THEORETICAL ANALYSES ON DESIGN OF SHEAR EXTRUSION DIE[①]

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ABSTRACT A set of explicit formulas for the design of shear extrusion die, including the layout of die opening and specification of die channel length were given. The extrusion of slab and triangular sections were discussed and the influences of the width, position of the die opening, the reduction of area of the processes on the die design were analyzed. The calculated results are in good agreement with industry practice.

Key words shape extrusion die design element deformation analysis method

1 INTRODUCTION

Shear dies are widely used in the extrusion industry. But the use of shear die in the extrusion of complex shapes always leads to a complicated problem of metal flow imbalance that often results in shape defects. And the die design, generally including location of die orifice and die land length specification, is the most important step to obtain a straight and true product in size. Although attempts have been made to derive laws concerning the die design, which is still conventionally performed by experienced tool makers and by going through a costly and time-consuming process. This situation is urging extruders to develop some adequate qualitative design models and introduce CAD/CAM technology as soon as possible.

Although some general principles for the design of flat-faced shape extrusion die have been introduced[1-5], only a few attempts have been made to give theoretic analysis of this process because it is quite difficult to analyze such a 3 dimensions flow problem. Besides, it is hard to determine an optimum die design experimentally too. Researchers can only assess the design of the extrusion die by finding the exit velocity of each part of product or simply by observing the geometry of extrudate[6-10]. In 1970s, Russian researchers[6] once developed a mathematical model for predicting exit velocity of the product, carrying out optimum layout and land design of the extrusion die. Shivpuri and Momin[7] developed a method based on 2 dimensions FEM technique to modify die geometry including entry angle and die land of L-shaped sections. Mori *et al*[8] used 3 dimensions rigid-plastic FEM to predicate the curvature of an extruded bar and calculate the location of the die opening. Recently Stahlberg[9] used upper bound element technique to discuss the optimum position of die opening and die land length of two die openings. But the work above-mentioned leave much desire to die designing practice still. In the present work, a so-called element deformation analysis method was suggested which introduce a totally new design approach for shear extrusion die.

2 THE PROPOSED APPROACH

A sufficient condition for perfect control of the metal flow of shape extrusion process is to design a die so that all elements of a profile would run at the same speed irrelevant with each other. Based on this consideration, the cross section of product is divided into a number of small elements and analyzed respectively. As pointed

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out by Ref. 11, this method without taking account of the influence of the deformation path can give quite satisfying results when analyzing shape extrusion problems.

To make things simple, the deforming material is assumed to be isothermal, rigid-plastic and non-strain-hardening.

First, the cross sections of billet and product are divided into a number of conjugate elements. As shown in Fig. 1, element OAB on the billet cross section is converted into $OA'B'$ on the cross section of product after the deformation, which represents a process during which element OAB enters the deformation zone at the same velocity as V_0, of the extrusion ram and leaves the deformation zone at the geometry of $OA'B'$ at velocity V_j. For an ideal extrusion process which has uniform axis velocity along the exit surface of deformation zone, it keeps:

$$V_1 = V_2 = \cdots V_n \quad (1)$$

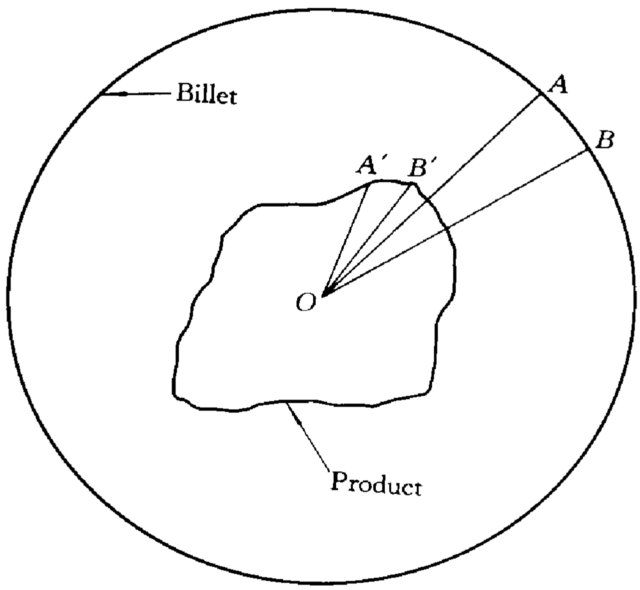

Fig. 1 Division of the cross sections of billet and product

To satisfy the above condition, it must satisfy that:

$$A_{j0}/A_j = \lambda \quad (j = 1, 2, \cdots n) \quad (2)$$

where A_{j0} and A_j denote the area of conjugate inlet and outlet elements OAB and $O'A'B'$ respectively, λ is the extrusion ratio of the process, n is the number of the pairs of the conjugate elements.

Assuming the deformation of each element A_{j0} into $A_j (j = 1, 2 \cdots n)$ undergoes independently, a general element deformation process is analyzed below.

Let T_j denote the dissipated power of the process, Q_j denote the average stress loaded by extrusion ram. Power balance principle gives:

$$T_j = Q_j A_{j0} V_0 \quad (j = 1, 2 \cdots n) \quad (3)$$

Apparently the difference of stress among elements is undesirable and minimum work consumption is desirable. It is reasonably concluded that a ideal flow can be obtained when

$$W_1 = W_2 = \cdots = W_n \quad (4)$$

$$\frac{\partial W_j}{\partial P_m} = 0 \quad (m = 1, 2, 3)(j = 1, 2 \cdots n) \quad (5)$$

$$\frac{\partial W_j}{\partial D_j} = 0 \quad (j = 1, 2 \cdots n) \quad (6)$$

where $W_j = T_j / A_{j0}$, D_j the length of deformation zone, P_m the location of the die orifice with respect to die center, and m is the freedom of the positioning of the die orifice.

From eq. (4), (5) and (6), the parameters needed to design an extrusion die, P_m, D_j and the land length of the die $L_j (j = 1, 2 \cdots n)$ can be calculated.

3 ANALYTIC EXPRESSIONS OF CONSUMED WORK W_j

The total work consumed through a deformation process is given as the sum of its components of ideal, shear, frictional works along dead metal zone surface and die bearing surface

$$W_j = W_{ji} + W_{js} + W_{jf} + W_{jb} \quad (7)$$

To get a set of simple equations to calculate those work components, a deformation theory based on methodology given by Ref. 11 is used here.

3.1 Deformation theory expression of ideal work of triangular elements

Generally speaking, the cross section of both the billet and product can be divided into a number of small triangle elements. If the areas of the elements are small enough, they can be seemed being deformed evenly. A deformation theory based approach is used to calculate the ideal work of the process as follows[11].

As shown in Fig. 2, if points (X, Y, Z)

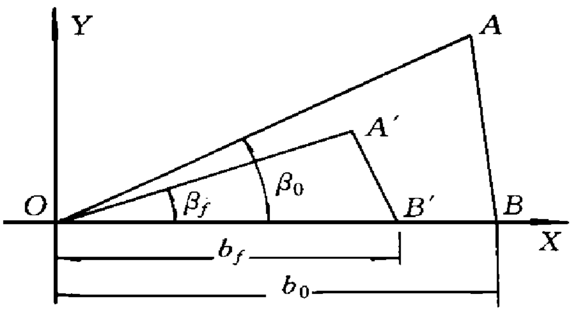

Fig. 2 Geometry of conjugate element

on section OAB moves onto (x, y, z) of section $OA'B'$ after the deformation, suppose the displacement field as:

$$\left.\begin{aligned} x &= (k_f b_0/b_f - k_0 b_f/(\lambda b_0))\,Y + \\ &\quad (b_0/b_f)\,X \\ y &= (b_f/\lambda b_0)\,Y \\ z &= \lambda Z \end{aligned}\right| \qquad (8)$$

where $k_0 = \tan\beta_0$, $k_f = \tan\beta_f$.

The principle values of the right Cauchy-Green tensor C of this displacement field are

$$\left.\begin{aligned} \mu_{1,2} &= (1/2)(G^2 + \sqrt{G^2 + (4/\lambda^2)}) \\ \mu_3 &= \lambda \end{aligned}\right| \qquad (9)$$

where

$$\begin{aligned} G = {} & (b_0^2/b_f^2 + b_f^2/(\lambda^2 b_0^2) + \\ & (k_b b_0/b_f - k_0 b_f/(\lambda b_0))^2)^2 \end{aligned}$$

So the logarithmic strain of the deformed body is

$$\left.\begin{aligned} E_{1,2} &= (1/2)\log\mu_{1,2} \\ E_3 &= \log\lambda \end{aligned}\right| \qquad (10)$$

Thus the deformation work consumed per time of the per area of the element is

$$W_{ji} = \bar{\sigma}_s E_e \qquad (11)$$

where $\bar{\sigma}_s$ is average yield stress of the process, E_e is effective strain.

3.2 Shearing work at entry and exit surfaces

Assume the flow lines of the deformation process are straight. As shown in Fig. 3, volume element dS is bent by an angle θ. at the entrance of the deformation zone under the influence of the shear flow stress τ_k. The shear work W_{js} yields

$$dW_{js} = \tau_k \mathrm{tg}\,\theta \cdot dS \qquad (12)$$

with $dS = V_0 y r\,dr$

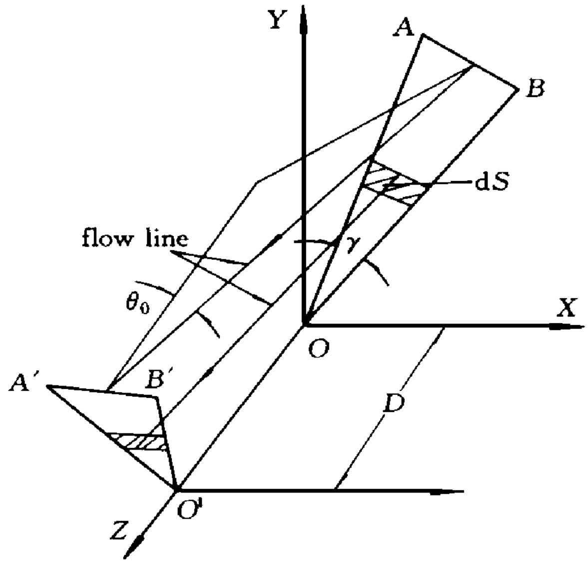

Fig. 3 Derivation of shearing work

where D is the length of its deformation zone along Z-axis, r is the distance between the center of dS and point O. Through substitution and integration, the work can be gained. Similarly, the shearing work for unbending at the die exit is the same as the entry one. So the total shearing work per time along element OAB and $O'A'B'$ can be written as:

$$W_{js} = (4/3)\,\tau_k \tan\theta_0 \qquad (13)$$

3.3 Frictional work along dead metal zone surface

The frictional work along dead metal zone of axis symmetric process can be estimated by the formulas obtained by equilibrium method, work balance method or upper bound method. For shapes other than axis symmetric, the frictional work increases due to the increase of the area of the interface between the dead metal and the deformation zone. Generally speaking, to calculate this frictional work of non-axis symmetric problems, the velocity field of the process must be given. To avoid the complicated process of setting up a supposed flow pattern, it is supposed that

$$W_{ji}/W_r = W_{jf}/W_{rf} \qquad (14)$$

where $W_r = \log\lambda$, $W_{rf} = \mathrm{ctg}\,\theta_0 \log(\lambda/\sqrt{3})$, which are obtained by body free equilibrium approach under constant friction consumption, are ideal deformation work and frictional work along dead metal zone surface of the axis symmetric extrusion problem with the same extrusion ratio.

Thus: $W_{jf} = (1/\sqrt{3})\mathrm{ctg}\,\theta_0 E_e$ (15)

where θ_0 is shown in Fig. 3.

3.4 Frictional work along die land surface

Assuming the friction along the die channel is constant, the power dissipated by the friction is

$$W_{jb} = mK \mid A'B' \mid L_j/A_j \quad (j = 1, 2 \cdots n) \qquad (16)$$

From the former published researches, the friction factor m is found to range from about 0.2 to values considerably less than one[5].

4 APPLICATION TO SOME SIMPLE EXTRUSION PROBLEMS

The extrusions of two simple sections, slab and triangle sections, are chosen to be analyzed below. To specify the conjugate elements of billet and product, first the position of the "neutral axis" is determined. The neutral axis is defined as an axis across which there is no metal flow during extrusion. As shown in Fig. 4(a), (b), the neutral axis position O is the line of intersections of line of symmetry X-X' with the line A-A'. The position of A-A' is determined such that the ratio of the area 1O2 to the area 1'O2' is equal to the extrusion ratio of the process. Then, as shown in Fig. 1, the area of the product section is divided into a number of elements, the cross section of the billet is divided by satisfying eq. (2) thereafter.

A program was developed to solve those problems. The results show that the increase of consumed work calculated with the increase of the number of the divided elements of the profile (Fig. 5). As can be observed, when the number of elements is big enough, a good result can be obtained. The consumed work is denoted as $W(j)$, where j denoting the number of conjugate elements, the converging criterion is defined as

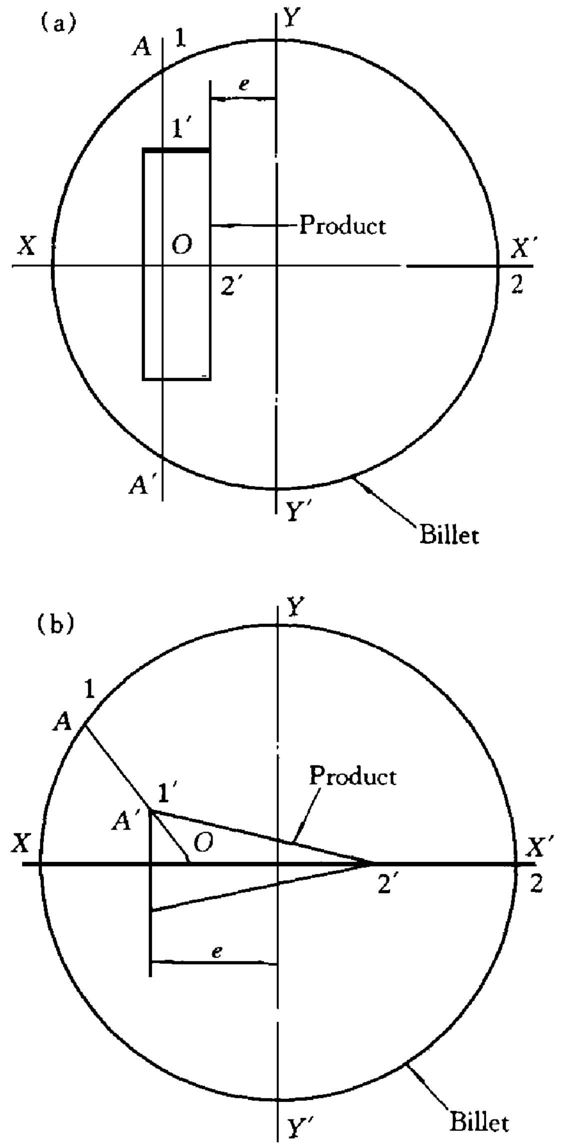

Fig. 4 Determination of position of neutral axis

(a) —Slab section; (b) —Triangle section

$$W(j+1) - W(j) < e \qquad (17)$$

where e is a small positive value.

From the experience, two important factors must be considered when the bearing length of each element of the extrudate is specified. One is its position and another is its relative wall width. All extrusion plants have their own rule of thumb to do so, as introduced in Ref. 4. Generally speaking[1-4], when an element's position is considered, bearing length increases 0.2~0.65 towards the center of the die. On the other hand, bearing length is made approximately proportional to the relative width of the die opening. In the present work, the extrusion of slab or rectangular and isosceles triangular profiles are analyzed to find the action mechanism of the two factors upon the bearing length design. The calculated bearing lengths are along the long side of slab profiles and side 1′2′ in Fig. 4(b) of triangle profile, respectively. When slab products are not symmetrically positioned, suppose the bearing lengths of its opposite element were the same to their average value.

Fig. 6 shows the influence of the width of the profiles on its bearing length design where the profiles are all on their symmetric position. It can be seen from the figure that the bearing

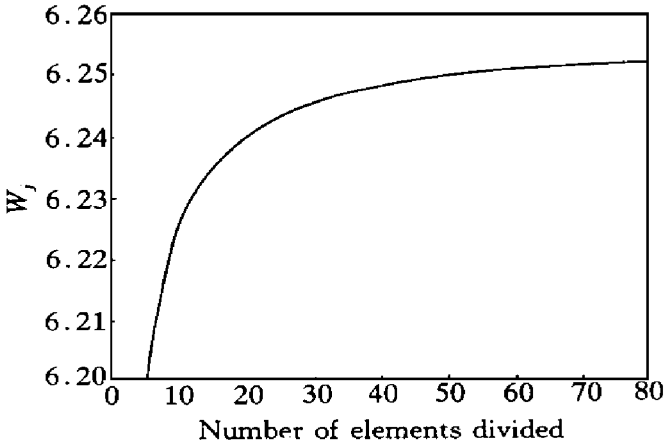

Fig. 5 Characteristic of convergence of method

Product shape: Rectangle, length= 40;
Width= 3; Container radius R= 30
Friction factor m= 0.4; Position: θ= 1.5

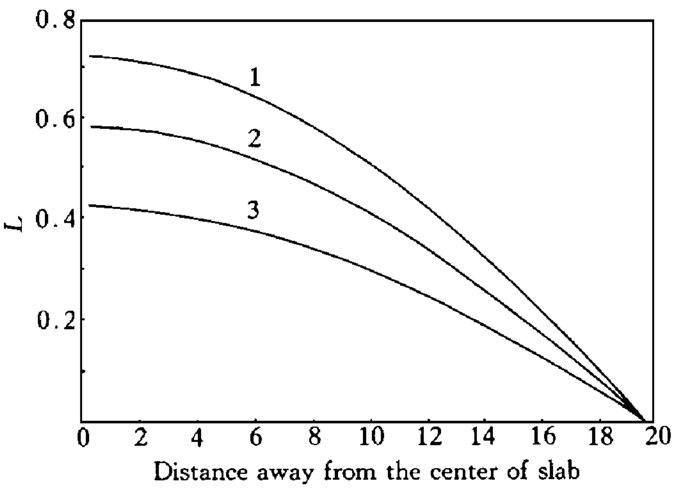

Fig. 6 Influence of elements′ width (l) on bearing length(L)

Product shape: Rectangle, length= 40
Container radius R= 30
Friction factor m= 0.4
1 —l= 4; 2 —l= 3; 3 —l= 2

length increases about 0.2~ 0.35 towards the center of die and wider product results in larger length increasing. The results are in agreement with regularity given above.

The influence of another factor, the extrusion ratio or reduction of area of the process, were also analyzed. This influence is generally ignored. But from the results shown in Fig. 7, it can be seen that the influence does exist.

The influence of the position of die opening is shown in Fig. 8. It can be seen that the

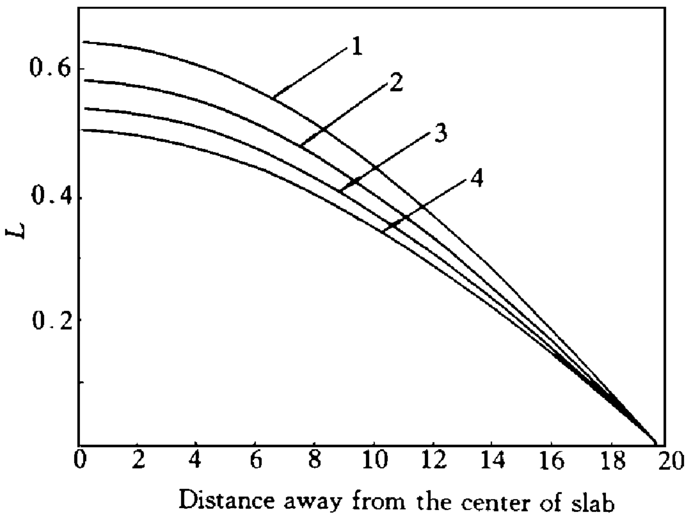

Fig. 7 Influence of extrusion ratio on bearing length

Product shape: Rectangle, length= 40;
Container radius R= 30; width= 3;
Friction factor m= 0.4; Position θ= − 1.5
1 —R= 25; 2 —R= 30; 3 —R= 25; 4 —R= 40

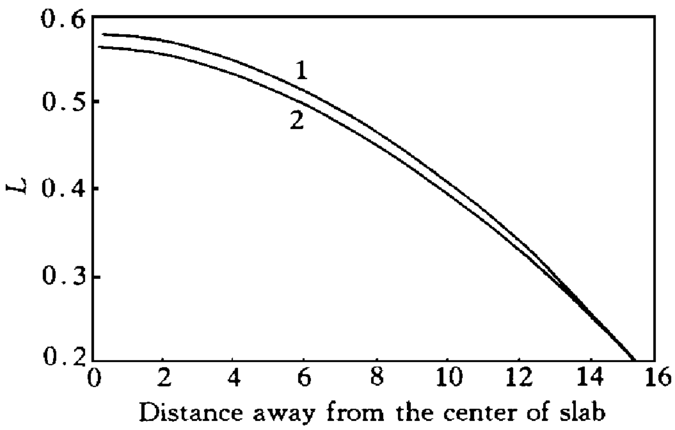

Fig. 8 Influence of the die opening position on bearing length

Product shape: Rectangle, length= 40;
Width= 3; Container radius R= 30;
Friction factor m= 0.4
1 —e= 1.5; 2 —e= 15

increase of the deviation of the die opening from its symmetric position causes the decrease of the maximum die land length, which is also confirmed by the extrusion practice.

As to the product without two axisymmetric axes, the problem of the determination of the optimum position of the die opening arouses. The extrusion of triangle product which was once discussed by Perlin[2] was analyzed. It can be seen from Fig. 9 that the optimum position where the consumed work is minimum is near its base than its vertex point 2′, which is also in agreement with Perlin's.

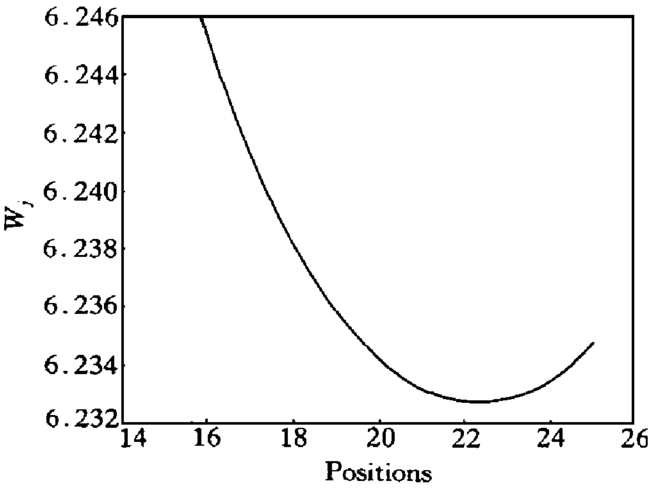

Fig. 9 Influence of die opening position on work consumed

Product shape: Triangle

Base= 6; Height= 40; Container radius R= 30

Friction factor m= 0.4

Fig. 10 shows the land length design of the extrusion of triangle product. Compared with the results shown in Fig. 6– 8, the maximum land length is much greater. With the influence of the product′s width considered, this result is also reasonable.

5 CONCLUSION

Element deformation analysis method is developed for the design of shear extrusion dies. By analysing the deforming elements independently, a set of explicit formulas for the task is given. The processes of the extrusion of some simple profile are analyzed. Being conformity with the

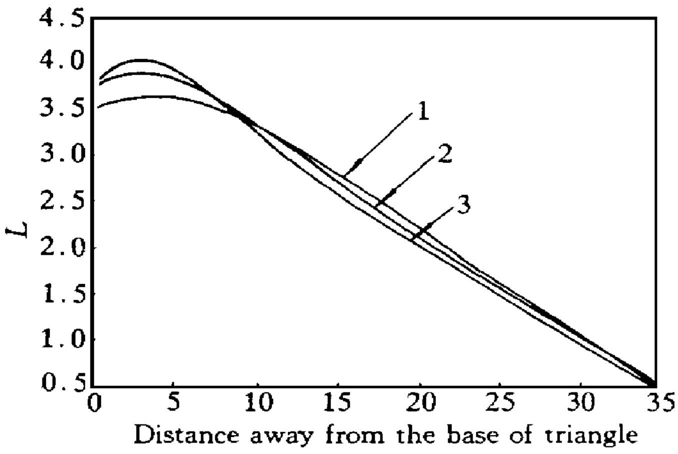

Fig. 10 Bearing length arrangment

Product shape: Triangle

Base= 6; Friction factor m= 0.4;

Height= 40; Container radius R= 30;

1 —e= 15; 2 —e= 20; 3 —e= 25

plant practice, the results apparently show the influence of several parameters such as element width and position on the die design. It is also shown that there exists influence of the extrusion ratio on the die design. The results show that this method completes the task of the die opening positioning and the bearing land design well.

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