3D FEM Simulation System for Optimization of Profile Extrusion

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ABSTRACT --- The paper presents 3D finite element system for simulation of extrusion. It simulates non-isothermal steady-state flow of visco-plastic material in container and die outlet. The developed code provides completely automated mesh generation, effective simulation of material flow and output of information on material flow, temperature distribution and some integral characteristics like profile bending and profile twisting which are necessary for prediction of product quality. The developed software was applied to simulation and optimization of different extrusion processes including profiles having opened and closed shapes. The FEM system supports the interface with solid and surface CAD systems through STEP and IGES format. The code is supposed to be effective tool for extrusion technology development in industry due to its user-friendliness and use of PC.

I. Introduction

Design of the dies for extrusion of products having complicated cross sectional shapes is still an art rather than a science. Die design for a new product is developed on the basis of previous experience and experimentation. In many cases costly experiments and in-plant trials can be replaced by numerical simulation. It is effective for analysis of material flow, temperature distribution and load estimation if die design is specified. But 3D simulation becomes time consuming when many simulation trials are required for development of die shape and searching for optimal position of orifice. In present study the solution is achieved by means of steady-state approximation of material flow in profile extrusion. The problem of material flow and die deformation problem is solved decoupled. Using steady state approach the simulation of profile extrusion becomes acceptable for industrial implementation.

II. MATERIAL FLOW FORMULATION FOR 3D FINITE ELEMENT MODEL

Extrusion process has three consequent stages of material flow: short initial stage when the die is filled and forward end of the product is formed; stage of steady-state material flow and final stage when the punch slows down and stops. From practical point of view the most important is steady-state stage when the product shape and properties are formed. During steady-state stage of the process some parameters (the temperature, the load) may vary but this variation does not influence material flow considerably. Thus steady-state stage of extrusion process can be simulated with acceptable accuracy using Eulerian approach.

In present work the material is considered as incompressible rigid-viscoplastic continua and elastic deformations are neglected [1]. The system of governing equations includes:

equilibrium equations:

$$\sigma_{ij,j} = 0 \qquad (1)$$

compatibility conditions:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}) \qquad (2)$$

constitutive equations:

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

incompressibility equation:

$$v_{i,i} = 0 \qquad (4)$$

energy balance equation:

$$\rho c\dot{T} = (k_1 T_{,i})_{,i} + \beta\bar{\sigma}\dot{\bar{\varepsilon}} \qquad (5)$$

and expression for flow stress:

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \qquad (6)$$

where σ_{ij} = stress, $\dot{\varepsilon}_{ij}$ = strain-rate and v_i = velocity components respectively, σ'_{ij} = deviatoric stress tensor, $\bar{\sigma}, \bar{\varepsilon}, \dot{\bar{\varepsilon}}$ = effective stress, effective strain and effective strain-rate, respectively, T = temperature, β = heat generation efficiency which is usually assumed as β = 0.9-0.95, ρ = density, c = specific heat and k_1 = thermal conductivity.

In equations (1)-(5) summation convention is used. Comma denotes a derivative with respect to the axis following it. The indexes i and j for three-dimensional problems vary from 1 to 3 and repeated subscript means summation.

Equations (1-4) were transformed into discrete form by means of virtual work-rate principle and finite element technique resulting in non-linear system of algebraic equations where nodal values of velocity components and mean stress are considered as independent variables. Velocity and mean stress are approximated by quadratic and linear shape functions respectively within the 15-node prismatic or 10-node tetrahedral elements with curved sides. Energy balance equation (5) is treated by means of weighted residual (Galerkin) method. Iterative updating of heat generation and flow stress provides thermo-mechanical coupling of the problem. The container, punch and die are treated as rigid bodies with specified friction and heat transfer conditions. The present study is applied to different cases of the profile extrusion and extrusion die design (see Figure 1).

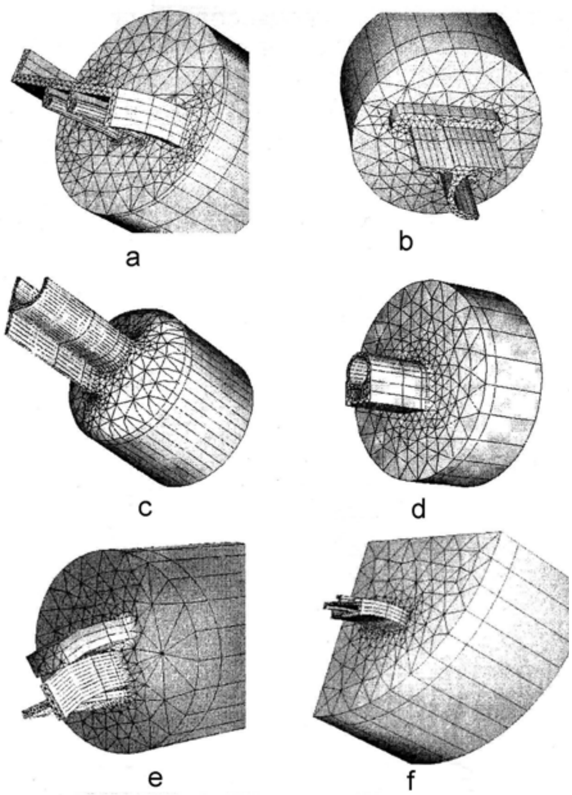


Figure 1. Different cases of profile extrusion: a – shear die; b – shear die with feeder plate; c – streamlined die; d – die with mandrell; e – multi holes die; multi-holes die with planes of symmetry

Finite element mesh is generated automatically for space domain that includes the billet in the container and the part of the product having sufficient length to be rigid at its front end. Product shape can be arbitrary. Source data for mesh generation include the following geometry models: the container, the die, the mandrel, the billet and the punch. The die may be combined with container and mandrel in single solid body.

The solid body from CAD system is transferred to the program for simulation through STEP or IGES file format. The type of the model depends on the CAD system. The geometry transfer through STEP or IGES provides accurate import geometry from any CAD system without loss of the accuracy and smoothness of the model. On Figure 2 you can see CAD model of the flat die with container and finite element (FE) representation of the same die in the program.

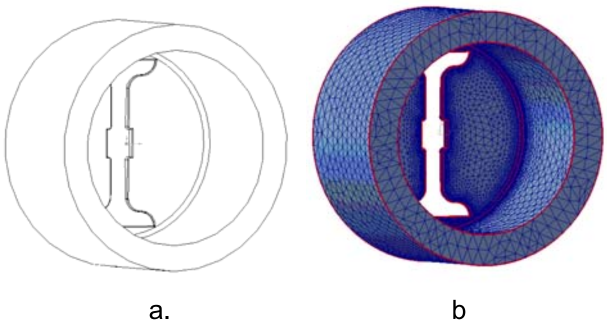


Figure 2. Flat die and container: a – solid model in CAD system; b – FE model ready for simulation

FE mesh is generated automatically. Originally at the first stage of the development of this software[2] it was based on the prism elements (see Figure 1) while later the tetrahedral FE mesh was also implemented (see Figure 2b). The code of 3D-extrusion model is realised as an extension of commercial software system QForm3D[3]. Program has reliable interface to CAD systems, provides fully automatic 3D FE mesh generation in the dies and billet and completely automatic simulation of the profile extrusion process. Limited amount of source data required for simulation makes it easy-to-use by inexperienced users.

III. Prediction of the parameters of extruded product

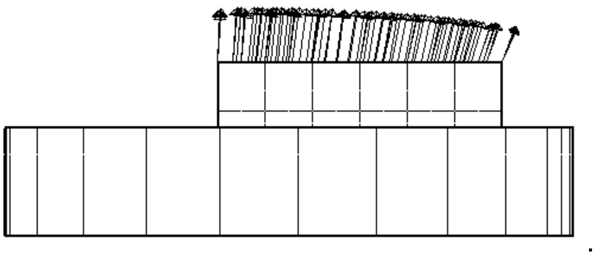
Prediction of general parameters of the extruded product by means of simulation is very important for successful industrial implementation of the program. In steady-state approach we have the values of the components of the velocity vector in the nodes of the FE mesh. Using the components of the velocity vector inside of the profile it is possible to calculate the following parameters:

- Profile bending in mm per 1 m of the profile length;
- Twisting of the profile in radians per 1 m of the profile length;
- Non-filling of the local parts of the extruded profile.

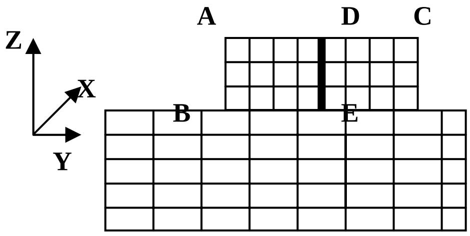
The algorithm of calculation of these parameters consists of two stages:

1. Estimation of the profile shape after its exit from bearing zone using the velocity field.
2. Calculation of the bending and twisting and non-filling of the profile using the FE mesh with the nodes that were displaced due the velocity in these nodes.

Let us consider the profile shape calculation using the velocity vector values (see Figure 3).



a.



b.

Figure 3. Velocity vectors at the end of the extruded product calculated by 3D-model (a) and the sheme of the algorithm for profile shape distortion evaluation (b).

At the end of the profile in the exit from bearing zone (see line BE on Figure 3b) it is necessary to calculate the absolute minimum of velocity $V_{z\ min}$ and for the line AC of the profile the absolute maximum velocity V_{max}. Then we consider the flow of the material along the line DE. Along Z direction for every points of the line DE we can calculate the time increment during the movement of the material point $dt=dz/V_{max}$. Then using this time increment dt it is possible to calculate the displacement of each point of the profile after leaving the bearing zone in X and Y directions using the following expressions:

$$dX_{i+1}=dX_i+dt\ V_{x\ i+1} \quad (7)$$

$$dY_{i+1}=dY_i+dt\ V_{y\ i+1} \quad (8)$$

Where i – is the number of the point along flow line ED

Because the velocity component V_z in cross section of the profile is not constant it is necessary to calculate the displacements along Z direction:

$$dZ_{i+1}=dZ_i+dt\ (V_{z\ i+1}-V_{z\ min}) \quad (9)$$

It is evident that the described algorithm is rather approximate. Meanwhile it satisfies two important requirements:

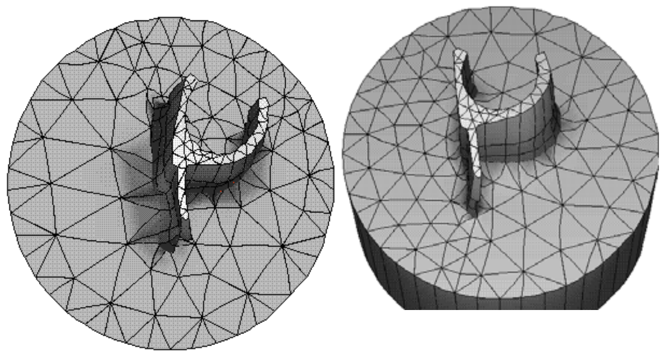
the displacements dX_{i+1}, dY_{i+1} and dZ_{i+1} in the nodes in the case of straight material flow without bending and twisting of the profile will be equal to zero;

the values of the displacement of the nodes in X, Y and Z directions are proportional to the profile velocity deviation from straight direction.

Thus this method though approximate can be successfully used for calculation of the bending and twisting of the profile and minimization of the profile shape distortion.

IV. RESULTS AND DISCUSSION

The effectiveness of such optimisation is illustrated by the example of the extrusion of complicated shape shown on Figure 4 (the influence of orifice position on product bend obtained by 3D-model). Further optimisation can be done by variation of bearing length and/or making a chamber on flat-face die. In presented investigation the option with a chamber was selected.



a. b.

Figure 4 The influence of the orifice position on product bend simulated by 3D-model: product shape before (a) and after (b) optimisation of orifice position (deformation of the product is magnified).

After several trials with different chamber depths simulated by 3D model the final die design for extrusion with minimal bending and twisting was developed. It is shown on Figure 5.

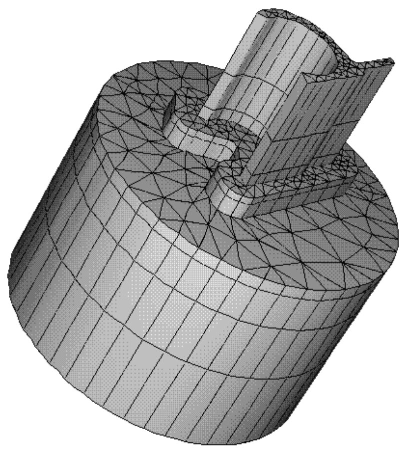


Figure 5. Shape of the product obtained after use of a chamber on the die (minimal bend and twist).

Let us consider the next example of die design optimization for extrusion of the profile from aluminum alloy AISI AA6101 for building industry. Its drawing is shown on Figure 6. Extrusion is performed in shear die with feeder plate. The goal of the optimization with the help of simulation was to find out the shape of the feeder plate and profile position that provides the minimum of the profile twisting. On Figure 7 are shown 3 variants of the shapes of the feeder plate.

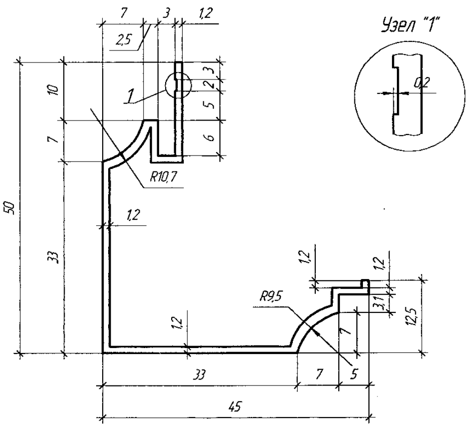
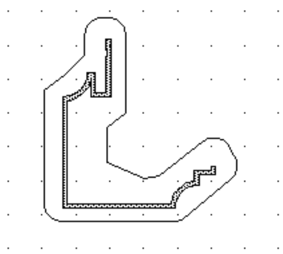
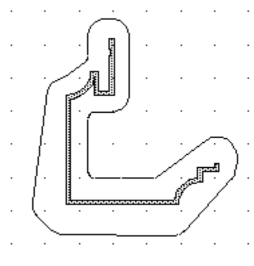


Figure 6 Drawing of the profile for building industry

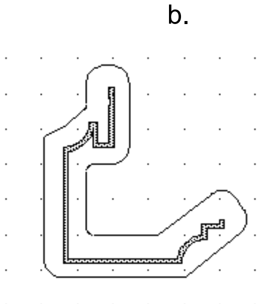
The depth of the feeder plate is 15 mm. The length of the container that was specified for simulation is 100 mm. The velocity of the punch is 4 mm/s. The extrusion ratio (elongation) for this profile is 130. Temperature of the billet after heating is 460 ^{o}C.



a.



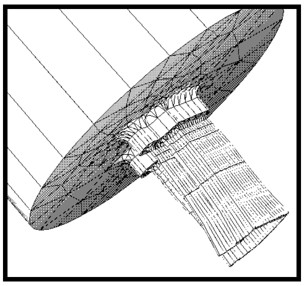
b.

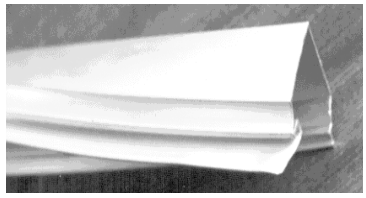


c.

Figure 7 Three different variants of the feeder plate shape. Calculated profile twisting: a –7.6 radian/m, b – 5.75 radian/m and c – 4.9 radian/m.

After calculation of twisting and bending for these variants the best one was found with twisting 4.9 radian/m. This shape of the feeder plate was machined and tested for actual extrusion. The experimental twisting was 3.2 radian/m that is even less than predicted (see Figure 8) and is acceptable. The final balancing of the profile is performed by special equipment.





a. b.

Figure 8. Twisting of the profile during extrusion: a – simulation results; b – photo of actual profile.

V. CONCLUSION

The described approach seems effective because of combination of fully automatic steady-state profile extrusion simulation with reliable prediction product parameters like twisting and bending. The program also provides die stress and deformation analysis but due to limited space of the paper these results are not presented. Further development of this approach also requires experimental verification and accumulation of statistics by means of industrial tests.

VI. REFERENCES

1. 1. Kobayashi S., Oh S.I., Altan T. *Metal forming and the finite element method,* Oxford university Press Inc., 1989

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