⊙ 研究論文

# A Study on the Asymmetric Forging Process Using Building Block Method

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# 빌딩블럭 방법을 이용한 비대칭 단조 공정에 관한 연구

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**Key words** : Asymmetric forging(비대칭 단조), Building block(빌딩블럭), Rib-web type(리브-웨브형), Dumbbell-type billet(아령형 시편), Die-cavity filling process(다이 충만 과정)

## 요 약

상계요소 해석(UBET) 프로그램은 비대칭 단조공정에서의 다이 충만과정과 단조 하중 등을 예측하기 위하여 개발되었다. 보다 용이하게 단조 공정을 해석하기 위하여 비대칭 형상의 단조공정을 평면변형부(길이 부분)과 축대칭변형부(라운딩 부분)으로 나누었다. 평면변형부와 축대칭 변형부의 경계는 전단에너지를 고려하여 결합하는 빌딩 블록 방법(building block method)을 이용하였다. 그리고 본 연구의 비대칭 형상을 단조하는데 최적의 초기시편 형상으로 아령형의 시편(dumbbell-typed billet)을 제시하였다. 또한 실험은 상온에서 플라스티신을 사용하여 수행되었고 수치해석 결과와 실험결과는 비교적 잘 일치하였다.

## 1. Introduction

There are many components of cross section of rib-web type in the airplane and various other vehicle structures. A lot of research was done about rib-web type forging, most of which was about plain-strain or axisymmetric problems. Few studies were done about asymmetric shape because of the difficutties in analysis

Several studies were performed about asymmetric shapes. The asymmetric forging problem having side flash was analyzed by Kiuchi[1),2)] with UBET. The material was divided into various elements which were then possible to analyze. In the analysis of asymmetric forging, a UBET simulator(FORMS)[3)] was developed by Kiuchi to study the velocity fields of complex shapes integrated by the easy forging

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processes (upsetting, extrusion etc.). In addition Kiuchi et al[4,5] performed a study on developing generalized 3 - dimensional kinematically admissible velocity fields by using the upper bound method for the forward extrusion problems having various cross section shapes. It was difficult to formulate the 3 - dimensional velocity fields which were very complicated. Wada et al[6] applied an upper bound method dividing the 3 - dimensional shape into rectangular parallelpiped, prismatic, right angle tetrahedron and right angle pentahedral elements. But because of the difficulties in optimizing many variables, it is not adequate to apply to complex shape.

In studies by FEM, Argyris et al[7] analyzed the airplane turbine blade at no friction condition, Pillinger et al[8] analyzed the forging process of aluminum connecting rod at constraint friction condition. In addition, for the asymmetric problem of ring, Marques et al[9] analyzed the forging process, where a circular cross section was formed by rectangular billet after dividing the entire material into plane - strain and axisymmetric parts.

In the present study, for the process design of asymmetric forgings of rib - web typed cross section, the asymmetric shape is divided into the plane - strain and axisymmetric parts. Then the building block method, which combines the two parts, is used. As a simulation method, we will adopt the UBET (Upper Bound Elemental Technique). In the case that the ratio of rib height to width is 1 : 1, the kinematically admissible velocity fields of each part is determined by minimizing the total energy which is the summation of the energy at the plane - strain deformation part, the axisymmetric part and the boundary of these two regions. By predicting the die cavity filling processes and the forging loads from various initial billet, we will study the characteristics of each billet.

To check the validity of this theory, a model material test was performed at MTS(Material Testing System).

## 2. UBET(Upper Bound Elemental Technique)

The analysis model in this study is shown in Fig. 1. An asymmetric shape of rib - web type is analyzed by dividing the total material into the plane - strain and axisymmetric parts and then by combining them again.

The plane - strain and axisymmetric parts are divided again into a few simple elements. The velocity field of each divided element should satisfy the velocity boundary condition between adjacent elements and volume constancy condition. For velocity fields we used those suggested by Oudin[10] and Kiuchi[11]. For the plane - strain deformation part, rectangular and trapezoid elements, which are suggested by Oudin[10], and for the axisymmetric part, rectangular and triangular ring elements which are suggested by Kiuchi[11], are used. The work hardening of the material is considered under the assumption that flow stress is dependent only on effective strain. Fig. 2 shows the flow chart for forward simulation.

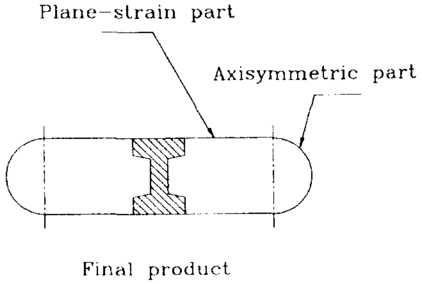


Fig. 1 Analytical model of asymmetric forging

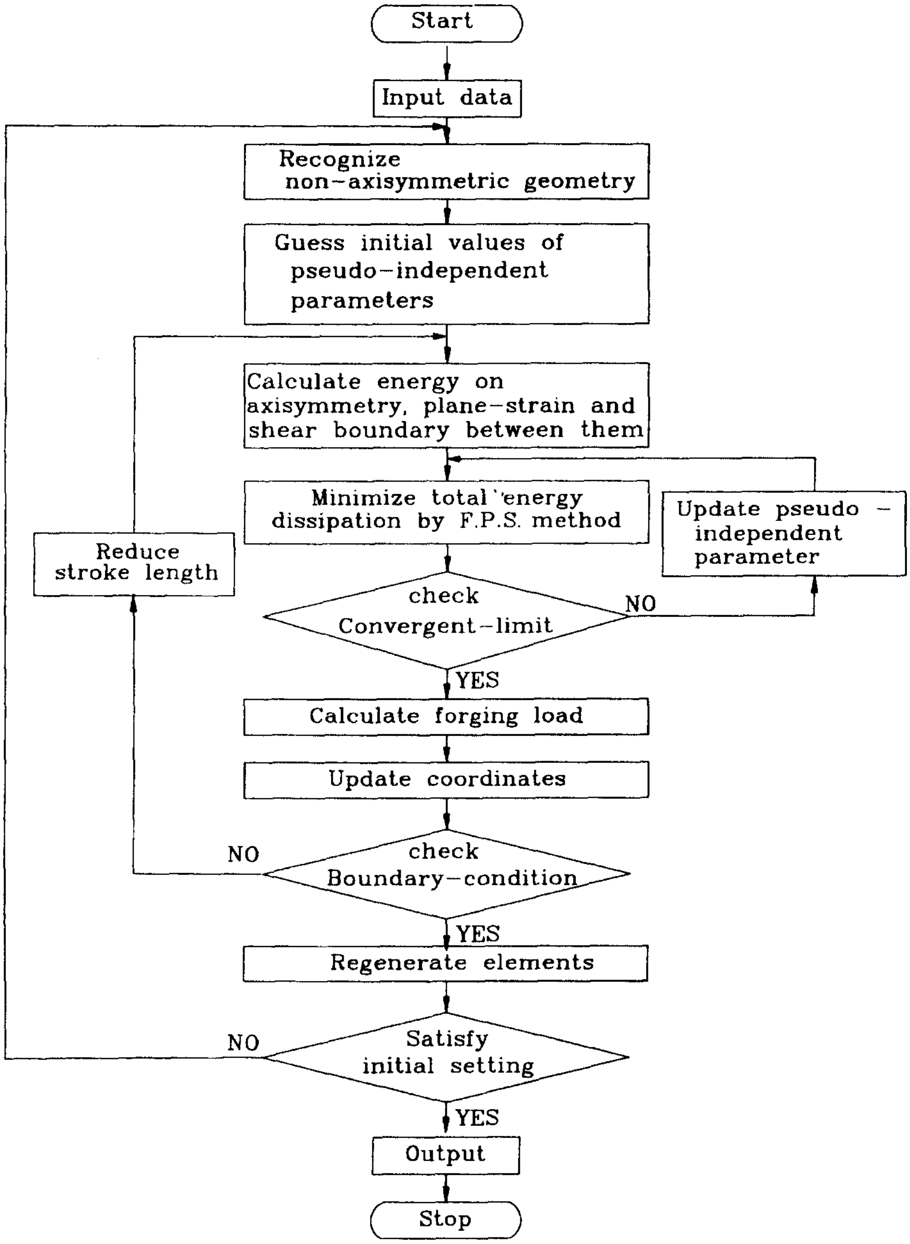


**Fig. 2 Flow chart for forward UBET simulation**

## 2.1. Kinematically admissible velocity fields

The total power consumption rate in a forging process is as follows ;

$$J^* = \Sigma \dot{W}_i + \Sigma \dot{W}_s + \Sigma \dot{W}_f \quad (1)$$

where, $\dot{W}_i$ is the internal power of the plane - strain and axisymmetric parts, $\dot{W}_s$ is the shear loss at the interface of two adjacent elements. This includes the shear loss between plane - strain and axisymmetric parts. $\dot{W}_f$ means the friction loss.

Internal power at each element, $\dot{W}_i$ is,

$$\dot{W}_i = \int_V \bar{\sigma}_t \dot{\bar{\varepsilon}}_t \, dV \tag{2}$$

where, effective strain - rate, $\dot{\bar{\varepsilon}}_t = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}$

In eq (2) $\bar{\sigma}_t$ is the effective stress of each element at time t, and we assume that $\bar{\sigma}_t$ is the function of only effective strain.

$$\bar{\sigma}_t = C\,\varepsilon_t^{\,n} \tag{3}$$

$\dot{W}_i$ means the shear loss along the velocity discontinuity surface and we can express it as follows ;

$$\dot{W}_s = \frac{\bar{\sigma}_o}{\sqrt{3}} \int_S |\Delta V_s| ds_s + \dot{W}_{boundary} \tag{4}$$

where, $\bar{\sigma}_0$ is the mean value of flow stresses of two adjacent elements. $|\Delta V_s|$ is the velocity discontinuity along the shear surface in plane - strain and axisymmetric deformation parts, $\dot{W}_{boundary}$ means the shear loss at the interface between plane - strain and axisymmetric deformation parts.

Also, the friction loss, $\dot{W}_f$ is as follows.

$$\dot{W}_f = m\frac{\bar{\sigma}_o}{\sqrt{3}} \int_{S_t} |\Delta V_f| ds_f \tag{5}$$

where, m is friction constant, $|\Delta V_f|$ means the velocity discontinuity along the surface between the die and material.

The total power consumption rate, $J^* = J^*(p_1, p_2, p_3, \ldots, p_n, a_1, a_2, a_3, \ldots, a_n)$ is minimized by FPS(Flexible Polyhedron Search) method[12] which is a kind of direct search method. Here, $p_i$, $a_i$ are the pseudo - independent paramenters at the plane - strain and axisymmetric parts respectively. By minimizing $J^*$, we can determine the kinematically admissible velocity fields at time t.

And the forming load, L, is given as follows ;

$$L = \frac{J^*}{V_D} \tag{6}$$

where, $V_D$ is the die velocity.

### 2.2. Element regeneration

To investigate the die cavity filling process, the total forming time is divided according to time incremental Δt. At each step, the coordinate of the deformed shape of each element is determined by the kinematically admissible velocity fields after minimization.

The coordinate of each element after time incremental Δt is as follows ;

$$X' = X + \Delta t \cdot U \tag{7}$$

where, X′ is the position of each element after deformation and X, U means the position and velocity of elemental boundary before deformation respectively.

After deformation, the sliding occurs between adjacent elements, resulting in the discontinuity of elemental boundary. Therefore, in order to proceed to next step, we use the element regeneration scheme[13] by vertical and horizontal projection.

### 2.3. Building block method

Products of a complex shape like an asymmetric problem can be approximated into the combination of a simple shape which can be easily analyzed. Fig. 1 shows schematic diagram of the final products. To simplify the analysis we assume that the two rounded parts of both ends deform axisymmetrically and the linear parts between the two rounded parts are a plane - strain problem because the length of them is much larger than width. Marques et al[9] also based their research on this kind of assumption. As the die proceeds, the plane -

strain and axisymmetric parts have different deformation patterns which result in the discrepancy of the elemental boundary. The analytical model of calculating the shear loss due to this boundary discrepancy is shown in Fig. 3.

The shear loss of the interface of plane-strain and axisymmetric parts is calculated as follows ;

$$\dot{W}_{\text{boundary}} = \frac{\bar{\sigma}_0}{\sqrt{3}} \int |\Delta V| ds \tag{8}$$

and, $|\Delta V| = \sqrt{(U_{\text{axi, R}} - U_{\text{plane, X}})^2 + (V_{\text{axi, Z}} - U_{\text{plane, Y}})^2}$
where, ds means the infinitesimal elemental boundary area owned by plane-strain and axisymmetric element at the same time, $U_{\text{axi,R}}$, $V_{\text{axi,Z}}$ mean R- and Z- directional velocity components of axisymmetric elemental boundary respectively. $U_{\text{plane,X}}$, $V_{\text{plane,Y}}$ mean X- and Y-directional velocity components of plane-strain elemental boundary respectively.

In Fig. 3, the element system is superposed along the boundary of each deformed part when the height reduction reaches a certain point.

As is shown in this figure, when the die proceeds, there is a boundary discrepancy between the plane-strain and axisymmetric parts owing to the difference of flow pattern at both parts. In this case the shear loss at each step is calculated as followings ;

Along the x-axis the node of each element is assigned the coordinate AX(1), AX(2), AX(3),···, AX(N). And the computer program will perceive the number of plane-strain or axisymmetric element corresponding to these assigned values. For element A, both the plane-strain and axisymmetric elements have element number, (1,1). Then the shear loss of element A is obtained from the boundary velocity and strain-rate value of element, (1,1) of both parts. For the element B between AX(3) and AX(4), the element number of plane-strain and axisymmetric parts are (3,1) and (2,1) respectively. Therefore for the plane-strain and axisymmetirc parts, the data of element number, (3,1), (2,1) are used to calculate the shear loss, respectively. For the case of element C, the shear loss is not calculated because only the element of plane-strain part exists. Each of every other element is included in one of the

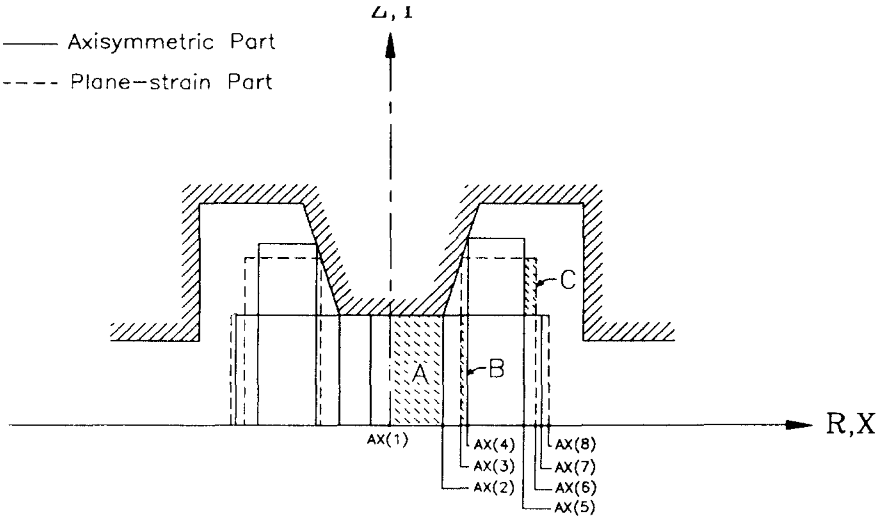


**Fig. 3 Overlap of flow pattern of boundary between plane-strain and axisymmetric parts**

element type, A, B, or C and analyzed likewise.

## 3. Experiment

For the forging experiments of the asymmetric products of rib－web type, we use pure plasticine. To obtain the flow stress and strain characteristics, the cylindrical billet, whose height and diameter are equal, is used. In the experiments using the vaseline lubricant($m \fallingdotseq 0.1$) which shows comparatively little bulging phenomenon, the cylinder is compressed up to 50% of its initial height with constant die velocity(0.5mm/sec) at room temperature. Fig. 4 shows the material characteristics from this experiments. The relationship of flow stress and strain of the material is as follows ;

$$\bar{\sigma}=0.178\,\bar{\varepsilon}^{0.082}(\mathrm{MPa}) \qquad (9)$$

To get information about material flow in the workpiece we use plasticine as model material. The billets are laminated with two colors(white and black), after being kneaded to remove air inside the material. Initially rectangular shape of billets are made into rounded shape at the ends.

The material of the die is S45C. To make it easy to divide the plasticine product from the die, the upper dies are divided two parts. And those are joined with pin and volt.

The experiments are performed with a MTS at a constant die velocity (0.5mm/sec). The lubricant is talc powder($m \fallingdotseq 0.4$). By using the X－Y plotter attached to MTS the load curve is obtained.

To keep the temperature of billets constantly during experiments, we put the die and billets in the oven for 24 hours, and the room temperature is kept constantly by using a thermo－hygrostat.

## 4. Results and discussion

When the ratio of height to width of rib is 1 : 1(H/B＝1 : 1), three billets in Fig. 5 are used. Fig. 6 show the numerical results of the billets in Fig. 5, those are final die－cavity filling by forward simulation. Here, when Billet 1 is used, at the plane－strain part the die cavity is filled and the flash is made adequately, but at

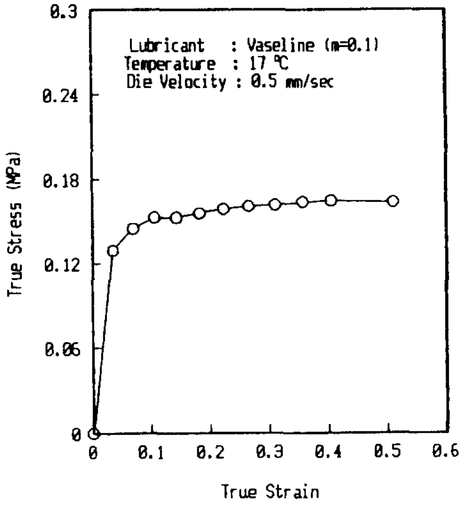
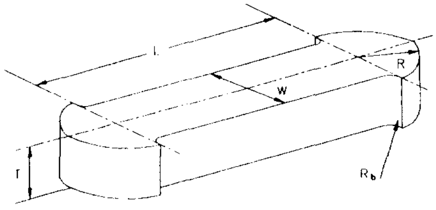


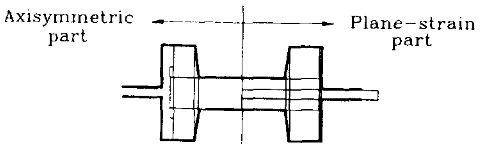
Fig. 4 True stress－true strain curve of plasticine



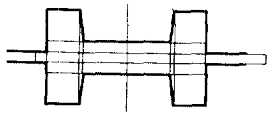
**Dimension of initial billets(H/B＝1 : 1)** (unit : mm)

| Dmension<br>Billet | T | W | L | R | $R_b$ |
|---|---|---|---|---|---|
| Billet 1 | 24.4 | 30.0 | 120.0 | 15.0 | 0 |
| Billet 2 | 24.4 | 30.0 | 120.0 | 18.4 | 2.0 |
| Billet 3 | 24.4 | 36.8 | 120.0 | 18.4 | 0 |

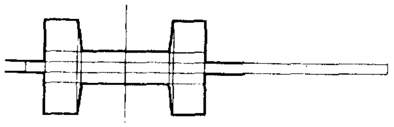
Fig. 5 Dimensions and configuration of initial billet for asymmetric forging(H/B＝1 : 1)



(a) Billet 1



(b) Billet 2



(c) Billet 3

**Fig. 6** **Die - cavity filling of final step for various initial billets in Fig. 5.**

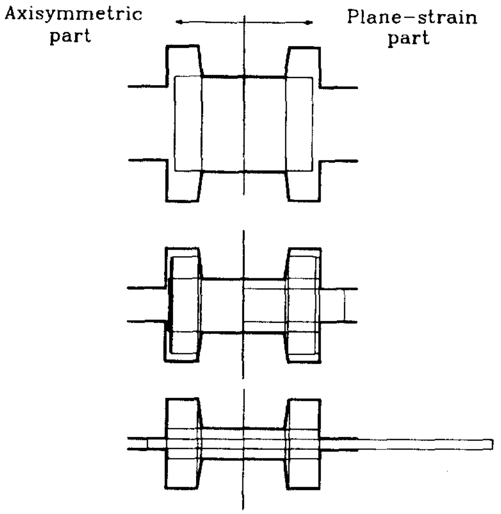


**Fig. 7 Die - cavity filling process of element system for Billet 3 in Fig. 5(H/B =1 : 1)**

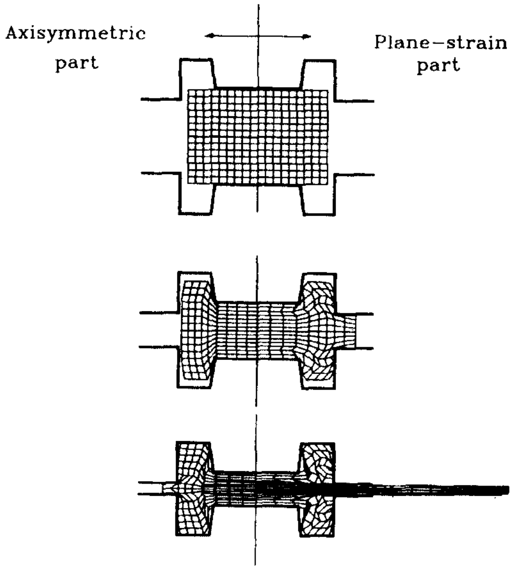


**Fig. 8 Die - cavity filling process of grid distortion pattern for Billet 3 in Fig. 5(H/B =1 : 1)**

the axisymmetric part material filling around the rib part is not completed. To enhance the die - cavity filling in axisymmetric rib part, the dumbbell - typed Billet 2 which is made by calibrating the volume to the outward direction of axisymmetric part, fills the die - cavity of plane - strain and axisymmetric parts, and also the amount of flash is adequate.

However, it is difficult to use the dumbbell - typed Billet 2 as a initial billet because it requires another process. Accordingly, the billet, which can ensure the die - cavity filling at the axisymmetric part and is comparatively simple shape, is needed. So we will extend the outside boundary dimension of axisymmetric part of Billet 2 up to the plane - strain part. The extended billet is Billet 3. In the case of Billet 3 even if quite more amount of flash than Billet 2 at the plane - strain part is made, the simplicity of the configuration is recognized.

Fig. 7~8 show the die - cavity filling and grid distortion processes of the plane - strain and axisymmetric parts of Billet 3 from initial to final step. Fig. 9 shows the die - cavity filling process at several steps of plasticine experiments by cutting one fourth of the billets. From the Fig. 7~9, it is noticed that the boundary of plane - strain and axisymmitric parts is out of agreement because, as the process goes on, the

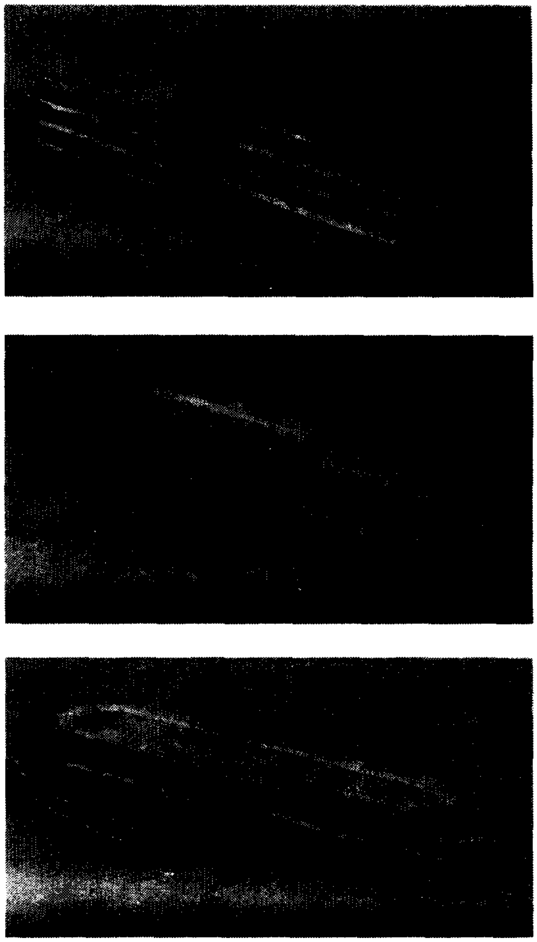


Fig. 9 Material flow pattern of multi-layered plasticine for Billet 3 in Fig. 5(H/B =1 : 1)

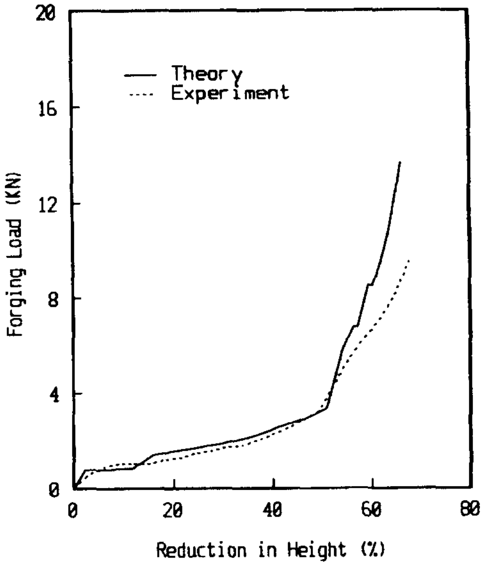


Fig. 10 Comparison between theoretical and experimental forging loads for Billet 3 in Fig. 5(H/B =1 : 1)

material flow to the upper and outward directions becomes different. This can be verified by the experiments whose results are in Fig. 9. So to analyze this boundary, the building block method of section 2. 3 is used. Besides, the flash at the plane-strain part is made first and at the moment when the die-cavity of the axisymmetric part is filled completely, the plane-strain part already has much amount of flash. Fig. 10 shows the forging load variation for the case of Billet 3. In this diagram the fact that the results of numerical analysis are a little higher than those of experiments, is due to the upper bound analysis. However, as a whole it is acceptable.

## 5. Conclusions

In this study, to predict the initial billet of asymmetric forging procuct, upper bound elemental technique has used. In the analysis, the material is divided into plane-strain and axisymmetric parts. And the total power consumption rate including the shear loss at the boundary of both parts is optimized to approach the asymmetric problem easily. The excellence of dumbbell-typed billet is varified by the plasticine experiment and numerical analysis. There is a good agreement between the simulation and experiment in forging load and material flow. Yet, to design the initial billet of asymmetric forgings, more developed design method is needed.

## References

1) M. Kiuchi and A. Karato, "Application of UBET to Non-Axisymmetric Forging", Advanced Tech. of Plasticity, Vol. 11, pp. 967~972, 1984.

2) M. Kiuchi and A. Karato, "Simulation of Flow Behaviours of Billet to Fill Side-Flush Cavity of Die-Application of UBET to Non-Axisymmetric Forging Ⅰ-", J. of JSTP, Vol. 26, No. 290, pp. 307~315, 1985.

3) M. Kiuchi, T. Muramatsu and T. Imai, "Analysis on Non-Axisymmetric Complex Forging - Development of Simulation Method for Forging Process Ⅰ -", J. of JSTP, Vol. 30, No. 342, pp. 997~1003, 1989.

4) M. Kiuchi, H. Kishi and M. Ishikawa, "Upper Bound Analysis of Extrusion and/or Drawing of Square, Rectangular, Hexagonal and Other Asymmetric Bars and Wires.-Study on Non-Symmetric Extrusion and Drawing Ⅰ -", J. of JSTP, Vol. 24, No. 266, pp. 290~296, 1983.

5) M. Kiuchi and M. Ishikawa, "Upper Bound Analysis of Extrusion and/or Drawing of L-, T-, and H-Sections-Study on Non-symmetric Extrusion and Drawing Ⅱ -", J. of JSTP, Vol. 24, No. 270~729, pp. 722, 1983.

6) T. Wada and T. Nanba,"Numerical Method for Plastic Working Processes in Three Dimensions", Advanced Tech. of Plasticity, Vol. 11, pp. 1005~1012, 1987.

7) J. H. Argyris, J. St. Doltsinis and J. Luginsland, "Three-Dimensional Thermomechanical Finite Element Calculation of Three-Dimensional Analysis of Forming Processes", Proc. Int. Workshop Simulation of Metal Forming Processes by the Finite-Element Method (SIMON-Ⅰ), Stuttgart, 1985, Springer-Verlag, Berlin, pp. 125, 1985.

8) I. Pillinger, P. Hartley, C. E. N. Sturgess and G. W. Rowe, "A three-Dimensional Analysis of the Cold Forging of a Model Aluminium Connecting Rod", Proc. Inst. Mech, Engrs., Vol. 199, pp. 319, 1985.

9) M. J. M. Barata Marques and P. A. F. Martins, "A Rigid-Plastic Finite Element Analysis of Ring Forging", Advanced Tech. of Plasticity, Vol. 1, pp. 13~18, 1990.

10) J. Oudin and Y. Ravalard, "An Upper Bound Method for Computing Computing Loads and Flow Patterns in Plane-Strain Forging", Int. J. Mach. Tool Des. Res., Vol. 21, pp. 237~350, 1981.

11) M. Kiuchi and Y. Murata, "Study on Application of UBET(Upper Bound Elemental Technique). 1st Report-Simulation of Axisymmetric Metal Forming Process-", J. of JSTP, Vol. 22, No. 244, pp. 495~502, 1981.

12) D. M. Himmelblau, Applied Nonlinear Programming, McGraw-Hill, p.152, 1972.

13) Y. H., Kim, W. B., Bae, J. H., Lee, J. H., Kim and H. Y., Kim, "A Study on Optimum Design in Axisymmetric Forging Processes using UBET", Transations of the KSME, Vol. 18, No. 5, pp. 1117~1125, 1994.