ELSEVIER

Journal of Materials Processing Technology 63 (1997) 254-259

Journal of
Materials
Processing
Technology

STUDY ON HOT EXTRUSION OF TUBES

Su-Hai Hsiang * and Chao-Shun Liao**
Department of Mechanical Engineering , National Taiwan Institute of Technology
No. 43 , Keelung Road , Sec. 4 ,Taipei , Taiwan , R . O. C . 106

Abstract

In this study, a numerical simulation model for forward hot extrusion processes of tube is developed by combining the upper bound method with the finite difference method. It is proposed to predict the deformation behaviors and forming load during the extrusion process. Besides, in order to investigate the influence of process variables on the extrusion process, mechanical property tests of extruded tube are performed. The metal flow is observed on macro etched section of the billet remained in the container. In addition , the charge welding seams in the cross-section of the extruded tubes are observed. The strength of welded portions of extruded tube is evaluated by the expanding and flattening tests.

Keywords : Upper Bound Method, Finite Difference Method, Hot Extrusion, Tubes ,Expanding and Flattening Tests.

1. INTRODUCTION

How to obtain the optimal solution in the metal forming processes is the main target of the researchers engaged in this field. The upper bound method is one of the analytical methods used to investigate the metal forming problems. In hot extrusion process, the temperature of billet is an important variable affected deformation behaviors, and the finite difference method is an effective method to analyze temperature distribution in billet and in the interface of billet and die. In this study, the upper bound method and the finite difference method are used to investigate the deformation behaviors of hot extrusion of tubes. Using the upper bound method has the merits of saving computer's CPU time and the simulation can be executed in personal computer. Using the finite difference method the detailed informations with good accuracy can be obtained .

The analysis results of hot extrusion problems have been presented by many well-known researchers. H. S. Mehta et al. [1] , K. T. Chang et al. [2] and D. Y. Yang et al. [3] assumed different kinematically admissible velocity fields to investigate the metal flow pattern and stress(or strain) distribution. R. Akeret [4] neglected the influence of friction to discuss temperature and velocity distributions. T. Altan et al. [5] ,K. Nakanishi et al. [6] and T. Saiki et al. [7] used different models to analyze the flow stress and temperature distribution. Tseng [8] used experimental results to derive an equation of flow stress as a function of strain, strain rate and temperature. R.S. Lee et al. [9] and S. H. Hsiang et al. [10] combined the finite difference method and the upper bound method to investigate the deformation behaviors of hot extrusion of rod. T. Murakami et al. [11] and M. Kiuchi et al.[12] used the upper bound method to study the extrusion load and the influence of variables in hot extrusion of tubes through bridge die.

In this study, the velocity field of hot extrusion of tube is established and the energies of deformations are calculated, then the finite different method is employed to treat the heat transfer problems under deformation. Using this model, the extrusion load can be estimated, the flow pattern of material under extrusion ,the temperature distribution of billet and product can be obtained, and the optimal working condition can be found through the mechanical property tests of extruded tubes .

2 . DERIVATION OF VELOCITY FIELD

2. 1 The velocity field and strain rate

In the establishment of the velocity field,

* Associate Professor ** Graduate Student

0924-0136/97/$15.00
PII S0924-0136(96)02632-5

following assumptions are applied. (1) The billet is rigid-perfectly plastic material, and elastic strain is neglected. (2) In the plastic deformation zone, the velocity $\dot{U}_y$ is the same in any section. (3) The material obeys von Mises' yield criterion. (4) Beyond the plastic deformation zone, the material is regarded as rigid body.

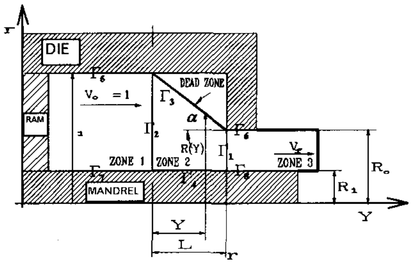


Fig.1 Velocity field of tube extrusion

The material under deformation is divided into four zones as shown in Fig. 1 . The velocity field in the cylinderical coordinate system (r, y, θ) proposed by K. T. Chang [2] is employed, the velocity components are

$$\dot{U}_r=\frac{R(y)\cdot R'(y)\cdot\left(1-R_i^2\right)\cdot\left(r^2-R_i^2\right)}{r\cdot\left(R^2(y)-R_i^2\right)^2}$$

$$\dot{U}_y=\frac{\left(1-R^2\right)}{\left(R^2(y)-R_i^2\right)}$$

$$\dot{U}_\theta=0 \qquad (1)$$

where $R(y)=1-y\cdot\tan(\alpha)$ and $R(0)=1, R(L)=R_0, L=\dfrac{1-R_0}{\tan(\alpha)}$

As shown in Fig. 1, V_0 and V_f are the velocities at inlet and outlet, respectively. Zone I and Zone III are rigid zones and Zone II is the plastic deformation zone. In the plastic deformation zone, the material has the velocity components in r and y directions is assumed. The velocity components and strain rates in each zone are

(1)Zone I :

$$\dot{U}_r=0$$
$$\dot{U}_y=V_0=1$$

(2)

(2)Zone II :

$$\dot{U}_r=\frac{R(y)\cdot R(y)\cdot(1-R_i^2)\cdot(r^2-R_i^2)}{r\cdot(R^2(y)-R_i^2)^2}$$

$$\dot{U}_y=\frac{(1-R_i^2)}{(R^2(y)-R_i^2)} \qquad (3)$$

Since $\dot{\varepsilon}_{rr}+\dot{\varepsilon}_{yy}+\dot{\varepsilon}_{\theta\theta}=0$,the velocity field satisfies the condition of volume constancy.

(3)Zone III :

$$\dot{U}_r=0$$
$$\dot{U}_y=\frac{1-R_i^2}{R_0^2-R_i^2}=V_f \qquad (4)$$

(4)Dead Zone :

$$\dot{U}_r=0$$
$$\dot{U}_y=0 \qquad (5)$$

2.2 Powers of Deformation

Using the upper bound method , the assumption of the velocity field will influence the prediction of load and metal flow. As the generalized velocity field of tube extrusion is established, the internal deformation power $\dot{W}_i$ in the plastic deformation, the shear losses $\dot{W}_s$ in the velocity discontinuity boundaries and the friction losses $\dot{W}_f$ in the material/die boundaries can be calculated, then the total power of deformation j can be obtained.

(1) Internal power of deformation

In zone II the material has plastic deformation, the internal power of deformation is

$$\dot{W}_j=\sum_{j=1}^{N_j}\overline{\sigma}_j\cdot\dot{\overline{\varepsilon}}_{eqj}\cdot V_j \qquad (6)$$

where V_j is the volume of each element , $\overline{\sigma}_j$ is the flow stress of each element , $\dot{\overline{\varepsilon}}_{eqj}$ is the equivalent strain rate of each element and N_j is the numbers of element in the plastic deformation zone.

(2) Shear losses

In the boundaries of velocity discontinuity ,Γ_1,Γ_2 and Γ_3 , slip occurs parallel to these surfaces , the velocity discontinuity is denoted as ΔV_s ,the shear losses consumption along these boundaries is no more than

$$\dot{W}_s=\sum_{j=1}^{L_j}\tau_{sj}\cdot\left|\Delta V_s\right|\cdot S_j \qquad (7)$$

where L_j is the numbers of element on the shear surface, τ_{sj} is the shear stress of the element and S_j is the shear surface area of each element.

(3) Friction lossess

In the boundaries of material and die ,Γ_4~Γ_8 , exist the velocity discontinuity ΔV_f, and the friction losses along the boundaries becomes

$$\dot{W}_f=\sum_{j=1}^{M_j}\tau_{fj}\cdot\left|\Delta V_f\right|\cdot F_j \qquad (8)$$

where M_j is the numbers of element on the friction surface , τ_{fj} is the friction stress of the element under the assumption of contact shear , F_j is the contact area of each element , and m is the constant friction factor .

3. HEAT TRANSFER MODEL

3.1 The Generation of Heat

In the process of hot extrusion, except the heating equipment in the container, there are two sources of heat that can affect the workpiece temperature, one is the material with plastic deformation and the other is due to the friction of material and die.

(1) Temperature increase due to plastic deformatin

In the hot extrusion process ,about 90~95% of the energy induced due to plastic deformation will transfer to heat [5] .It will affect the nodal point temperature of the element. Let the temperature increase at the nodal point of the element be ΔT_d ,the relationship between the plastic deformation energy and ΔT_d is described as

$$\Delta T_d = \frac{\bar{\sigma}.\Delta t.\dot{\bar{\varepsilon}}}{J\rho_1 C_1} \cdot \frac{\xi}{100} \tag{9}$$

where C_1 is the specific heat of material, $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is the equivalent strain rate, ρ_1 is the density of material, J is energy transform factor and ξ is the heat generation efficiency (it is usually assumed to be 0.9).

(2) Temperature increase due to friction heat

When material in the container is forced to flow along the inner die surface, the energy generated at the interface of material and die will transform into heat, and eventually increase the nodal point temperature. Let the temperature increase due to friction be ΔT_f , friction heat be ΔQ_f , the relationship between ΔT_f and ΔQ_f can be represented as

$$\Delta Q_f = \frac{\tau_f \Delta t |\Delta v_f| \Delta A}{J} \tag{10}$$

$$\Delta T_f = \frac{1}{C_a V_a \rho_a} * \Delta Q_f = \frac{m_1 \bar{\sigma} \Delta t |\Delta v_f| \Delta A}{\sqrt{3} C_a V_a \rho_a} \tag{11}$$

where m_1 is the constant friction factor, ΔA is the area of contact surface , ΔQ_f is heat consumption due to friction, τ_f is shear friction stress , $|\Delta v_f|$ is the velocity discontinuity along the material/die boundaries, J is energy transform factor, C_a is the mean value of specific heat of material and die, ρ_a is the mean value of density of material and die , and V_a is the volume of material an die .

3.2 Assumptions of analytical model

The variables affecting hot extrusion analysis are flow stress, friction factor ,film thickness of lubricant, velocity field, strain rate, specific heat, density and thermal conductivity of material and die. And the variables will change with respect to temperature variation. During the simulation of forming process, some assumptions are made in order to simplify the analytical model

(1)The surrounding of die is in constant temperature.

(2)The friction factor is a constant during the extrusion process.

(3) Ram moves with a constant speed.

(4)The film thickness of lubricant along material-die interface doesn't change under deformation.

(5)The characteristic coefficients (ρ, c, K_c) of ram ,die and material are constant.

For the purpose of reducing friction force and separating material from die surface , graphite films are coated along the boundaries of container-material ,ram-material and die-material .The heat transfer rate acrossing the boundaries can be expressed as

$$Q_L = \frac{K_L}{\delta} \tag{12}$$

where δ is the film thickness of lubricant, Q_L is the heat transfer rate across the boundaries, K_L is thermal conductivity coefficient of lubricant film.

3.3 Finite difference equation of nodal point

During the extrusion deformation, heat transfer by radiation, convection and conduction through the interface are considered. On the boundaries of ram-billet and die -billet ,heat conduction is assumed , and it is denoted as $q_L = \frac{K_L}{\delta}(T_2 - T_5)$ .If the billet and die are heated to the prescribed temperature and subsequently moved to the extruding machine ,the heat loss due to radiation and convection are assumed for this process. Radiation energy on the boundaries of billet-air and die-air are denoted as $q_R = \gamma\varepsilon\ (T_\infty - T_5)$, and convection energy through billet and die to air is denoted as $q_C = h_c(T_\infty - T_5)$. Where γ is Stefan-Boltzmann constant , ε is heat radiation rate , h_c is convective heat transfer coefficient ,T_2, T_5 are nodal point temperatures ,T_∞ is ambient temperature ,T_5^* is the absolute temperature of nodal point. As shown in Fig. 2 , the temperature of nodal point 5 affected by radiation and convection can be expressed as

$$T_5^{q+1} = T_5^q + \Delta t\left\{\beta\left(\frac{T_3^q - T_1^q}{\Delta x^2} + \frac{2T_2^q}{\Delta y^2}\right) + \frac{2}{\rho C \Delta y}\left[(-\gamma\varepsilon)(T_5^* - T_\infty^*)\right] + h_c T_\infty\right\} - \Delta t\left\{\left[\beta\left(\frac{2}{\Delta x^2} + \frac{2}{\Delta y^2}\right) + \frac{2h_c}{\rho C \Delta y}\right]T_5^q\right\}$$

where $\beta = \frac{K_c}{\rho C}$ (13)

Heat transfer equation at the boundary of lubricant film is expressed as

$$T_5^{q+1} = T_5^q + \Delta t\left\{\beta\left(\frac{T_3^q + T_1^q}{\Delta x^2} + \frac{2T_4^q}{\Delta y^2}\right) + \frac{2K_L T_2^q}{\delta\rho C\Delta y}\right\} - \Delta t\left\{\left[\beta\left(\frac{2}{\Delta x^2} + \frac{2}{\Delta y^2}\right) + \frac{2K_L}{\delta\rho C\Delta y}\right]T_5^q\right\} \tag{14}$$

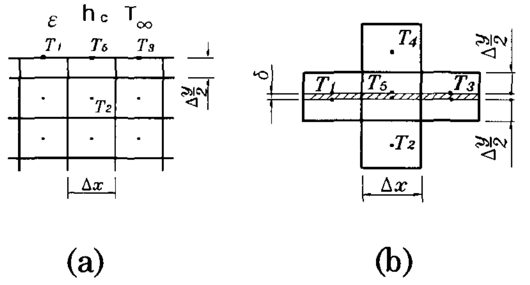


Fig.2 Heat transfer boundaries

4. ANALYTICAL SIMULATION

4.1 Flow stress of hot extrusion

The material used for analysis is aluminum , and its flow stress in hot working is different from that of in room temperature . In this study ,the flow stress of Tseng's experimental results [8] is employed, it is function of strain , strain rate and temperature .

$$\bar{\sigma} = \xi(\theta)\psi(\theta)\bar{\varepsilon}^{-i(\theta)}\left[\frac{\dot{\bar{\varepsilon}}}{5\times10^{4}}\exp\left(\frac{1.436}{8.6174\times10^{-5}\times933\times\theta}\right)\right]^{j(\theta)} \quad (15)$$

where A_0 is the section area before extrusion , A_f is the section area after extrusion , and $\bar{\varepsilon}=\ln\frac{A_0}{A_f}$, $\theta=\frac{TM^K}{TM^S}$, TM^K is the absolute temperature of material , TM^S is the melting temperature of material

$$\xi(\theta)=100\times\left[1-(\theta-0.08)\times\exp(1-\theta)\right]$$

$$\psi(\theta)=3^{0.5\times[1+i(\theta)+j(\theta)]}$$

$$i(\theta)=0.5\times\left\{1-\theta\times\exp\left[0.5535\left(1-\frac{1}{\theta}\right)\right]\right\}$$

$$j(\theta)=\begin{cases}0.055598\theta, & 0.0<\theta\le0.54716\\ 0.336(\theta-0.456), & 0.54716<\theta\le1.0\end{cases}$$

Besides, the physical properties of ram, die, and billet are shown in Table 1.

Table 1

	Density (Kg/m^3)	Specific heat ($J/(Kg*K)$)	Heat conductivity coefficient ($W/(m*K)$)	Initial temp (°C)
Ram & Die (SKD-61)	7860	501.6	54.76	420
Billet (A-6061)	2700	$285(T_d)^{0.205}$	$665(T_d)^{-0.17}$	500,550,600

T_d =average temperature of plastic deformation zone (^0K)

4.2 Temperature distribution

When the billet is moved from heating furnace to the extruding die , heat loss occurs during moving through air, and as the high-temperature billet contacts with the low-temperature die, conduction and convection heat losses occur on the billet-die boundary. Fig. 3 shows the temperature distribution when 500°C billet contacted with 420°C extruding die in the case of lubricant film thickness δ=0.06mm. On the contact surface, heat of the billet transferred to the die, therefore the temperature of billet decreased and the temperature of die increased . Also lubricant film thickness is an important factor affects heat transfer rate on the billet-die boundary, the thicker of the lubricant film the less of the heat transfer was obtained .

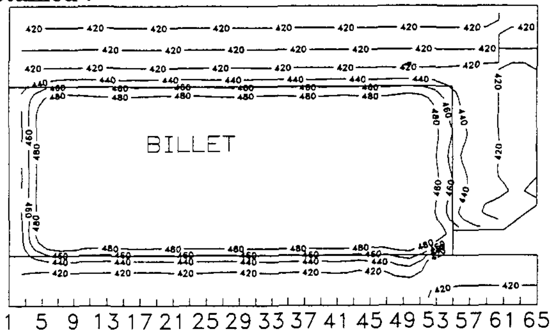


Fig.3 Temperature distribution of die and billet

4.3 Extrusion force

Using the mentioned velocity field, the metal flow pattern of billet in the container can be obtained, the effective strain rate can be calculated. Ram speed is a main factor that affecting the effective strain rate, as the ram speed increasing the effective strain rate will increase simultaneously. Fig. 4 shows the distribution of strain rate of ram speed $V_o=3.0$mm/s , it can be seen that the plastic deformation occurs in the zone II only. And it is obviously that the material deformed severely at the outlet of the die. The influence of ram speed on extrusion force is shown in Fig. 5. It is clear that the extrusion force increased with the ram speed. Except the influence of the ram speed, the initial temperature of billet is an important variable affecting the extrusion force. Since the flow stress decresased as the heating temperature increased, eventually the extrusion force decreased when the temperature of billet increased. In Fig. 6, the extrusion forces of different initial billet temperatures were calculated.

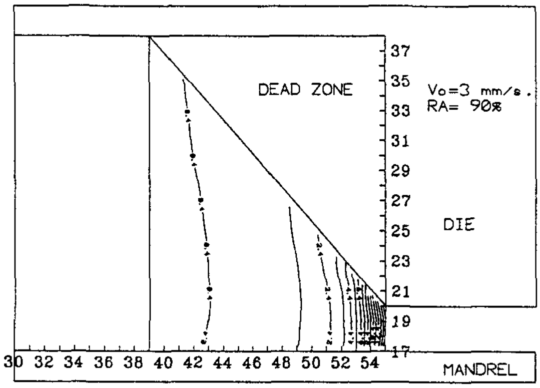


Fig.4 Strain rate distribution

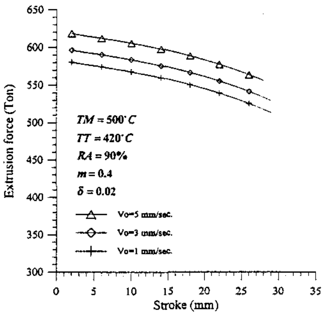


Fig 5 The influence of ram speed

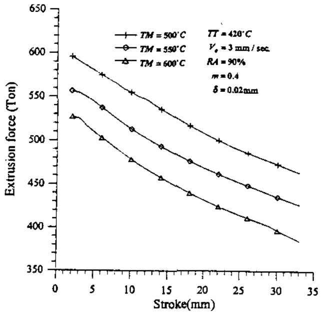


Fig. 6 The influence of initial temperature

5. EXPERIMENTAL RESULTS

5.1 Energy comparisons

For the purpose of examining the availability of this numerical simulation model, aluminum alloy A-6061 were extruded at different conditions. Table 2 shows the extruding conditions executed in this study, and the comparisons of the maximum extrusion forces with the analytical results. The comparisons done here are divided into three categories, there are : (1) Billets with the same heating temperature but different ram speeds, such as specimens A, B, C. (2) The ram speeds keep the same but the heating temperatures of billet are different, such as specimens B, D, F. (3) Single extrusion and continuous extrusion, such as specimens D,E. Continuous extrusion means in the process when the first billet still has remainders stay in the container then the second billet is placed and following extruding operation is proceeded.(E)

Table 2

NO.	Billet temp (℃)	Container temp (℃)	Ram speed (mm/s.)	max force (experiment) (ton)	max force (analysis) (ton)
A	500	420	1	504	581
B	500	420	3	515	596
C	500	420	5	533	618
D	550	420	3	479	556
E	550	420	3	548	556 *
F	600	420	3	450	526

The constant friction factor m used in the analysis, referred the ring compression test with graphite as lubricant in the temperature of 550 ℃ [10], $m = 0.4$ was chosen. Fig. 7 shows the experimental results of billets with the same heating temperature ($T = 500°C$) but different ram speeds. The maximum extrusion force will increase with increase in the ram speed. Fig.8 shows the comparison of experimental result with analytical result under the conditions of heating temperature $T = 500°C$ and ram speed $V_o = 3.0 mm/s$. Since in analysis the material deformation is assumed under steady state, result of unsteady state is not shown. The analytical extrusion force is higher than that of experiment.

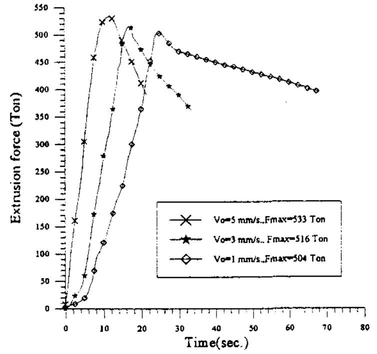


Fig.7 Force comparison of different ram speeds

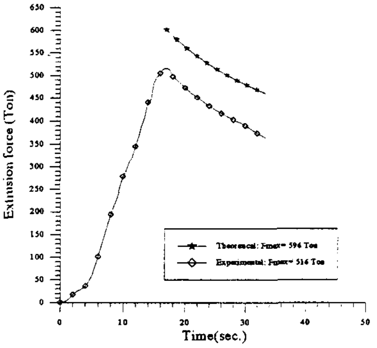
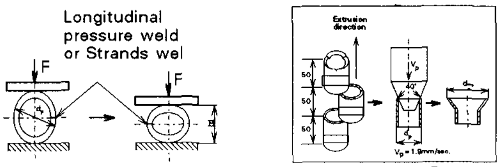


Fig.8 Comparison of experiment and analysis

5.2 Strength of the extruded tubes

The quality of extruded tubes were checked by measuring the outside diameters, its tolerances were within the range of ±0.2mm met the requirement of commercial products. The mechanical properties of the tubes were examined by expanding test and flattening test, the schematic illustrations of the tests are shown in Fig.9 In the expanding test, the expanding rate ψ is defined as $\psi = d_{ma}/d_p$, where d_{ma} is the maximum diameter without fracture after expanding, d_p is the diameter before expanding. The expanding rates obtained in this study are shown in Table 3. Here S_e is the distance that the specimen taken from the end of the tube. The extruded tube has the greater strength with respect to the larger expanding rate. The results of flattening test are shown in Table 4, the flattening rate w in defined as $\omega = H/d_p$,where H is the height without fracture after flattening, d_p is the diameter of the tube. The requirement of the commercial products is $\omega \leq 0.75$, and ω values obtained in this study are under 0.38, that means the tubes extruded in this study have the enough strength to meet commercial requirements.



(a) Flattening (b) Expanding

Fig.9 Schematic illustration of tests

Table 3

Temp.	No.	Ram speed	Se	Expanding Rate
500	11	3	50	1.26
	12	3	100	1.25
	13	3	150	1.35
550	14	3	50	1.43
	15	3	100	1.55
	16	3	150	1.50
600	17	3	50	1.46
	18	3	100	1.40
	19	3	150	1.45

Table 4.

Temp.	No.	Ram speed	Se	Flattening Rate
500	21	3	200	0.35
	22	3	250	0.38
	23	3	300	0.36
550	24	3	200	0.25
	25	3	250	0.25
	26	3	300	0.25
600	27	3	200	0.25
	28	3	250	0.30
	29	3	300	0.25

6. CONCLUSIONS

1.The extrusion force increases with the ram speed. And the same result can be obtained from the velocity field, since the strain rate and flow stress will increase with increase in ram speed.

2.The extrusion force decreases with respect to the increasing of the heating temperature.

3.The heat transfer rate decreases with respect to the thicker of the lubricant film.

4.Sounded tubes can be extruded, and its diameters meet the requirement of commercial products.

5.The results of expanding test and flattening test show that the extruded tubes have enough bonding strength.

6.From the observation of the fracture sections,the strength of welded portion is stronger than that of the original material.

ACKNOWLEDGMENT

This research was supported by National Science Council, Taiwan, Republic of China under contract NSC84-2212-E011-009.

REFERENCES

1.H.S. Mehta, A.H. Shabaik, and Shiro Kobayashi, "Analysis of Tube Extrusion," J. Eng. Industry, Trans., ASME, May 1970, pp.403-411.

2.K.T. Chang, and J.C. Choi, "Upper-Bound Solutions to Tube Extrusion Problems through Curved Dies," J. Eng. Industry, Trans, ASME,Nov.1972, pp.1108-1111.

3.D.Y. Yang, H.S. Kim, and C.H. Jan, "Analysis of Three-Dimensional Extrusion of Arbitrarily Shaped Tubes," Int. J. Mech. Sci., Vol.32, 1990, pp.115-127.

4.R. Akeret, "A Numerical Analysis of Temperature Distribution in Extrusion," J. Inst. Metals 95., 1967, pp. 204.

5.T. Altan, and G.D. Lahoti, " Prediction of Temperature Distributions in Axi-Symmetric Compression and Torsion," ASME, J. Eng. Materials Technology, 1975, pp.113-120.

6.K. Nakanishi, S.I. Okamura, and T.Nakamura, "Analysis of Axisymmetric Hot Extrusion of Aluminum by the Visioplasticty Method Combined with the Numerical Calculation Method for Predicting the Flow Curves," JSTP ",Vol.18, No.203, (1977-12),pp.990-998.

7.T. Saiki, Y.Sekiguchi, and S. Shimizu, " The Upper : Bound Analysis of 2-Dimensional Flow in Hot Forging Processes," JSTP ",Vol.23, No.253, (1982-2), pp. 168-176.

8.Tseng, A.A., "A Generalized Finite Difference Scheme for Convection-Dominated Metal Forming Problems," Int. J. Num. Met. Eng.,Vol.20, 1984, pp.1885-1990.

9.R.S. Lee, and J.J. Sheu, " A Numerical Model for Simulating Temperature and Speed Effects in Hot Extrusion of Rod," Int. J. Mech. Sci., Vol.33, 1991, pp.985-998.

10.C. C. Liao, "Study on the Injection Upsetting Process,"Master dissertation in Dept. of Mech. Eng. N.T.I.T. , June.1995

11.T. Murakami, J.X. Xie, H. Takahashi, K. Ikeda, and K.I. Takaku, "Forming of A7475 and A5056 Pipes by Hot Multi-Billet Extrusion: Hollow Section Forming by Multi-Billet Extrusion," J.of the JSTP Vol.33, No.380, Sep.1992, pp.1045-1051.

12.Manabu Kiuchi,and Michihiko Hoshino, "Numerical Simulation of Forward Extrusion of Pipes through Bridge Die," J.of the JSTP Vol.32, No.361, Feb.1991, pp.175-181.