研　究　速　報

FLOW OF SOLID METAL DURING EXTRUSION: THREE-DIMENSIONAL SIMULATIONS BY FINITE ELEMENT METHOD·3

押し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—

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INTRODUCTION.

In the present paper, a three dimensional rigid-plastic FEM code COPRESS System[1)] is again applied to the analysis of extrusion process. In the previous works[1)~3)] the extrusion process simulations of square, rectangular and angle sections were presented. In this work the simulated cases for angle sections are extended and a more complex section is analyzed: channels. As before, in order to study the effect on the metal flow characteristics, the aspect ratio of the cross-sections of the extruded product and the eccentricity of the die are varied. Also, as in the previous works, the extrusion process is assumed to be carried out from round billets through flat-faced dies. Results on the velocity distribution, stream-lines distribution and predictions of the average extrusion pressure are presented.

METHOD FOR SIMULATION.

COPRESS System is a finite element code based on the rigid-plastic theory[1),4)]. By using COPRESS, extrusion processes of angle and channel sections from round billets through flat-faced dies are simulated.

Conditions of numerical case studies are as follows:

Material: a rate dependent material, with the flow stress given by

$$\bar{\sigma} = 117.6\dot{\bar{\varepsilon}}^{0.13} \quad \text{[MPa]}$$

Container length : 100 mm
Container radius : 50 mm
Ram speed : 10 mm/s
Coefficient of Coulomb friction : 0.1

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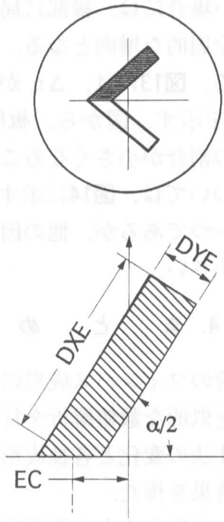
In Table 1 and 2 are summarized the dimensions of the products for angle and channel sections, respectively.

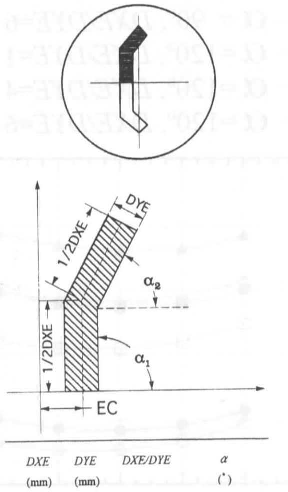
Because of the geometric characteristics of this kind of sections, it is interesting to determine the optimum eccentricity of the die which gives the minimum extrusion pressure. Therefore, the eccentricity of the die is varied

Table 1　Computational models of rectangular sections from round billets.



DXE (mm)	DYE (mm)	DXE/DYE
20.00	10.00	2
40.00	10.00	8
48.99	4.08	12
56.57	3.54	16

Table 2 Computanional models of angle sections from round billets.



DXE (mm)	DYE (mm)	DXE/DYE	α (°)
10.00	10.00	1	90
20.00	5.00	4	90
24.50	4.08	6	90
10.00	10.00	1	120
20.00	5.00	4	120
24.50	4.08	6	120

from $-3/5\ R_O$ to $2/5\ R_O$, where R_O is the container radius.

It is noted that in order to investigate into the effect of the geometry of the section on the characteristics of the metal flow, the extrusion ratio ((cross-sectional area of billet) / (cross-sectional area of extruded product)) is kept constant for all the sectional shapes described above.

The contact algorithm implemented in COPRESS requires a discretization of the tool surface into a mesh of spatial triangular elements. A typical mesh system used for tooling, bearing and ram, is shown in **Fig. 1**. In the particular case shown in the figure, the model consists of 178 triangular elements interconnected at 128 nodal points.

Fig. 2 and **3** show typical finite element models for angle and channel section used in FEM calculations, respectively. Depending on the section, the number of elements and nodal points varies; a typical mesh includes a total of 1288 eight-node hexahedral elements interconnected at 1770

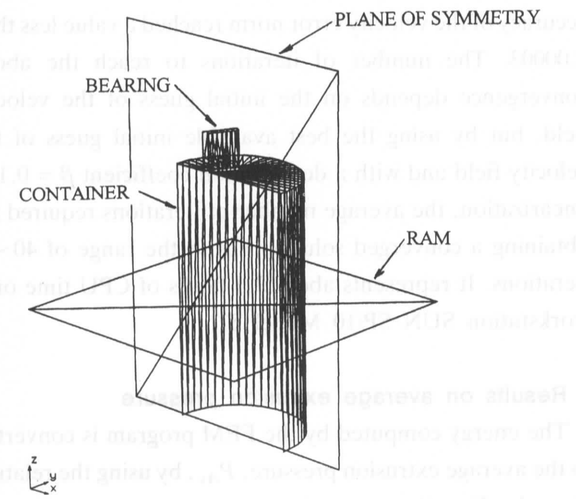


Fig. 1 Tool discretization for three-dimensional extrusion simulation.

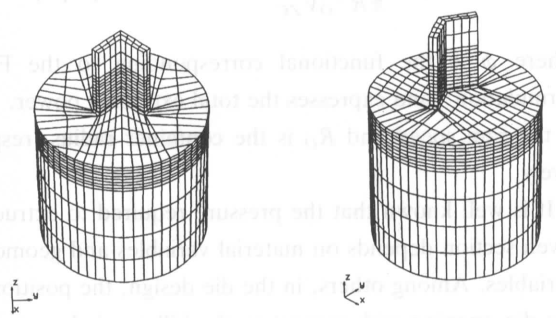


Fig. 2 Finite element models of workpieces for angle sections: (a) AR = 8, $\alpha_1 = 90°$; (b) AR = 12, $\alpha = 120°$.

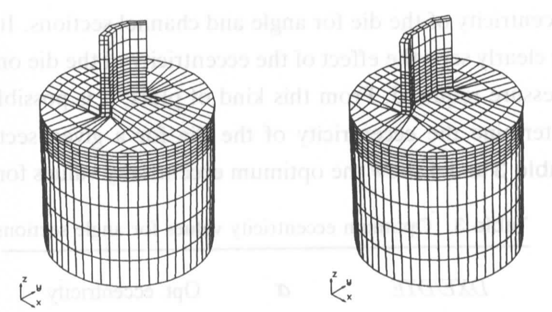


Fig. 3 Finite element models of workpieces for angle sections: (a) AR = 8, $\alpha_1 = 90°$, $\alpha_2 = 60°$, (b) AR = 12, $\alpha_1 = 75°$, $\alpha_2 = 45°$.

nodal points. In the figures are shown the complete models, but in actual calculations, due to the symmetry, only one half of the geometry is considered.

RESULTS AND DISCUSSIONS.

The computations were performed for each case until the accuracy of the velocity error norm reached a value less than 0.00003. The number of iterations to reach the above convergence depends on the initial guess of the velocity field, but by using the best available initial guess of the velocity field and with a deceleration coefficient $\beta = 0.1$ in linearization, the average number of iterations required for obtaining a converged solution lies in the range of 40~60 iterations. It represents about 3.5 hours of CPU time on a workstation SUN SP/10 Model 51.

Results on average extrusion pressure

The energy computed by the FEM program is converted to the average extrusion pressure, P_{Av}, by using the relation given by Eq. (1):

$$P_{Av} = \frac{\phi}{\pi R^2_O V_{ZC}} \quad [\text{Mpa}] \qquad (1)$$

where ϕ is the functional corresponding to the FEM formulation[1] and expresses the total extrusion power. V_{ZC} is the ram speed and R_O is the container radius, respectively.

It is well known that the pressure required to extrude a given section depends on material variables and geometric variables. Among others, in the die design, the position of the die opening with respect to the billet axis has a great influence on the metal flow, and therefore, on the extrusion pressure required. **Fig. 4** shows the variation of P_{Av} with the eccentricity of the die for angle and channel sections. It can be clearly seen the effect of the eccentricity of the die on the pressure required. From this kind of plots, it is possible to determine the eccentricity of the die for a given section. **Table 3** and **4** show the optimum eccentricity values for the

Table 3 Optimum eccentricity values for angle sections.

DXE/DYE	α (°)	Opt. eccentricity EC/R_0
1	90	-0.17
4	90	-0.20
6	90	-0.27
1	120	-0.01
4	120	-0.12
6	120	-0.15

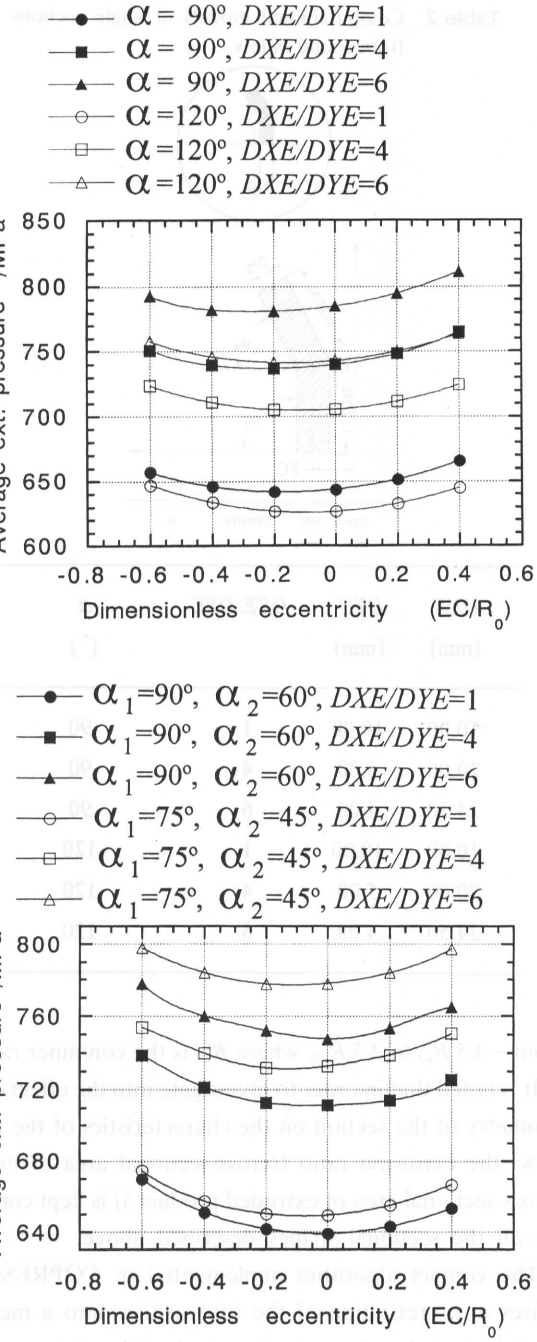


Fig. 4 Variation of P_{Av} with the aspect ratio and the eccentricity of the die for: (a)angle and (b) channel sections.

angle and channel sections given in **Table 1** and **2**, respectively.

Results on velocity distribution

The general trend of the velocity distribution is similar for each of the analyzed sections, a typical example is given in

Table 4 Optimum eccentricity values for channel sections.

DXE/DYE	α_1 (°)	α_2 (°)	Opt. eccentricity EC/R_0
1	90	60	-0.01
4	90	60	-0.05
6	90	60	-0.05
1	75	45	-3.82
4	75	45	-2.00
6	75	45	-5.75

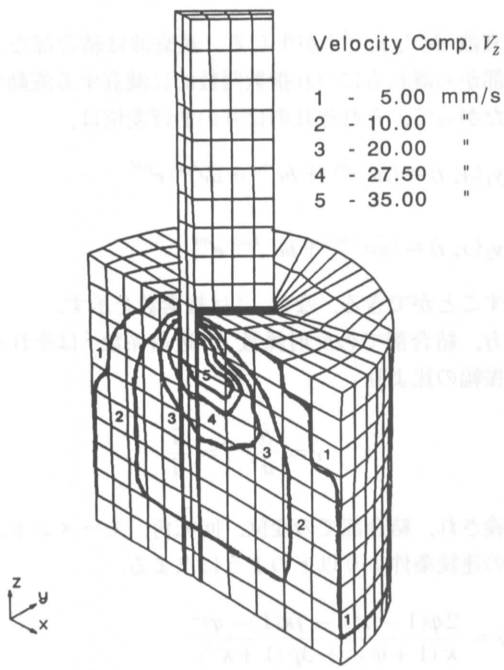


Fig. 5 Distribution of the component V_Z.

Fig. 5, where the velocity distribution of the component V_Z is plotted for the container section.

For die design purposes, it is important to know the velocity distribution at the entrance of the die. **Fig. 6** shows this information for one case of the analyzed sections. In these plots, the nodal velocities corresponding to the die entrance plane are plotted as function of the nodal points coordinates, making possible to see a 3-D surface representing the velocity distribution for a specific plane. Comparison between them clearly shows the more complex metal flow characteristics for channel sections.

CONCLUDING REMARKS.

By using COPRESS a comprehensive investigation into

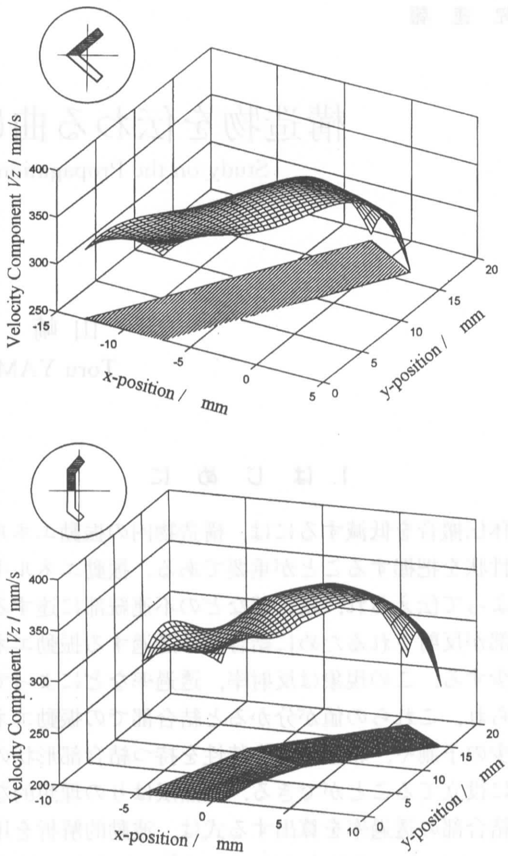


Fig. 6 Velocity distribution, V_Z, at the entrance of the die: (a) Angle: $AR = 8$, $\alpha = 120°$, (b) Channel: $AR = 12$, $\alpha_1 = 75°$, $\alpha_2 = 45°$.

the deformation characteristics of angle and channel sections in extrusion processes was carried out. The deformation mechanics was summarized in terms of the velocity distribution and average extrusion pressure. The investigation illustrates quantitatively the effect of the geometrical complexity and the eccentricity of the die on the metal flow characteristics. It is demonstrated again the usefulness of COPRESS as an effective tool for the analysis and design of industrial extrusion process.

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