特　集　8
研 究 速 報

Flow of Solid Metal during Extrusion: Three Dimensional Simulations by Finite Element Method・1

押出し加工時の塑性流動
——有限要素法による3次元シミュレーション・1——

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1. INTRODUCTION

Extrusion is one of the most important process in metal forming. It is extensively used to produce rods, bars, pipes, sections and various other products, including very complex ones.

Traditionally, flat-faced dies and their variants have been used to extrude easy-to-extrude metals such as aluminum alloys. The shape and the deforming zone of flat die and workpiece are shown in Fig. 1. The flat die produces an intensely deforming shear surface which separates the deforming zone from the dead metal zone. The shear surface acting like a shaped die with very high friction. In general the flat-faced die may suffer serious drawbacks, some examples are: non-uniform metal flow, excessive redundant work, high extrusion pressure, possibility of internal cracking and non-uniform material property of the product. However, they are relatively easy to design and manufacture, and in most cases this practice has the advantage of attaining high productivity and producing products with new and oxide-free surfaces.

Among various methods for analysis of extrusion, the upper-bound method as an analytic method [1–9] and the weighted residuals method [10] or FEM [11–13] as numerical methods have been used effectively. In respect to upper-bound solutions, for example, Nagpal and Altan [1] analyzed extrusion of non-axisymmetric shapes by using the concept of stream functions. Their analysis was limited to simple product shapes such as an ellipse, and it is difficult to find stream functions for extrusion for more complex shapes. Yang and Lee [3] found kinematically admissible velocity fields in the extrusion of billets by using the concept of conformal mapping. Gunasekera and Hoshino [5, 8] suggested a new method for extrusion of regular polygonal sections from round billets using the concept of stream lines and proportionate deformation in plastic flow. Kiuchi *et al.* [6, 7] proposed the generalized formulas of the kinematically admissible velocity fields which can be used in all kind of extrusion analyses. In reference with the application of FEM, relatively a limited number of works have been reported [11–13]. Yang [12] reported the three-dimensional hot extrusion of elliptic and trocoidal sections through curved dies.

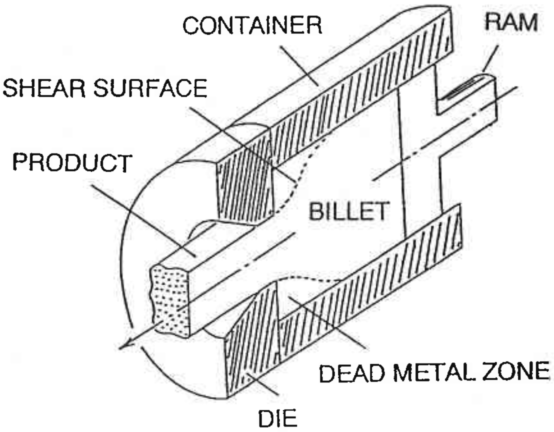

Fig. 1　Round-rectangle extrusion through a flat-faced die.

In this paper, a three-dimensional rigid-plastic finite element code, COPRESS System, is developed and applied to the analysis of extrusion process. As computational examples, extrusion of rectangular sections from round

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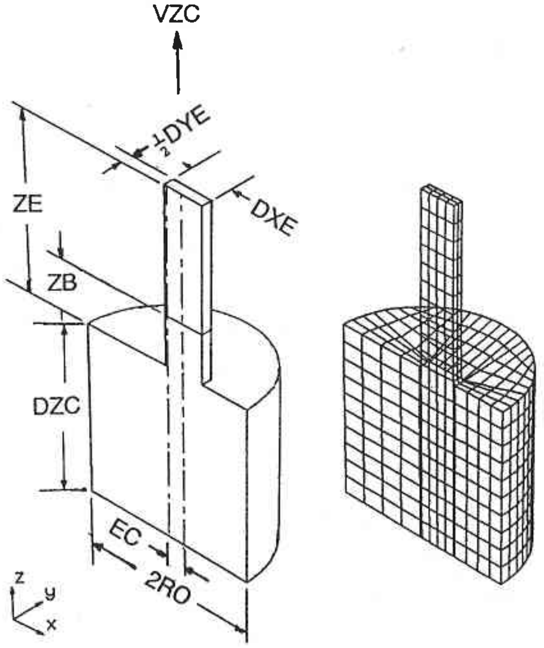
*Institute of Industrial Science, University of Tokyo billets through flat-faced dies is treated. Besides the prediction of extrusion pressure, the effects of the aspect ratio of the product cross-section and the eccentricity of the die on the metal flow behaviour are studied.

2. APPLICATION OF COPRESS SYSTEM TO THREE-DIMENSIONAL EXTRUSION

Using the COPRESS system, extrusion of rectangular sections from round billets was simulated, as shown in **Fig. 1**. The computational conditions for the simulation are shown in **Table 1**. **Fig. 2 (a)** shows a schematic diagram that depicts in detail the meaning of the parameters.

Table 1 Extrusion process conditions for computation.

CONTAINER LENGTH	DZC = 100 mm
CONTAINER RADIUS	RO = 50 mm
BEARING LENGTH	ZB = 30 mm
PRODUCT LENGTH	ZE = 100 mm
PRODUCT WIDTH	DXE = SEE TABLE 2
PRODUCT THICKNESS	DYE = SEE TABLE 2
ECCENTRICITY	EC = SEE TABLE 2
RAM SPEED	VZC = 10 mm/s
FRICTION COEFF.	μ = 0.1
MATERIAL	IAW EQ. (1)



(a) (b)

Fig. 2 (a) Dimensions of product and tools. (b) Mesh system.

The stress-strain relationship of the workpiece used in the analysis is expressed by

$$\bar{\sigma} = 12\,\dot{\bar{\varepsilon}}^{0.13} \qquad [\mathrm{Kg/mm^2}]\,. \qquad (1)$$

The extrusion ratio E. R. for each case is 39.18, which is calculated taking into account the actual geometry of the FEM model.

The finite element model includes a total of 1060 elements interconnected at 1470 nodal points, as shown in **Fig. 2 (b)**. It must be noted here that, in performing the computations, the die entrance was slightly modified by connecting the two blocks by adding a small element. This modification was made in order to avoid high singularities in the velocity components near the die entrance.

3. RESULTS AND DISCUSSIONS

The computations were performed for each case until the accuracy of the error norm reached a value of $\cong 10^{-5}$. This corresponds to the error norm of nodal velocity $\|\Delta u\|/\|u\| \cong 0.00009$. The average number of iterations required for the final solution was 100~150 iterations.

For the nine cases in Table 2, the extrusion load and the energy components, internal and frictional, are summarized in **Fig. 3**.

Fig. 3 (a) shows that the extrusion load increases slightly with the eccentricity of the die, but an important increment is observed when the aspect ratio, DYE/DXE, is decreased. The same trend is observed for the internal shear energy component, **Fig. 3 (b)**.

The general trend of the velocity distribution is the same for all analized cases. A typical example is given in **Fig. 4**

Table 2 Dimensions of the extruded product and eccentricity of the die.

CASE	DXE	DYE	DYE/DXE	EC
1	14.14 mm	14.14 mm	1	0 mm
2	〃	〃	〃	10 mm
3	〃	〃	〃	20 mm
4	20.00 mm	10.00 mm	1/2	0 mm
5	〃	〃	〃	10 mm
6	〃	〃	〃	20 mm
7	40.00 mm	5.00 mm	1/8	0 mm
8	〃	〃	〃	10 mm
9	〃	〃	〃	20 mm

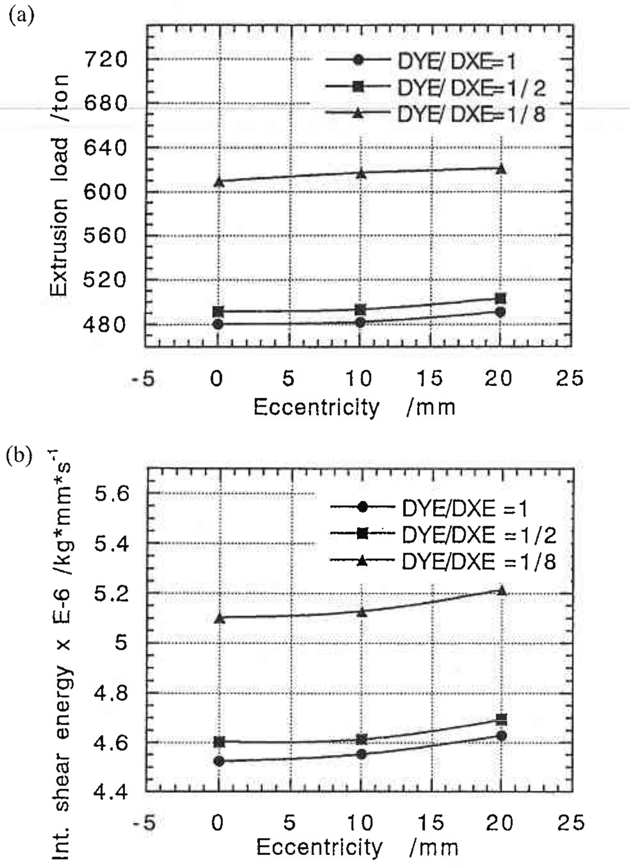


Fig. 3 (a) Extrusion load. (b) Internal shear energy component.

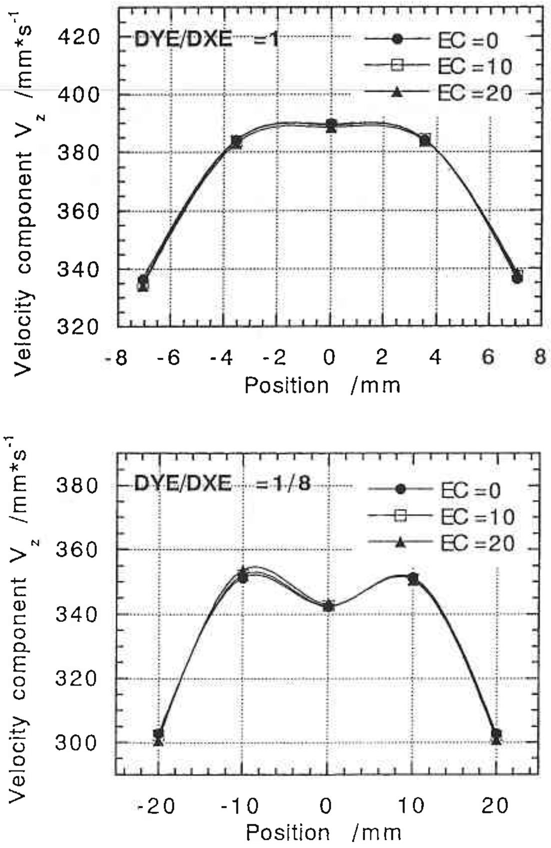


Fig. 5 Velocity distributions at the entrance of the die.

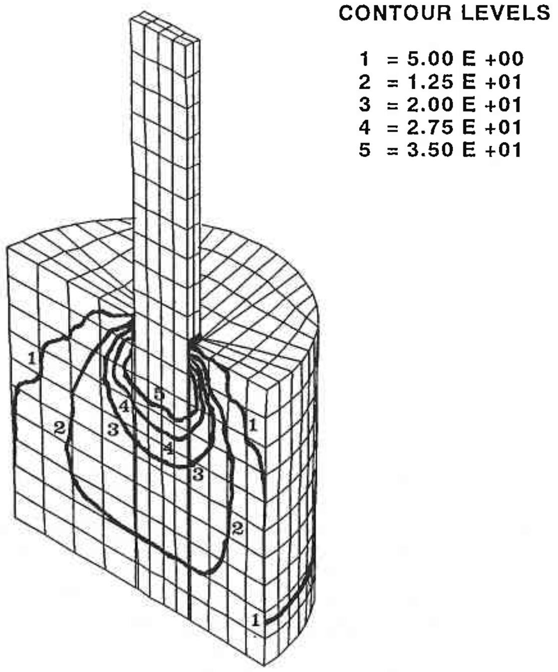


Fig. 4 Distribution of the component velocity V_z.

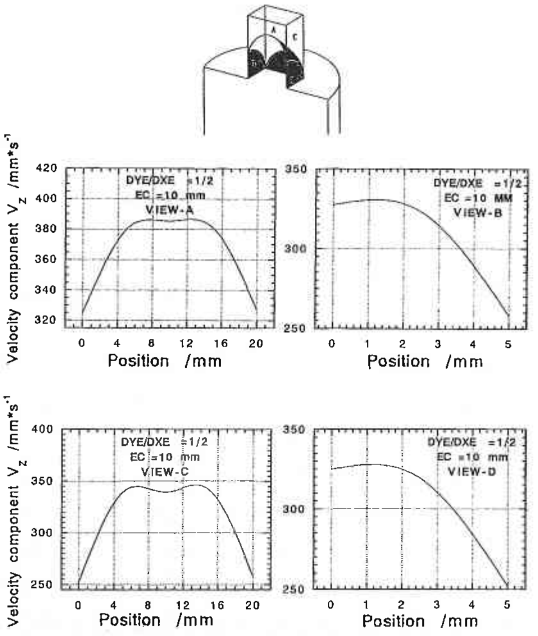


Fig. 6 Velocity distributions along the entrance of the die.

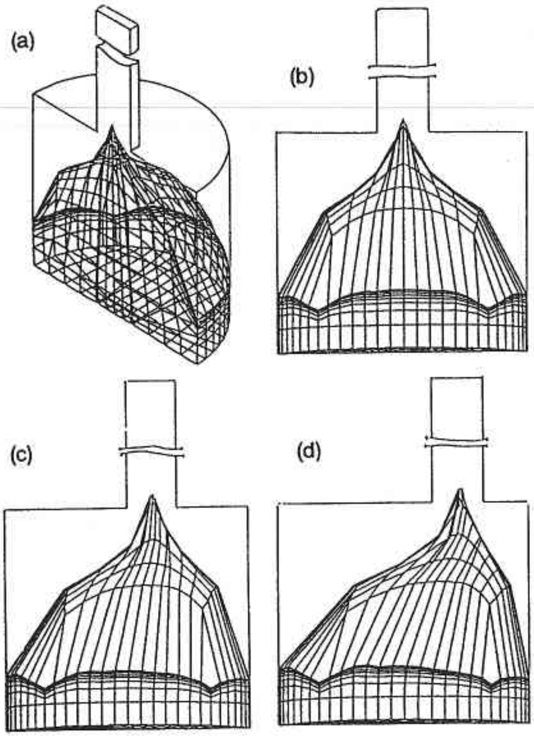


Fig. 7 Grid distortion patterns. (a) 3-D view case 4. (b)~(d) 2-D views for cases 4~6, respectively.

where the velocity component V_z is plotted in all the volume. **Fig. 5** shows, the distribution of V_z at the entrance of the die and for the plane $y = 0$. It is of interest to note that the velocity distribution shows non-uniformity. Higher values are observed in positive positions (taking as reference 0 value for the mid-plane of the product, see **Fig. 2 (a)**).

Fig. 6 shows the distributions of the nodal point velocities, V_z, along the four faces of the die-workpiece interface at the entrance of the die and for the plane $y = 0$. As in **Fig. 5**, the velocity distribution shows non-uniformity. Results like this may be very helpful for predicting bending or twisting of the product.

Detailed differences of deformation characteristics due to eccentricity of the die and the aspect ratio of the product, are more clearly indicated, for example, in grid distortions. **Fig. 7 (a)** shows a three-dimensional view of grid distortion for case 4 and **Figs. 7 (b)~(c)** show the grid distortion at the plane $y = 0$ for cases $4 \sim 6$. The figures clearly show that there is a concentration of deformation towards and near the die entrance. The metal towards the bottom of the billet has not entered the deformation zone so far, and as such, it is not distorted. The figures also show the shape and the relative size of the dead-metal zone.

4. CONCLUSIONS

To demonstrate the simulation capability of a newly developed FEM code, called COPRESS, the metal flow generated by extrusion through a flat-faced die of rectangular cross-section shape from round billet was simulated. The effect of the aspect ratio and the eccentricity of the die on the mechanics of the deformation were obtained. Comparisons of the results with those of experiments and other analysis were not performed yet. Thus, the discussions were made only in terms of reasoning numerical results. Despite this, it is concluded that COPRESS is indeed a useful tool which provides valuable information on the detailed deformation characteristics for various process variables. In order to ascertain the accuracy of the solutions presented in this work, however, further research work is still needed in order to evalute the effect of the other important variables on the metal flow during three-dimensional extrusion.

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