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COUPLED THERMOPLASTIC ANALYSIS OF NON-STEADY STATE BAR DRAWING WITH FEM

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In bar drawing, the diameter of a round bar is reduced by pulling the bar through a conical die. During the process, the bar and the die are heated due to the deformation and friction. The non-steady state deformation of the bar drawing process is analyzed by the FEM program ALPIDT. Based on the rigid-plastic theory, program ALPIDT also takes into account the heat generation and heat counduction during the process. One of the difficulties encountered in the simulation is to limit the control volume in the analysis. This problem is solved by introducing an automated remeshing scheme suitable to the steady-state deformation. The deformation mechanics were discussed in terms of solution. The predicted temperature distributions at steady state are compared with the experimental measurement. The comparison shows excellent agreement with the measured and predicted values.

Key Words : Bar Drawing, Non-Steady State Deformation, Automated Remeshing, Heat Generation, Thermovisco Plastic Analysis.

1. INTRODUCTION

Temperature plays an Important pole in metal forming processes because it influences the flow stress of the deforming material and the friction conditions. Thus, the temperature infulences the metal flow considerably during a metal forming process. In metal forming processes, most of the deformation energy is converted into heat, causing the tmperature to rise. Temperature is also affected by the interface energy dissipation due to friction between the die and workpiece. At the same time, heat conduction is taking place due to the temperature difference between the different locations of the die and workpiece.

In the past, there were various attempts to simulate metal forming processes, taking heat generation and heat conduction into consideration(Siebel and Kobitzsch, 1943 ; Bishop, 1956 ; Altan and Kobayashi, 1968 ; Zienkiewicz and Heinrich, 1978). Recently, Rebelo and Kobayashi(Rabelo and Kobayash, 1980a ; Rabelo and Koboyash, 1980b) developed a finite element method using a coupled thermo-viscoplastic formulation. Their formulation had been implemented into the general purpose FEM code ALPIDT(Oh et al., 1981). The FEM code ALPIDT is based on the rigied-viscoplasic theory. The code is capable of handling two dimensional metal forming processes with arbitrarily shaped dies. The prediction of temperature distribution through heat conduction is also included in the formulation.

In the present investigation, a bar drawing process is analyzed by using the FEM code ALPIDT. In the analysis, the bar drawing process is treated as a non-steady state deformation. One of the difficulties encountered in the simulation is to limit the control volumn in the analysis. In order to overcome this difficulty, an automated remeshing scheme suitable to the bar drawing process is developed. The transient solutions of the bar drawing process are obtained, and metal flow and temperatures are predicted. By comparing the experimental measurement with the predictions, the capability of the program ALPIDT, in predicting temperatures, has been evaluated.

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2. METHOD OF ANALYSIS

The method used in the present study is based on rigid-viscoplastic formulation. It is an extension of the rigid-plastic finite element method, developed by Lee and Kobayashi(1973). The details of the present method are discussed in earlier publications (Oh et al., 1978 ; Oh, 1982).

The rigid-viscoplastic material is an idealization of an actual one, by neglecting the elastic response. The material shows the dependence of flow stress on strain rate in addition to the total strain and temperature. Also, it can sustain a finite load without deformation. The rigid-viscoplastic material, which was introduced for the analytical convenience, simplifies the solution process with less demanding computational procedure. Moreover, it seems that the idealization offers excelent solution accuracies due to the negligible effects of elastic response at large strain in the actual material. Therefore, the rigid-viscoplastic material is especially suitable for metal forming analysis at elevated temperatures.

The constitutive equantion during forming is represented by

$$\sigma_{ij}' = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij} \quad (1)$$

where σ_{ij}' is a component of the deviatoric stress, $\dot{\varepsilon}_{ij}=1/2(v_{i,j}+v_{j,i})$ is a component of strain rate, v_i is a velocity component, (,) denotes differentiation, and $\bar{\sigma}$ and $\dot{\bar{\varepsilon}}$ are the effective stress and effective strain rate, respectively.

The effective stress $\bar{\sigma}$, in general, is a function of total strain and strain rate and expressed as

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon},\ \dot{\bar{\varepsilon}},\ T) \quad (2)$$

In the case of rigid-plastic formulation, $\bar{\sigma}$ becomes a function of the total effective strain only.

The variational principle functional for rigid-viscoplastic material can be written as

$$\phi = \int E(\dot{\varepsilon}^*)dV - \int \underline{F}\cdot\underline{v}^*\ dS + \int \frac{1}{2}K(\dot{\varepsilon}_{kk})^2 dV \quad (3)$$

Here the work function $E(\dot{\varepsilon})$ can be expressed as

$$E(\dot{\varepsilon}) = \int \bar{\sigma}\, d\dot{\bar{\varepsilon}} \quad (4)$$

and K is a large positive constant which penalizes the dilation strain rate component. It can be readily shown that the mean stress is $\sigma_m = K\dot{\varepsilon}_{kk}$. The above functional reduces to that of rigid-plastic material if $\bar{\sigma}$ is a function of $\bar{\varepsilon}$ only.

The thermo-viscoplastic coupled analysis can be achieved by combining the heat transfer analysis with deformation analysis. (Rebelo and Kobayash, 1980a ; Rebelo and Kobayash, 1980b) The weighted residual expression of the heat transfer process can be written as

$$\int_V kT_{,i}\delta T_{,i}\,dV+\int_V \rho c\dot{T}\delta T\,dV-\int \nu\bar{\sigma}_{ij}\dot{\varepsilon}_{ij}\delta T\,dV - \int_{S_q} q_n T\delta dS_q=0 \quad (5)$$

where k is the heat conductivity, ρ the density, c the heat capacity, and q_n is heat flux at the boundary. Here ν represents the portion of the mechanical energy transformed into heat, and it is assumed to be 0.95.

The time integration scheme used in the temperature calculations were

$$T_{t+\Delta t}=T_t+\Delta t\cdot\left[(1-\beta)\dot{T}_t+\beta\dot{T}_{t+\Delta t}\right. \quad (6)$$

where β is chosen as 0.75. The datails of the coupled analysis can be found in a previous publication(Rebelo and Kobayash, 1980a)

3. REMESHING PROCEDURE

In the analysis, bar drawing is treated as a non-steady state deformation problem. The Lagrangian FEM mesh employed here moves with the material point when the bar was pulled through the die. The bar length, required for the drawing process to reach steady state, is unknown. The larger the bar that is chosen, the more degrees of freedom are needed to describe the deformation process which will require unnecessary computational efforts.

Since the deformation is limited near the die during the bar drawing process, it is sufficient to consider the workpiece near the die in the analysis. The choice of control volume is rather intuitive, but it should fully describe the deformation process without losing any important information and causing too much computational burden. One way to handle this situation is to use a remeshing procedure during simulation.

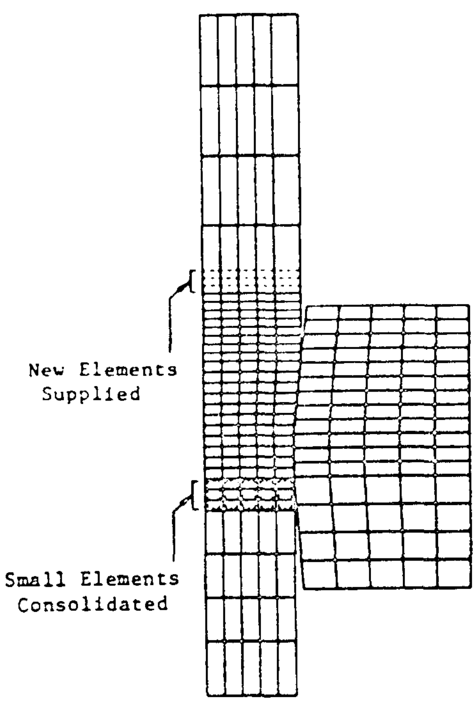

Fig. 1 Undeformed FEM mesh and remeshing scheme.

Unlike the procedure in non-steady state(Badawy and Oh, 1983 ; Tang et al., 1983) the FEM mesh in bar drawing can be rearranged without using sophisticated interpolation between "old" and "new" mesh systems.

In the present investigation, the undeformed grids were chosen as shown in Figure 1. The mesh system is kept the same until a few layers of small mesh pass through the die land. Then, several layers of mesh are consolidated into one large layer, at the exit side, while the same number of small layers of elements are supplied at the entrance side. These procedures are also shown in Figure 1. With this rearrangement, the nodes were renumbered in the FEM program. Also, the strains of the elements were reassigned so that the overall distribution of strain remains the same.

4. COMPUTATIONAL CONDITIONS

For comparison purposes, the process conditions were chosen to be the same as those in experiments performed by Kopp(1968). A round bar of 44mm (1. 73 in) diameter was drawn at room temperature through a conical die with 12 degrees of included angle, and reduced to a diameter of 40. 4mm (1.59 in). Drawing velocity was lll. 7mm/sec (4.40 in/sec), and a friction factor of 0.07, which may be a typical value in cold drawing operations, was specified in the simulation.

The billet material is AISI 1010 steel, whose effective stress-strain relation was represented by $\bar{\sigma}=226$ MPa (32. 8ksi) for $\bar{\varepsilon} < 0.0115$, and $\bar{\sigma}=687 * \bar{\varepsilon}^{0.25}$ (in MPa) for $\bar{\varepsilon} > 0.0115$. It was assumed that 95 percent of the plastic work has converted into heat and that the heat generated by interface friction flows equally into both the workpiece and die. Thermal properties used in the analysis(Touloukian ; Editor) were the following :

Conductivity of the workpiece	: 46.7N/SK
Heat capacity of the workpiece	3.61N/mm²K
Conductivity of the die	: 45.16N/SK
Heat capacity of the die	: 3.93N/mm²K
Radiation coefficient	: 85×10^{-13}N/mmSK^4
Convective heat transfer coefficient	: 0.00295N/Smmk
Heat transfor coefficient of lubricant film	: 4/SmmK

Because of the symmetry, only half of the wire cross section is analyzed. The finite element grid is composed of 150 four-node elements in the workpiece and 80 in the die, as shown in Fig 1. The time increment chosen for the geometry update is 0.00895 sec. so that one-half of an element passes through the die at each increment. The boundary condition, used at the drawing side of control volume was given in such a way that the exit velocity is constant for the deformation analysis. For heat conduction, it is the exit side of the boundary.

5. RESULTS AND DISCUSSION

Figure 2 shows the predicted FEM grid distortion at the drawn length of 1.508R and 3.26R, where R represents the undeformed billet radius. As expected, the grid distortion relative to the undeformed grid is small. Because new grids are supplied at the entrance side, the predicted grid line represents the flow lines at steady state.

This is confirmed by the predicted velocity distribution in the simulation, as shown in Fig 3. It is seen in the figure that the particle velocities are all aligned with the grid lines lying along the drawing direction.

The predicted drawing load is shown in Fig. 4 as a function of drawn length. The figure shows that the drawing load reaches the "steady state" at the drawn length of approximately 15 mm. The fluctuation in the load prediction is due to the finite length of the elements. The fluctuation becomes periodic because of the way the new elements are supplied at the entrance section.

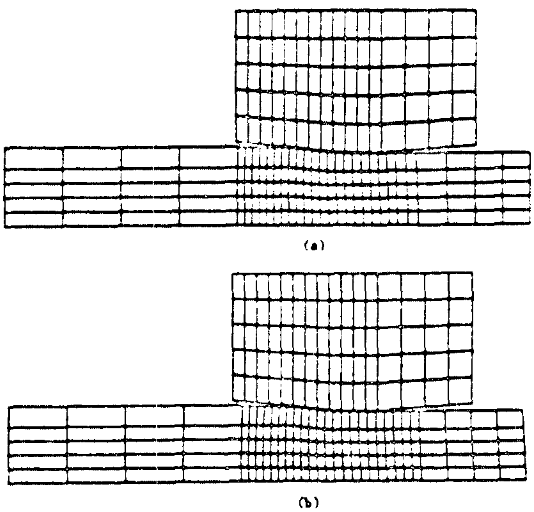

Fig. 2 Predicted FEM Grid distortion at drawn length of (a) 1.508R and (b) 3.26R

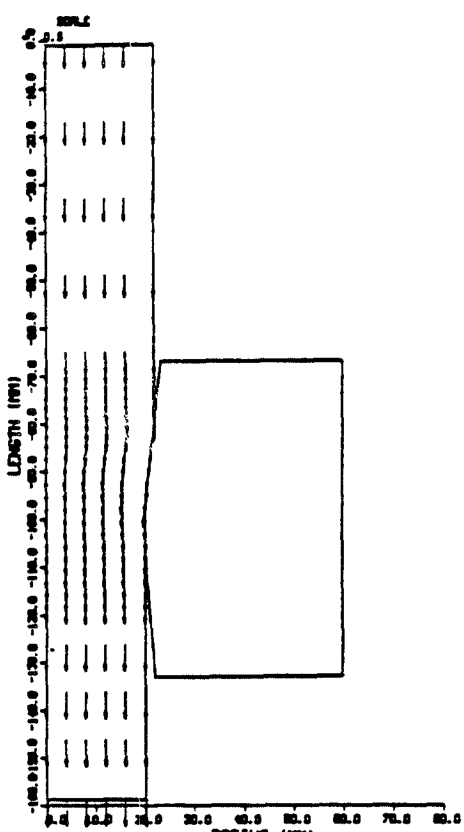

Fig. 3 The predicted velocity distribution in the bar drawing process

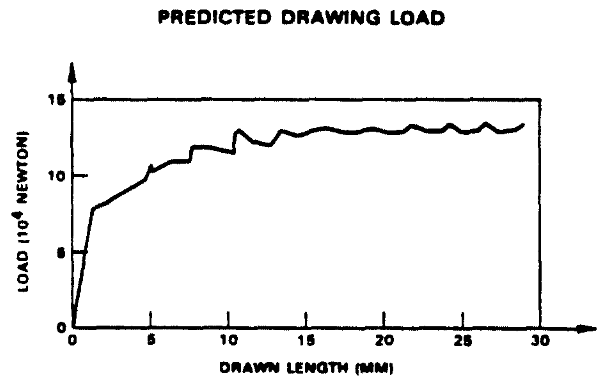

Fig. 4 The predicted load-displacement curve for bar drawing

The predicted temperature distributions, at the drawn lengths of 21.67 mm, 44.11 mm, 55.04 mm and 71.72 mm, are shown in Fig. 5. As can be seen in the figure, the temperature rise in the workpiece takes place at the deformation zone and spreads towards the exit while the die is heated near the workpiece-die interface. Figure 5(b), (c) and (d) shows that the temperature distribution in the deforming zone remains the same, implying that the steady state temperature has been reached at the drawn length of 71.72 mm. The prediction also shows that once the temperature rise takes place in the deforming zone, the material point temperature stays almost the same because of the slow diffusion speed of heat

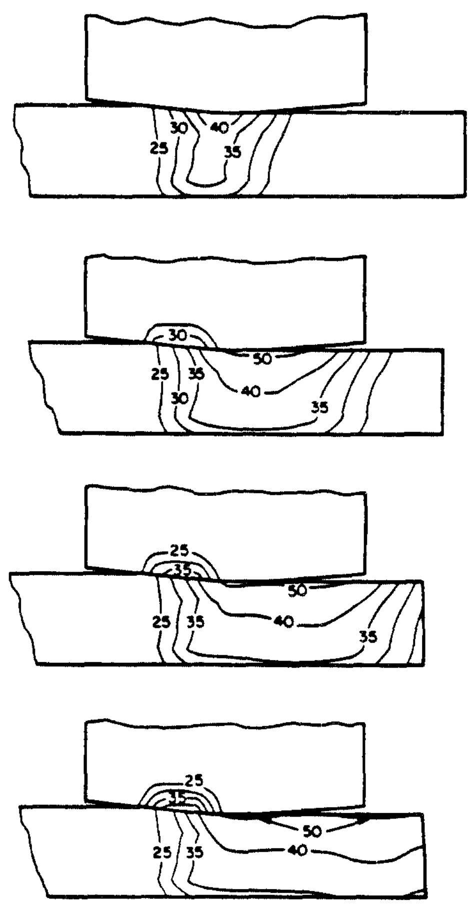

Fig. 5 The predicted temperature distribution at drawn length equal to : (a) 21.67 mm (b) 44.11 mm (c) 55.04 mm (d) 71.72 mm

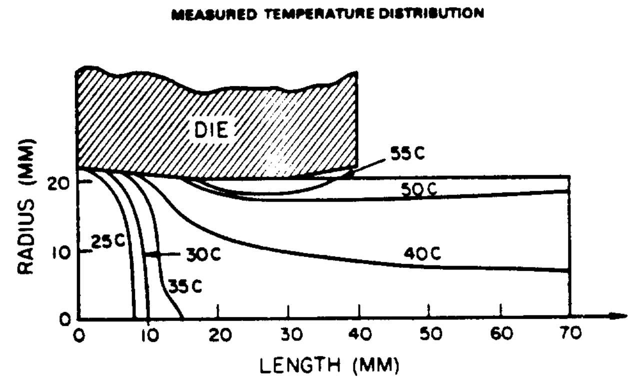

Fig. 6 Measured steady state temperature distribution for bar drawing by kopp(1968)

compared to drawing speed. The experimentally measured temperature distributions by Kopp(1968) are shown in Fig. 6. The figure shows that the predictions are in excellent agreement with the measurements. Figure 5 also shows the temperature distribution in the drawing die. As can be seen in the figure, the temperature rise in the die is confined to the small region near the dieworkpiece interface. The highest die temperature, about 45C (113F), is at the interface. This temperature is presumably lower than that of the actual drawing trials, since the temperature in the die hasn't reached steady state in the simulation. Figure 7 shows the predicted strain distribution at the drawn lengths of 21.67 mm, 44.11 mm, 55.04 mm, and 71.72 mm. The distribution

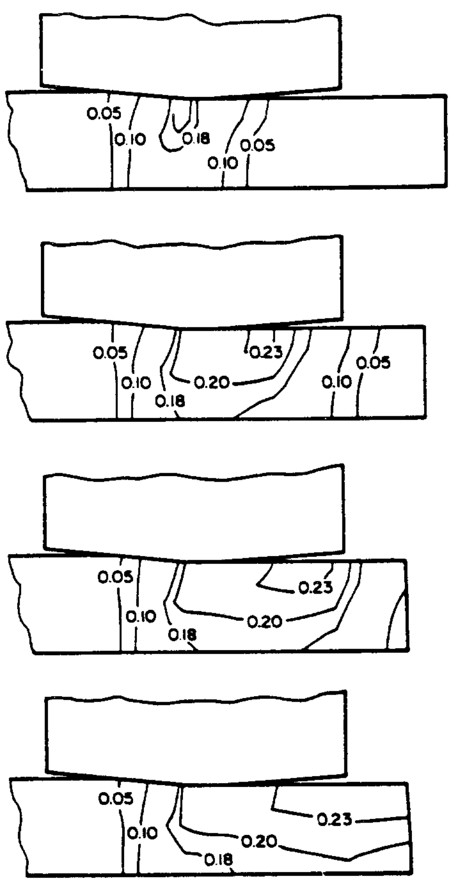

Fig. 7 Total effective strain distribution at drawn length equal to : (a) 21.67 mm (b) 44.11 mm (c) 55.04 mm (d) 71. 72 mm

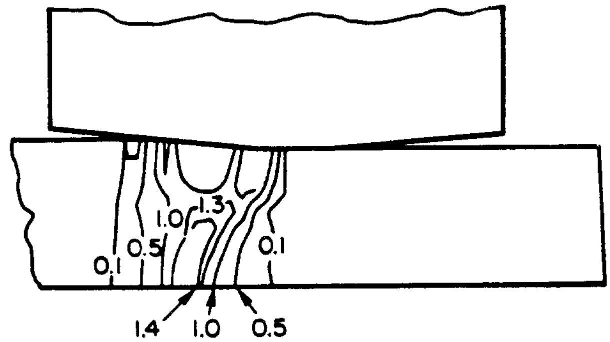

Fig. 8 The predicted strain rate distribution at drawn length equal to 71.72 mm

trend is similar to the temperature distribution. This trend is natural because the heat generation is closely related to the deformation. It may be noted that contour line $\bar{\varepsilon}=0.23$ is located outside of the die land. This suggests that the deformation continued after material particles passed through the conical section of the die. The prediction shows that the average effective strain of the drawn bar is about 0.22. Comparing this to the case of uniform deformation, where $\bar{\varepsilon}=0.17$, a redundant strain of 0.05 is predicted.

Figure 8 shows the predicted strain rate distribution at the drawing length of 71.72 mm. Since the strain rate is the instantaneous quantity, the distribution pattern remains the same during the drawing process. It can be seen near the die area. A similar trend has been reported previously by Chen et al.(1979) in their analysis of bar drawing by FEM.

6. SUMMARY AND CONCLUSION

A bar drawing process has been analyzed by the FEM code ALPIDT in terms of its deformation mechanics and temperature rise in the workpiece and die during the process. In the analysis, the bar drawing process is treated as a non-steady state deformation. In order to limit the control volume in the simulation, a remeshing scheme suitable to the bar drawing process has been introduced. Predictions are compared with the experimental measurements, available in literature. The comparison shows excellent agreement between the predictions and measurements. Since the FEM code ALPIDT is capable of handling coupled thermo-viscoplastic deformation with arbitrarily shaped dies, it is expected that the program can be used effectively in analyzing other deformation processes where temperature behavior is important.

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