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ORIGINAL ARTICLE

Effect of inner cone punch on metal flow in extrusion process

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Abstract Using numerical simulation and experiment, the mechanical mechanisms of metal flow behavior were investigated in the extrusion process with inner cone punch. 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 inner cone punch 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 indicated that inner cone punch was beneficial to the extrusion process and the promotion of product quality.

Keywords Extrusion · Metal flow · Inner cone punch · Numerical simulation

1 Introduction

Extrusion process is one of the most important metal-forming processes due to its high productivity, low cost, and increased physical properties. In recent years, extrusion process is widely used in the manufacture of construction pieces structure components which are used in the aviation and machine areas in the area of aeronautics, astronautics, and mechanical manufacture [1, 2].The metal flows in the closed cavity during extrusion, which induces the process difficulty to analysis the process due to unpredictable behavior of metals flow during extrusion. This makes it difficult to establish extrusion processes and design mold tools.

Finite element method can help to understand the whole process of extrusion forming, including information of metal flow, temperature, strain, and stress of each stage during forming, which is helpful to die and process design. So it is important to study the metal plastic deformation behavior to control metal flow and prevent the generation of defects, therefore, numerical simulation is a common method in studying extrusive forming at present [3, 4]. A large number of studies with the finite element method have been carried out to improve the product quality and production efficiency. Darani and Ketabchi [5] studied the extrusive forming regulation of the type L-section mold material by means of the upper-bound method, results demonstrate that metal plastic flow chooses the minimum energy state, and choose the best mid-section shape between the first and the last section. Lee et al. [6] make use of DEFORM-3D to study metal flow, weld pressure, and squeeze load force of the congealed tube in a car during extensive forming process, and three-dimensional finite element analysis was carried out, then making its benefit take shape during extrusion. Damodaran and Shivpuri [7] developed the finite element mold about glass powder lubricating the hot extrusion process, the molds include every aspects correlated with the hot extrusion process, such as inducement heating, glass powder lubrication, and metal flow. In order to set up complicated three-dimensional finite element, simulation was used, the mold was applied to extrude complicated construction pieces of space navigation titanium. Narayanasamy et al.[8] tried many designing

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methods to improve mold tools, for example, using square multinomial curve district mapping painting technique and tines painting technique etc. which promise both extruding square type material and metal flowing from the surface to the center entirely, and this will benefit metal extrusive forming. Muller [9] proposed ISA extrusion method and studied about it by means of numerical simulation and experiments, the result showed that common anti-extrusion would come true if only the load force is 38% of the biggest deformation force at the beginning stage of billets extrusive forming. The productivity will increase 8–10% than opposition extrusion of the squeeze condition is improved.

There are many factors that affect metal flow during extrusion, but due to innate characters of deformation forms and mold tools structures, it is difficult to avoid some defects during extrusion. Traditionally, the way to improve metal flow during extrusive forming is to simply optimized process parameters, but it can not prevent the generation of defects radically. To avoid above shortage, study on extrusion made use of punch with inner cone structure was carried out in this paper and analyzed the metal flow condition by means of numerical simulation during deformation comparison with common extrusion process.

2 Finite element simulation

2.1 Finite element model

DEFORM™-2D was used to simulate the extrusion process. Because of 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. 1.

In order to improve metal-deforming flow condition and prevent the generation of defects during extrusion, the application of round cone structure at the axis of punch end was proposed; as shown in Fig. 2, it is applied to make a comparison study about metal-deforming flow condition in the container with common extrusion process.

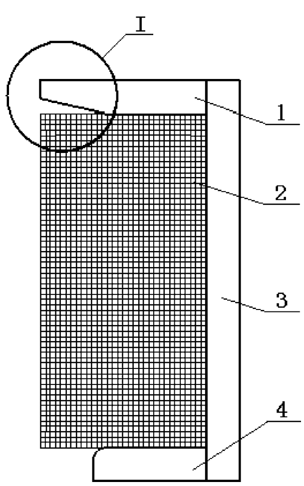

Fig. 1 Finite element model (*1* ram, *2* billet, *3* container, *4* die)

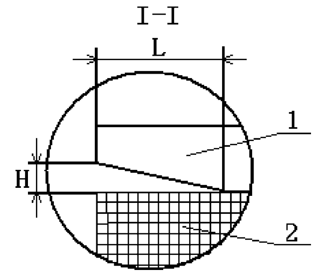

Fig. 2 Punch model (unit: mm)

The size of inner cone punch can be expressed with the H and the L. Here, the cone-altitude H is 3.5 mm, the cone-radius is 10 mm. Through adding inner cone punch, a filled process happens during extrusion, which changes the metal-deforming flow condition at the axis and has an important effect to avoid defects.

2.2 Simulation setup

The diameter of billet was 50 mm and the height was 50 mm. In this study, rigid plastic finite element model was used. The billet was considered as plastic body. The punch, the container, and the die were considered as rigid bodies. The billet was meshed by 2,000 four-nodal elements. The speed of punch was 1 mm/s. The extrusion temperature was 435°C and the extrusion ratio was 9.8.

The coefficient of friction between billet and container was 0.3 according to the hot ring compression experiment carried out at 435°C. The material property of the billet was aluminum alloy corresponding to 7,050 in the experiments. The chemical composition of 7,050 aluminum alloy is shown in Table 1.

3 Simulation results analysis

3.1 Final stage of extrusion

It is well known that it is easy to generate defects during conventional extrusion, because of the complexity of the

Table 1 Nominal composition 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

metal deformation and flowing at the bottom of the container. So how to improve metal deformation flow condition in the container, the inner cone punch is applied to extrude, and the comparison between the velocity field and deformation behavior during two extrusive processes was carried out, as shown in Fig. 3.

Figure 3 shows the comparison between the mean stress field and deformation with and without inner cone punch at the corner of the container. It can be seen that for extruding without inner cone punch, as shown in Fig. 3a, the value of mean stress increases along the direction to the die pocket so does along the direction to the corner. However, when inner cone punch is used, as shown in Fig. 3b, no such stress field is obtained in this area, and a mean stress is raised only along the direction to the die pocket. Moreover, the grids shapes of this area are mostly the parallelogram. This indicates that the deformation and flow of the metal is more homogeneous. Therefore, it is easier for the metal to flow out of the die pocket without the formation of dead zone.

Figure 4 shows the velocity field with and without inner cone punch at the bottom of the container. It can be seen from Fig. 4a that without inner cone punch, there is an obvious metal flow interface at the bottom of the container. Some metal moves towards the die aperture, while the other toward the container and the dead zone is formed. When inner cone punch is employed, as shown in Fig. 4b, the metal near the container flows to the die aperture homogeneously, and no velocity interface is observed in the plastic deformation zone. The metal almost flows towards the die aperture radially without large angle turning, which not only decreases the generation of flow line turbulence, dead zone and overlaps, but also improves the extrusion product quality.

3.2 Final stage of extrusion

Figure 5 shows the contrast of the equivalent strain between two kinds of extrusion at the final stage of extrusion. It is shown from Fig. 5a that the uniformity of metal deformation flow along the radial direction obviously enlarges during common extrusion. The uniformity still increases continuously as extrusion goes on. The metal deformation flow at the axis is bigger than that at the edge of the die which causes surrounding metal hard to reinforce in time, so it is easy to generate shrinkage hole at the end of the axis at the final stage of extrusion. Figure 5b shows that, after adding inner cone structure on the punch, the stress equivalent lines in the container distribute in parallel with the bottom of the mold and gradually enlarge from the die entrance along the axis. The numerical discrepancy of the equivalent strain at the axis and the lower corner of the bottom die is not great. Metal flow trends to more uniformity in the deformation area, the minimum equivalent strain distributes at inner cone punch which avoided the tendency of the generation of shrinkage hole because metal flows too fast at the axis.

When extruding short billet or at the final stage of extrusion process, the metal near the central line flows faster due to the decreasing of compressive stress at the billet top, and the metal can not fill in time, so that the shrinkage cavity appeared. Figure 6 shows the comparison of the axial stress σ_z acting on the billet top with and without inner cone punch at the last stage of extrusion process.

The axial stress σ_z at the central zone is tensile during the final stage of extrusion without inner cone punch, and it is changed into compressive stress as the increasing of the distance from the axis. Therefore, the central metal flows

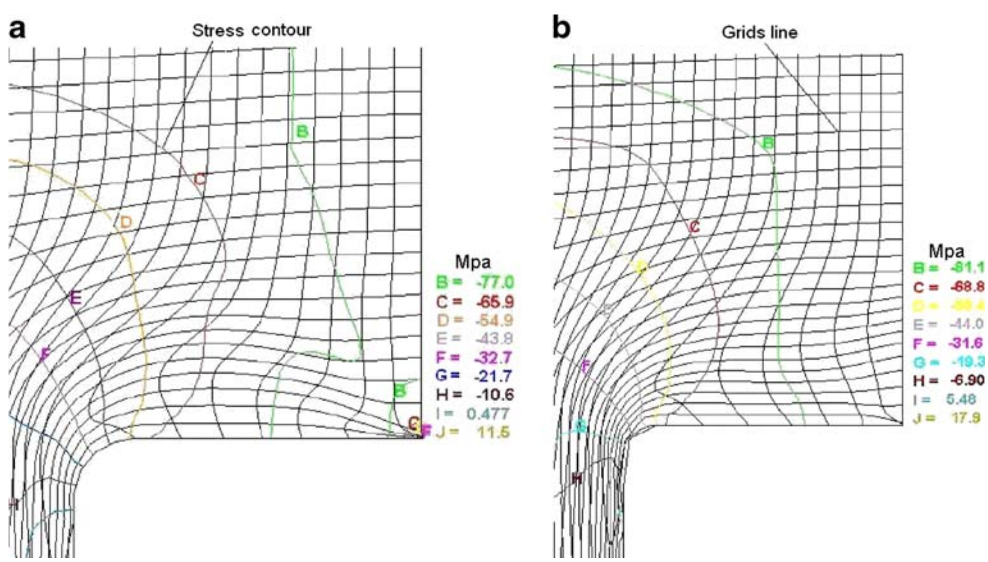

Fig. 3 Comparison between the mean stress field and deformation at the bottom of the container **a** without and **b** with inner cone punch

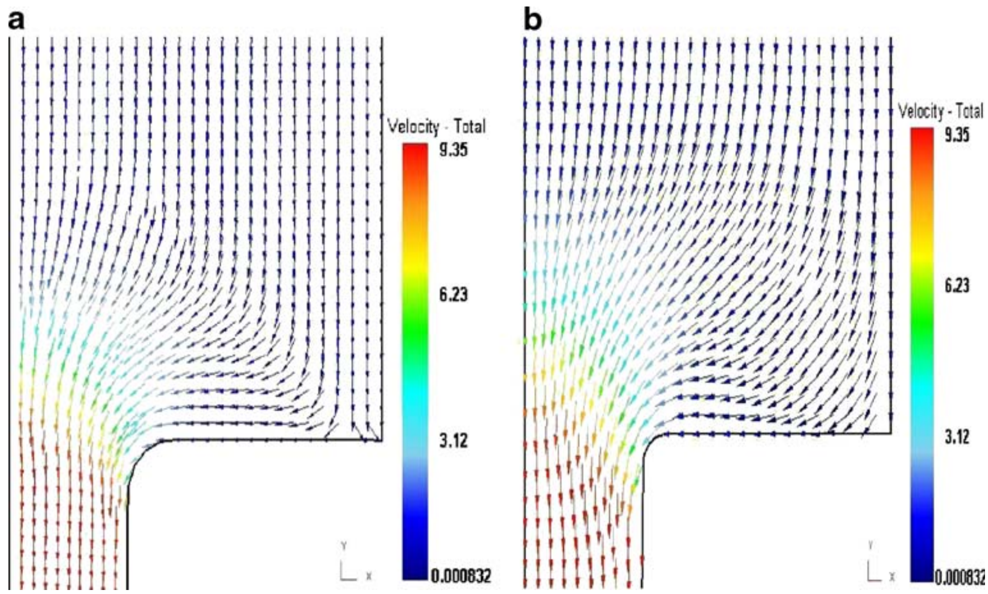

Fig. 4 Comparison of velocity field at the bottom of the container **a** without and **b** with inner cone punch

faster, the metal of this area tends to easily leave the punch and the shrinkage cavity is formed.

As shown in Fig. 6, with inner cone punch, the axial stress σ_z at the central zone is changed from tensile to compressive. Hence, the shrinkage cavity of the extrusion can be solved.

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 further analysis.

4.1 Method of deformation division

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 play a very important role in plastic forming analysis [10].

In extrusion, the metal in some regions of a billet cannot satisfy the plastic deformation condition and the plastic deformation would not occur due to the friction. For convenience, the Von-Mises yield criterion can be described as [11]:

$$J_2 = \frac{1}{3}\sigma_S^2 \tag{1}$$

Where, J_2 is the second invariant of stress deviator, σ_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 inner cone punch can be shown in Fig. 7. The regions marked with shadow represent the areas where a plastic deformation occurs.

Figure 7a shows that without inner cone punch, the region of the work piece in the upper part of the container

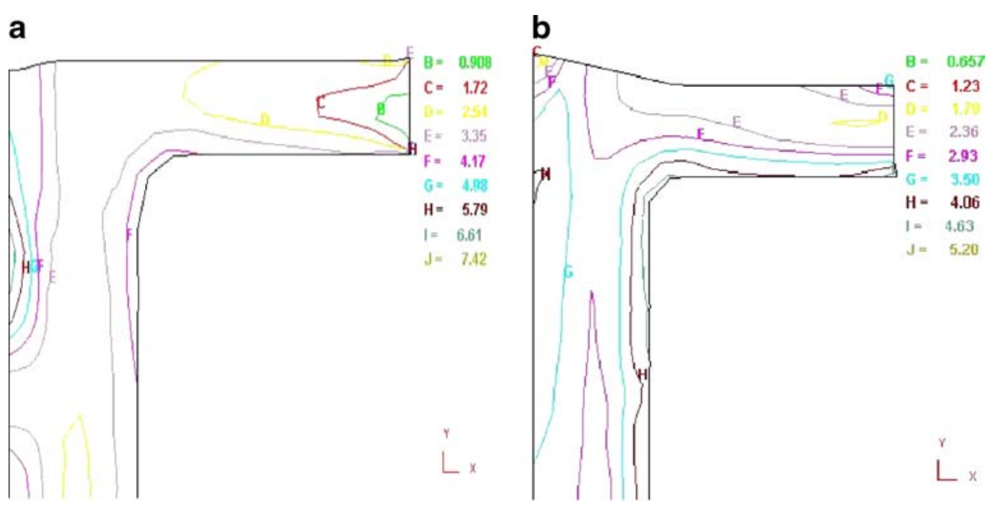

Fig. 5 The equivalent strain distribution at the final stage of extrusion **a** without and **b** with inner cone punch

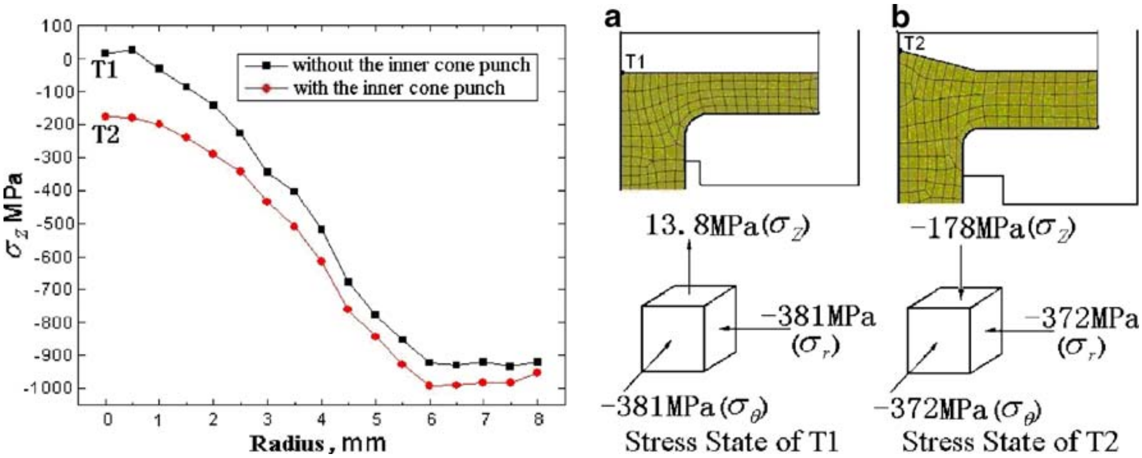

Fig. 6 Distribution of the axial stress σ_z on the billet top

and in the lower corner of the container does not deform plastically. In the extrusion with inner cone punch, as shown in Fig. 7b, the plastic region is larger, and there is no dead zone. So it can be assumed that inner cone punch increases the amount of plastic deformation of the metal at the bottom corner of the container.

4.2 Types of deformation

Lode's parameter μ 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. Example, when $-1\leq\mu<0$, it is tensile strain state, when $\mu=0$, it is plane strain state and when $0<\mu\leq1$, 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 [12, 13]. 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. 8a that without inner cone punch, 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 inner cone punch, the strain in the plastic region is everywhere tensile, as shown in Fig. 8b. So

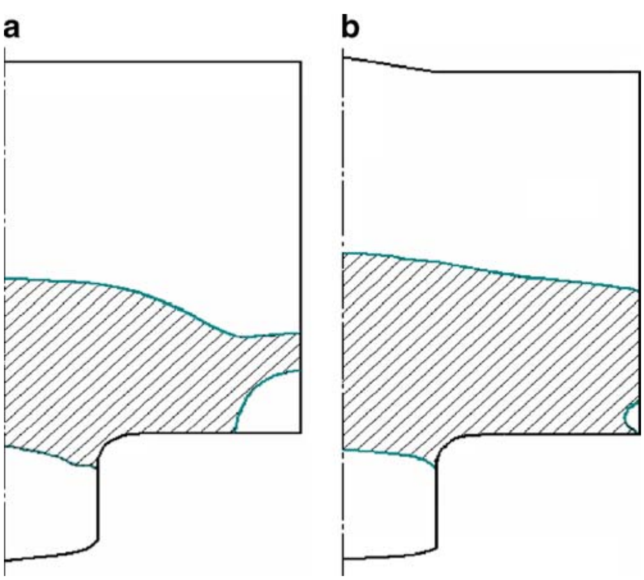

Fig. 7 Division of rigid and plastic region **a** without and **b** with inner cone punch

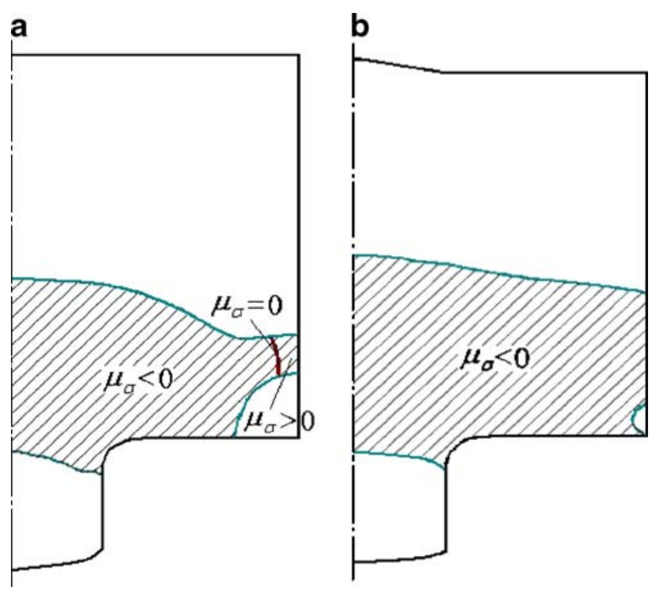

Fig. 8 Comparison of deformation division **a** without and **b** with inner cone punch

compared to the extrusion without inner cone punch, the metal flow in the container is more homogeneous.

4.3 Stress and strain analysis

According to the plastic 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. Figure 9 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 inner cone punch, 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 inner cone punch, the deflection angle between the maximum principal stress and the direction of axis is less than for extrusion without inner cone punch.

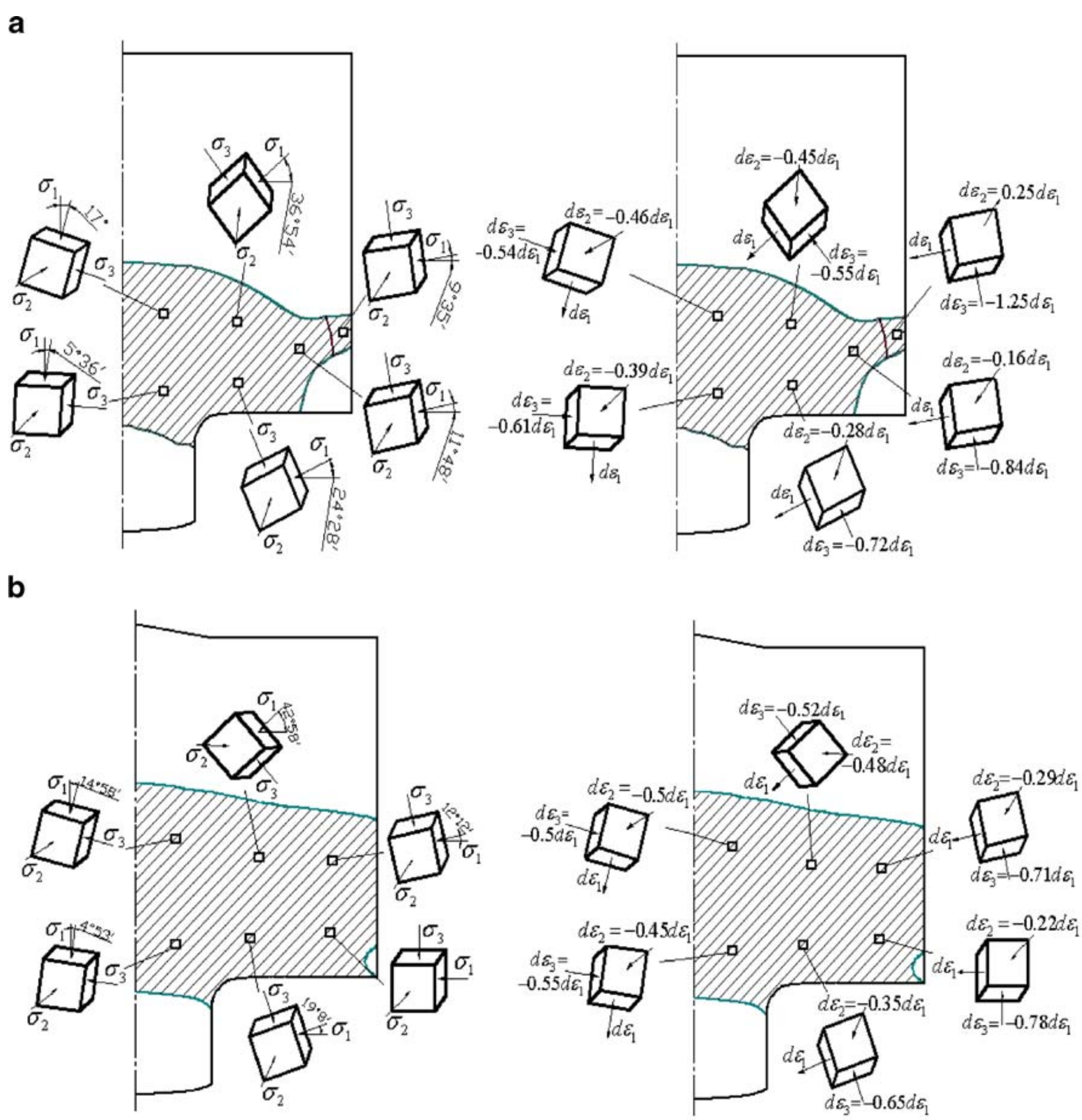

Fig. 9 Schematic of stress and strain vector distribution **a** without and **b** with inner cone punch

Figure 9a also shows that in the plastic region of extrusion without inner cone punch, the increment of maximum principal strain of the material being the extension strain state almost 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 out in the die aperture and the other portion stays in the container. For the extrusion with inner cone punch, as shown in Fig. 9b, 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 3,150 kN. The diameter of billet was 50 mm and the height was 50 mm. The billet was split into two halves along its axis, and 3×3 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 the same as the numerical simulation.

5.2 Experimental results

In order to study the influence on metal deformation flow when used inner cone punch during extrusion, taking the press deal as 25 mm, comparing the flow lines of billet section between two extrusion forms, as shown in Fig. 8.

It can be seen from Fig. 10a that, during extrusion without inner cone punch, due to the friction of the side wall and bottom, the metal close to the bottom of the container was largely affected, therefore, metal deforming and flowing are non-homogeneous obviously in this zone, the flow lines accessed to the bottom are bended obviously, even crack. The flow lines sheered besides some remit extrusion metal to form fold, the rests are gradually stored at the bottom of the container to form dead zone. It can be concluded that the more access to the side wall and bottom of the container, the more difficulty metal deformation flow.

After using with inner cone punch to extrude, as shown in Fig. 10b, the flow lines on the section in the container become homogeneous comparing with common extrusion, the bending degree decreases largely, moreover, the metal close to the side wall of the die is tend to deform and flow toward the die pocket, although the area close to the bottom of the container is relatively difficult to deform at this time, the scale contrasts largely. It is shown that, after changing the punch structure, the scale of plastic deformation zone in the container increases obviously, meanwhile, the scale of fold and dead zone depressed. As a result, it will more beneficial for metal to extrude forming to adopt the punch with inner cone punch to extrude.

6 Conclusion

1. Using the second invariant of stress deviator J_2 and the Lord's parameter μ, the deformation region can be identified in the extrusion process with and without inner cone punch. The results indicate that in extrusion with inner cone punch, the dead zone occurring on the corner of the container disappear completely and the strain types of material in the plastic deformation area decreased from three into a single type of tension.
2. When the inner cone punch is used, the shrinkage cavity is eliminated because the axial stress of the metal in the central zone is changed from tensile stress to compressive.
3. The stress state at the bottom of the container with inner cone punch is different from that without inner

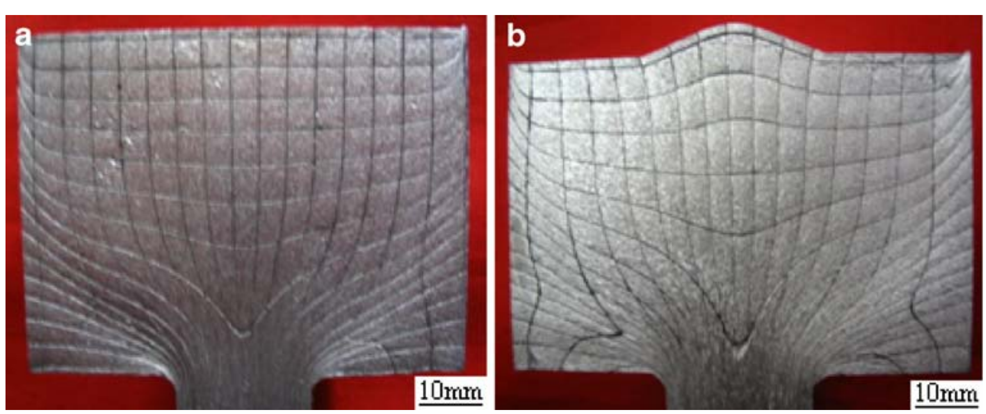

Fig. 10 The flow line on the section at the middle stage of extrusion **a** without and **b** with inner cone punch

cone punch. The metal flow is more homogeneous and the tendency to generate the dead zone is reduced remarkably as the inner cone punch is used.

4. After contrasting the results of experiment and simulation, it is found out that the inner cone punch is more beneficial for metal to extrude forming.

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