Key Engineering Materials Vols. 504-506 (2012) pp 505-510
Online available since 2012/Feb/03 at www.scientific.net

doi:10.4028/www.scientific.net/KEM.504-506.505

The Model for Coupled Simulation of Thin Profile Extrusion

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Keywords: Extrusion, aluminium, profiles, dies, FEM, simulation.

Abstract. The paper presents the latest development of the numerical model for extrusion of industrial profiles having complex shapes. The simulation predicts possible shape deterioration due to uneven material flow through the bearing zone and helps to equalise it by means of optimisation of the bearing design, chamber and feeding channels. To increase the accuracy of the model the material flow analysis has been coupled with mechanical problem in the tooling set thus it takes into account the influence of the die deformation on the material flow through the die. The described model has been implemented in QForm-Extrusion program that effectively simulates production of hollow and solid profiles with very high elongation ratios and is widely used by industry.

Introduction

QForm-Extrusion is a special-purpose program for aluminium profile extrusion simulation that has been developed by QuantorForm Ltd. It shares postprocessor with the versatile metal forming simulation program QForm3D but is actually a stand-alone application. The extrusion model is based on Lagrange-Euler approach [1]. The model also includes the assumption that the tool set is completely filled with the material prior to the beginning of the simulation thus the solution is to be found in the domain that is inside of the tooling set. On the other hand the free end of the profile increases in length very quickly after passing through the orifice. Due to non-uniform material flow the profile that leaves the orifice may bend, twist or buckle. The simulation is capable of predicting this undesirable shape deterioration and finding ways to minimize it. Validation of the model has been performed for prediction of load, material flow pattern, profile temperature and die deformation using special model experiments and numerous industrial case studies [2]. Comprehensive analysis of the program accuracy has been also done within the International Extrusion Benchmark Tests in 2007, 2009 and recently in 2011 (see, for example, [3, 4]) by means of comparison of the simulation results with precisely measured experimental data.

The numerical model description

When the material is considered as incompressible rigid-plastic continua and elastic deformations are neglected the system of governing equations includes:
equilibrium equations:

$$\sigma_{ij,j} = 0, \tag{1}$$

compatibility conditions:

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

constitutive equations:

$$\sigma'_{ij} = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij}, \tag{3}$$

incompressibility equation:

$$v_{i,i} = 0, \tag{4}$$

and expression for flow stress:

$$\bar{\sigma}=\bar{\sigma}(\bar{\varepsilon},\dot{\bar{\varepsilon}},T), \tag{5}$$

where σ_{ij} and $\dot{\varepsilon}_{ij}$ – components of stress and strain-rate tensors, v_i – velocity components, σ'_{ij} – deviatoric stress tensor, $\bar{\sigma}, \bar{\varepsilon}, \dot{\bar{\varepsilon}}$ – effective stress, strain and strain-rate, respectively, T – temperature.

In Eq. 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.

Energy balance equation for thermal problem in workpiece is

$$\rho c\dot{T} = (kT_{,i})_{,i} + \beta\bar{\sigma}\dot{\bar{\varepsilon}}, \tag{6}$$

where β – heat generation efficiency ($\beta = 0.9 \div 0.95$), ρ – density, c – specific heat and k – thermal conductivity. Similar equation but without the last term is valid for the thermal problem in the tools where no heat is generation due to no plastic work inside of the body.

In case when elastic strain components are to be taken into account the model described by the system of Eq. 1–5 is to be modified and complemented by elastic governing equations

$$\sigma'_{ij} = 2G\varepsilon'^{e}_{ij}, \tag{7}$$

$$\sigma_o = K\varepsilon_V, \tag{8}$$

where G is the shearing elastic module, ε'^{e}_{ij} is the deviatoric elastic strain tensor, σ_o is the mean stress, K is volumetric elastic module, ε_V is the volumetric elastic strain. Total strain is the sum of elastic ε^{e}_{ij} and plastic ε^{p}_{ij} strain

$$\varepsilon_{ij} = \varepsilon^{e}_{ij} + \varepsilon^{p}_{ij}. \tag{9}$$

Differentiation of Eq. 7-9 with respect to time helps to represent all the expressions in terms of strain-rate that in turn can be expressed through the velocity as written in (2). The derivatives of the stress can be approximated as follows:

$$\frac{d\sigma}{dt} \approx \frac{\Delta\sigma}{\Delta t} = \frac{1}{\Delta t}(\sigma - \tilde{\sigma}), \tag{10}$$

where σ is the stress at current instant of time, $\tilde{\sigma}$ is the stress at previous instant of time and Δt is the time increment.

Finally the expressions for elastic-plastic deformation can be written as follows:

$$\sigma'_{ij} = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}} + \frac{1}{\Delta t}\tilde{\bar{\varepsilon}}^{e}}\left(\dot{\varepsilon}_{ij} + \frac{1}{\Delta t}\tilde{\varepsilon}'^{e}_{ij}\right), \tag{11}$$

$$\sigma_o = K\Delta t\,\dot{\varepsilon}_V + \tilde{\sigma}_o, \tag{12}$$

where the sign `~` is used to denote the value of the function in previous instant of time and implicit integration is supposed to be used.

The deformed shape of the tools is the result of application of the load from the deformed body to the tool surface. This deformed shape can be used for the simulation of the material flow at the next time increment. Schematic diagram of this procedure is shown on Fig. 1. Let u_i are the present displacements at time t^e_i. Difference between elastic solution u^*_i for current load P_i and this value is

$$\Delta u_i = u^*_i(P_i) - u_i. \tag{13}$$

Elastic solution u^*_i is to be found using Eq. 7-8. Additional velocities of tool points during time increment Δt^e_i could be defined as

$$v_j = \frac{\Delta u_i}{\Delta t^e_i}. \tag{14}$$

Value of Δt^e is independent with time increment for solution of plastic problem. The velocity of any point on the tool surface is the sum of its velocity as a rigid body plus the velocity of its elastic deformation v_j in the same point. Thus synchronous displacement of workpiece and tool surfaces is guaranteed. With such approach it is not necessary to combine all deformed bodies into a single system that may significantly increase the simulation time. Even though with this approach we get additional inaccuracy caused by the use of the load from previous configuration the error is supposed to be insignificant due to use of small time increments. Some examples of solving of coupled problems of metal forming using this approach can be found in [5].

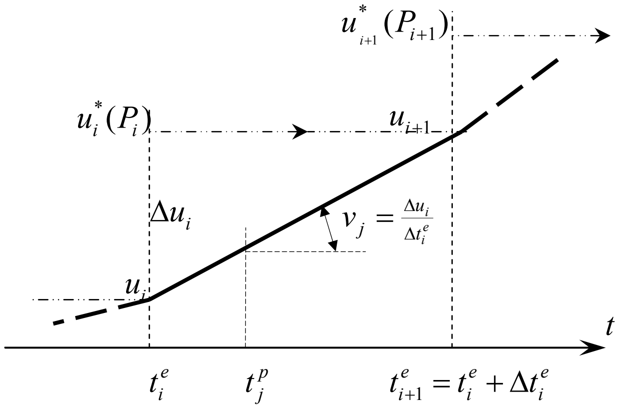


Fig. 1. Schematic diagram for solution of couple elastic-plastic deformation problem.

The simulation of the material flow in the program is performed within a so-called simulation domain that is the volume of the extruded material that partially fills the container and completely fills the inner space of the die assembly up to the exit from the bearing. The mesh inside the domain is built using tetrahedral elements. The quality of the finite element mesh is critical to obtain accurate results. Mesh of insufficient density or with too big a gradient of the element size may cause non-convergence problem and deteriorate the quality of the simulation. It is especially critical if the mesh has improper density distribution at the entrance to the bearing area where the most intensive deformation takes place. In QForm-Extrusion such mesh optimisation is performed automatically without user intervention [6].

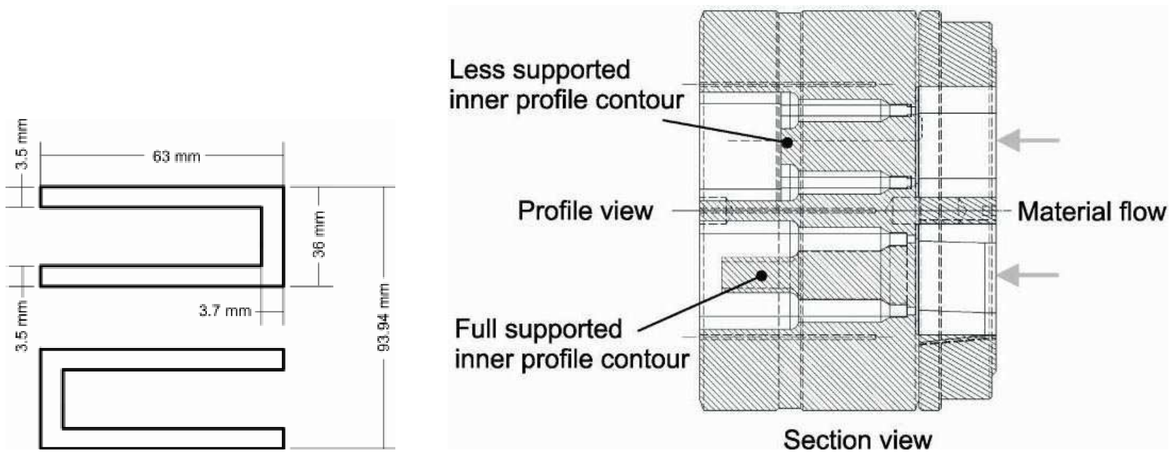
For accurate prediction of the material flow in extrusion process it is also necessary to take into account realistic friction and heat transfer conditions between extruded material and the tooling set. Numerous experimental and theoretical studies show that friction traction on the interface between the tool and deformed material can be represented as a combination of adhesive friction force and the force that is required to deform surface asperities. Consequently depending on the value of the normal contact stress it is necessary to apply different mechanisms of friction as it is explained in our work [7].

The influence of the die deformation on the material flow

The numerical model described above has been tested to find out the influence of the die deformation on the material flow. Die deflexion is difficult to measure and special dedicated laboratory tests are to be performed. One of such tests has been done as a case study for the Extrusion Conference and Benchmark ICEB 2009 and it has been reported in [8] where the data summary and experimental results can be found. Using these source data we have done the simulation for rigid and deformable die. The profiles sketch and the tooling set drawing are shown in Fig. 2.

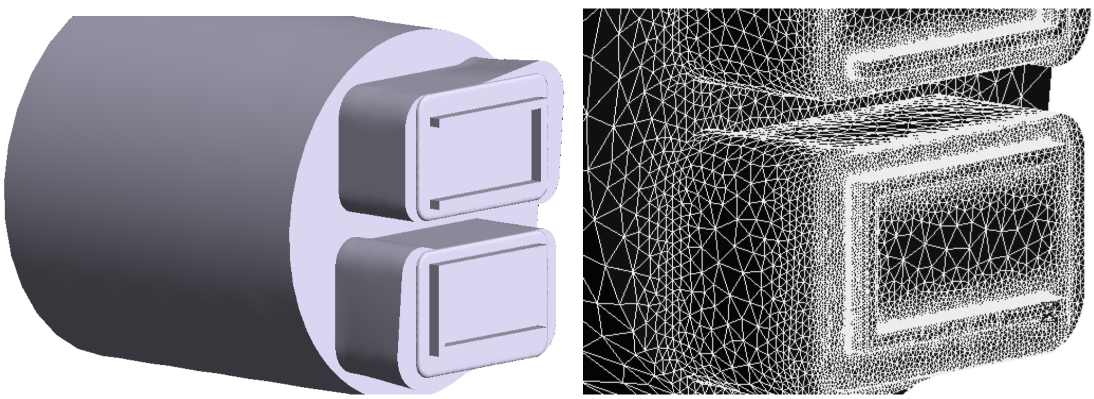
As seen from the drawings both profiles are identical and are placed using rotational symmetry on the die plate. Thus there are no reasons for the material to flow differently through both orifices except it may be caused by different deformation of the die within them. This may happen because one of the tongues intentionally has been done with longer support than the other. In Fig. 2, b these two tongues are marked as “less supported” and “fully supported” ones. The experiment has shown the difference in the displacement of the tongues about 0.5 mm with respect to each other that potentially may cause the difference in material flow [8]. The solution domain and the finite element mesh used for the simulation are shown in Fig. 3.

The displacement distribution in the die obtained by simulation is in Fig. 4. It is clearly seen that both tongues deform differently. Moreover, each tongue has different displacement on its container side that is close to bearing area comparing to its outlet side where the experimental measurement of the deflection has been actually done. Meanwhile overall deflection of the die is probably less important than local distortion of the bearing that actually controls the material flow (Fig. 4 c).



(a) (b)

Fig. 2. The scheme of the profiles used for the test (a) and crosscut of the die done through the tongues showing different support conditions (b). Both pictures are taken from [8].

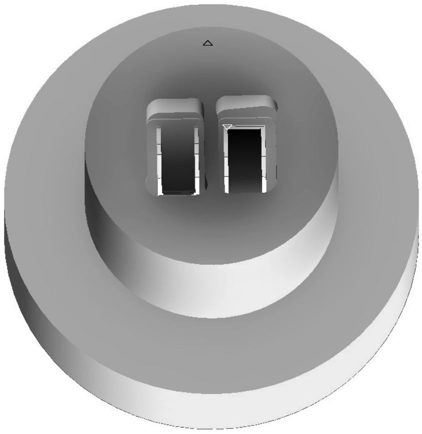


(a) (b)

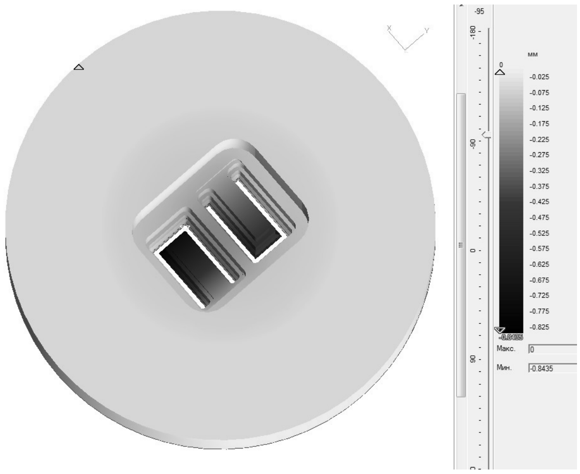
Fig. 3. The simulation domain used for the test (a) and the fragment of FE mesh at the beginning of the simulation (b).

Opposite sides of the bearing have different displacement and they slightly shift with respect to each other. The result of this deformation is variation of the bearing angle and change of "effective" bearing length. This alteration of actual bearing shape may influence the material flow conditions in both channels that in our case are different due to different tongue support.

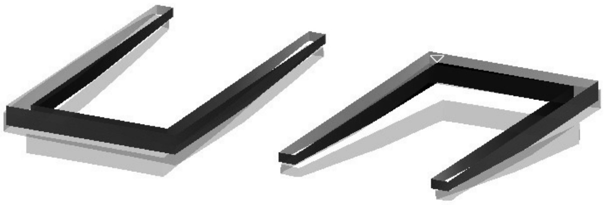
To check how effectively the coupled numerical model of extrusion may detect the influence of the die deformation on the material flow the test described above has been simulated two times, i.e. once using the rigid die and secondly with elastically deformable die using coupled model. In the first case with the rigid die, as it can be expected, both profiles flow similarly with just slight bent towards each other. It is important to notice that in this case there is no bend of the profile within its symmetry plane (see Fig. 5 a). On the other hand as soon as the simulation has been performed using the deformable die the profile with less supported tongue started to flow with the bent towards its bridge as shown in Fig. 5 b.



a)



b)

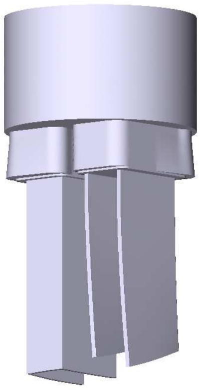


c)

Fig. 4. The axial displacement of the die in mm shown from the container side (a) and from the outlet side (b) and local displacement of the bearing area (c). Colour scale shows the value of the displacement while pink contour in (c) is the deformed shape of the bearing magnified for better visibility.

The same bending direction of the profile going from the orifice with less supported tongue has been reported by the authors of the experimental work [8] (compare pictures on Fig. 5 b and c) even though it is difficult to estimate their correspondence quantitatively because no information about the bending radius is available. Nevertheless we can conclude that die deformation may cause some effect on material flow and taking it into account in simulation by means of coupled model provides higher accuracy of the numerical results.

a)



b)

c)

Fig. 5. Simulation of the test extrusion: with the rigid die both profiles go straight (a); with deformable die one profile bends (b); photo of the experiment [8] with one profile bending (c).

This effect may not always be significant and probably in many cases the simulation with the assumption that the die is rigid provides sufficient accuracy for practice. Meanwhile in some cases when the die has long tongues or in case of hollow profiles the mandrels are supported by narrow and relatively flexible bridges the die deformation may be critical. In latter case it is impossible to achieve the simulation accuracy required by industrial practice without use of coupled modelling as it has been illustrated in present work. Further investigation of the problem for more complex solid and hollow profiles is still to be done.

Conclusions

1. Numerical model used in QForm-Extrusion program has been enhanced to include coupled simulation of the material flow and die deformation during extrusion process.
2. The simulations show that die deformation causes alteration of the bearing area and by these means may influence the material flow.
3. The model and the program have been tested using the case with available experimental data on die deflection and profile shape and the simulation has shown the same bending of the profile presumably caused by bigger deformation of the less supported tongue.

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Material Forming ESAFORM 2012
10.4028/www.scientific.net/KEM.504-506

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