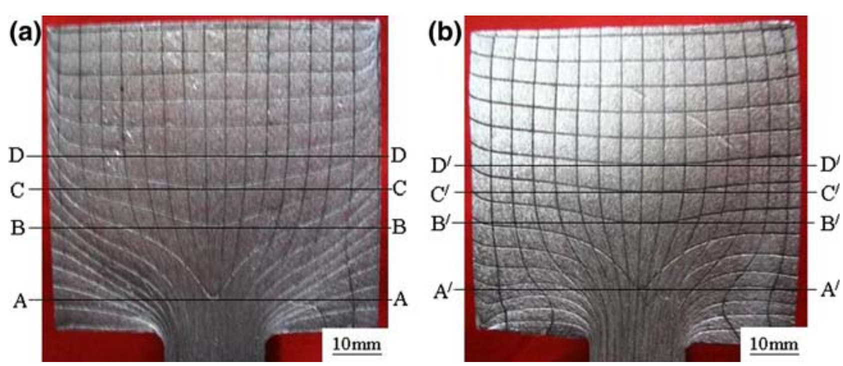


**Fig. 10** Deformation patterns of the grids on a diametric section (a) without active friction and (b) with active friction

halves along its axis, and $3 \times 3$ mm grids were carved on one of the cross sections. The isothermal method was adopted to decrease the loss of heat. The water based graphite was adopted as lubricant. Other experimental parameters are same as the numerical simulation.

### 5.2 Result Analysis

Figure 10 shows the deformation of grids on the cross section of the billets after extrusion using of the two types of extrusion.

It can be seen from Fig. 10(a) that without active friction, the flow and deformation of metal in the container is rather nonhomogeneous. The longitudinal flow lines near the side wall of the container bends obviously when accesses to the bottom of the container.

When extruding with active friction, as shown in Fig. 10(b), the distribution of flow lines on the cross section of billet becomes quite homogeneous. Even the longitudinal flow lines of grids close to the corner of the container tend to deform and flow towards the die aperture.

A comparison of relative axial displacement along the four transversal lines of the same initial position is presented in Fig. 11. For the convenience of measurement, the transversal line at the position of the greatest displacement, as shown in Fig. 10 is using as datum. Figure 11 shows the relative axial

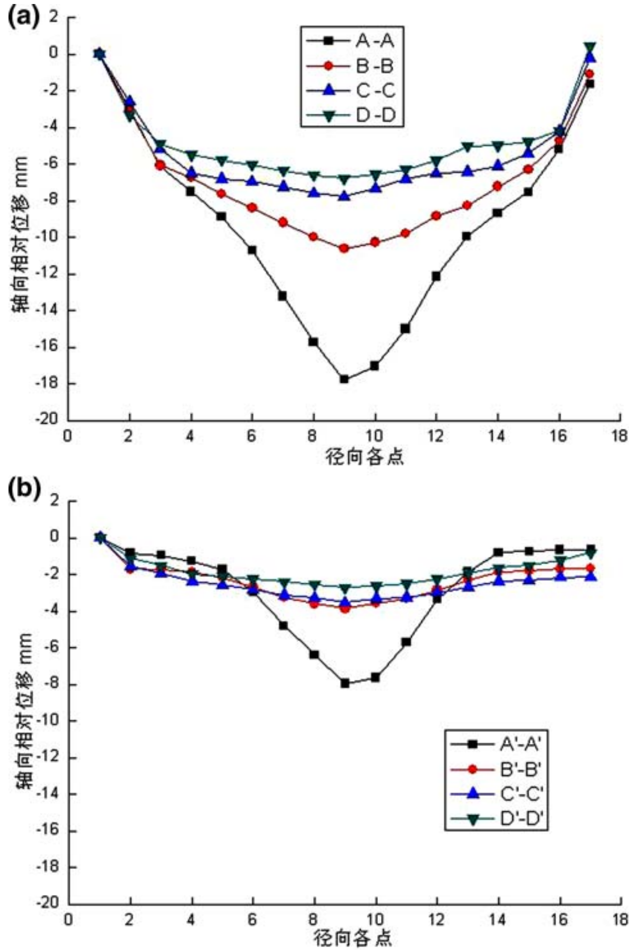


**Fig. 11** The relative axial displacement of grid lines (a) without and (b) with active friction

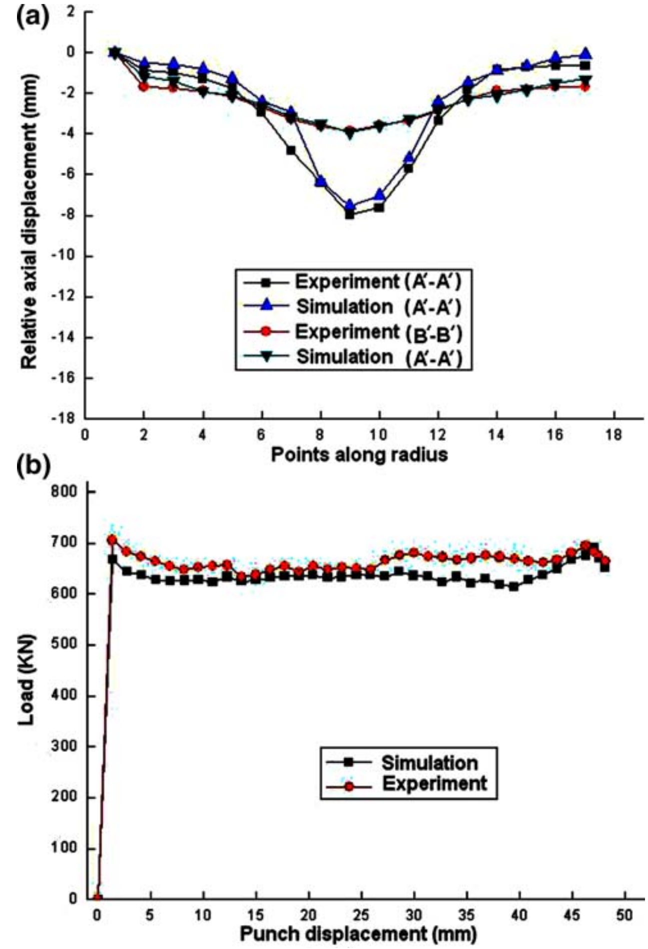


**Fig. 12** Contrast between experiment and simulation (a) The relative axial displacement of gird and (b) The curve of load and displacement

displacement of the points along the four transversal lines after extrusion.

From Fig. 11, it can be seen that in both types of extrusion process with and without active friction, the relative axial displacement along the four transversal lines is nearly in a state of symmetrical distribution along the axis. The closer to the axis, the greater the value of the relative axial displacement, i.e., the metal on the axis flows fastest.

Figure 11(a) shows that without active friction, the relative axial displacement differs greatly on the different transversal lines and the relative axial displacement of the axis on the transversal line A-A reaches 17.76 mm; whilst in the process of extrusion with active friction, the relative axial displacement of the axis on the transversal line A′-A′ with the same original position of A-A remains as the maximum value, as shown in Fig. 11(b). However, compared to the former one, the value decreases greatly to 7.98 mm. It can be concluded that the homogeneity of metal deformation and flow is enhanced extraordinarily and it is beneficial to increase the property of the extruded parts in the process with active friction.

The load-displacement curve of the two sections A′-A′ and B′-B′ are contrasted between the result of the experiment and the simulation, as shown in Fig. 12.

From Fig. 12(a), it can be seen that the relative axial displacement of experiment and simulation is correlated well both on the values and the trends. From Fig. 12(b), it can be seen, although the load of experiment is higher than that of simulation, the trends of the two curves are correlated well.

## 6. Conclusion

(1) Using the second invariant of stress deviator $J_2$ and the Lord stress parameter $\mu$, the deformation region can be identified in the extrusion process with and without active friction; The results indicate that in extrusion with active friction, the dead zone occurring on the corner of the container disappears completely and the strain types of material in the plastic deformation area decreased from three into a single type of tension.

(2) The stress state near the die aperture, with active friction, is different from that without active friction. The deflection angle between the maximum principal stress direction and the axis reduces significantly.

(3) The maximum relative axial displacement of the axis in extrusion without active friction is 17.76 mm and the one in the extrusion with active friction decreased to 7.98 mm. That is, the homogeneity of metal deformation and flow is improved.

(4) After contrasting the results of experiment and simulation, the relative axial displacement and the load are correlated well on both values and trends.


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