

However, depending on the geometry of the extrusion tooling (for example in the bearing region), the deformation of the material may be relatively small, and elastic effects may locally play a non-negligible role. In that case, general solute-dependent elasto-viscoplastic constitutive models based on the Sellars-Tegart law can be used^[8].

Aluminum alloys in the range of considered temperature [400°C-580°C] can be modeled by using fluid models with pseudo-plastic rheological properties. Temperature and rate-of-deformation dependent viscosity laws are introduced in the momentum equation. Conservation of mass is imposed through the incompressibility constraint, while the evolution of temperature with time is derived from the conservation of energy.

Plane-strain slip-line field theory^[13] and upper bound analysis^{[6],[12]} have been generally used in the past to numerically investigate the mechanics of extrusion. With the advent of powerful computer resources, most refined simulations are now based on flexible finite element methods,^{[8],[14],[16]} although developments with the upper-bound method have been carried out in particular three-dimensional geometries^[6]. This method may be considered as an efficient alternative to heavy FEM simulations.

Friction and slippage of the materials on the neighboring walls in the bearing section is a very important aspect to be taken into account in order to obtain a suitable computational model^{[1],[11],[15]}.

Model Description

To model the aluminum flow through the tooling, five unknown quantities have to be predicted: three components of velocity, pressure and temperature. Three conservation equations are considered to obtain the equivalent fluid model. Conservation of mass is obtained by the continuity equation, which enforces a divergence-free velocity field:

$$\nabla \cdot \vec{v} = 0$$

Since the ram speed is low enough, Stokes equation is used for momentum conservation:

$$\nabla \cdot (-p\vec{I} + 2\mu(\|\overline{\overline{D}}\|, T)\overline{\overline{D}}) = 0$$

Temperature is determined by solving the energy equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p (\vec{v} \cdot \nabla) T - \nabla \cdot (k \nabla T) - 2\mu(\|\overline{\overline{D}}\|, T)\overline{\overline{D}} : \overline{\overline{D}} = 0$$

In the previous set of equations, the quantities $\overline{\overline{D}}, \vec{I}, \vec{v}, T, \rho, C_p, k, \mu$ respectively ,

denote the rate-of-strain tensor, identity tensor, velocity, temperature, density, heat capacity, thermal conductivity, and viscosity. The viscosity is a function of temperature and magnitude of the rate-of-strain tensor ($\|\overline{\overline{D}}\| = \sqrt{2D_{ij}D_{ji}}$).

The viscosity is obtained by fitting parameters of the equation:

$$\mu(\dot{\phi}, T) = A \exp(-\alpha(T - T_{ref}))\dot{\phi}^n$$

to existing data from hot torsion tests^[2]. The parameters n and α must be considered as functions of temperature to obtain good fits.

The flow stress k_f and strain rate $\dot{\phi}$ are related by the equation:

$$k_f = 3\mu\dot{\phi}$$

These equations have been solved by the FEM^[3]. A weak (Galerkin) formulation is used to transform the previous set of equations into integral equations, which are discretized in space with classical low-order finite elements^[3] and in time with finite difference schemes. A decoupled technique is used to solve the overall set of equations. The mass-momentum set of equations is first solved with a prescribed temperature distribution to obtain the pressure and velocity fields using either a Picard (fixed-point) or a classical Newton-Raphson iterative procedure. Then the produced velocity field is inserted in the energy equation via the convection and heat source terms, which is solved for the temperature field. These two steps are carried out until convergence criteria on the various fields are satisfied. A specific FEM environment, optimized to obey specific requirements (quick meshing and CPU time, user friendliness) have been developed on the basis of the Djinn-Phys^[4] finite element library, whereas the necessary validation and benchmark procedures were realized with the commercial program POLYFLOW^[9].

Principle of the Experimental Validation and Model Calibration

The profile exit velocity can easily be observed, whereas the velocity field into the die is difficult to measure. Here it is assumed that the measurement of pressure and temperature at some critical positions in the die are sufficient to validate the model.

The model validation and calibration proceed in the following standardised manner:

1. Equip specific extrusion tools with measurement devices such as thermocouples and pressure gauges, located at various crucial positions (internal surface of the weld chamber, recipient and bearings). The measurements are performed over several press cycles.

2. Repeat the experiments under further process conditions (example: by varying the billet temperature, initial die temperature, extrusion speed, alloy composition, etcetera. Most important is to check the effect of changing geometrical parameters (for example, profile thickness, weld chamber height, bearing lengths).

3. Perform FEM press cycle simulations under the same conditions.

4. Compare transient measurements with results of simulations for a given tool and well-defined process conditions (one series of press cycles).

5. Perform comparisons between cycles corresponding to different process conditions or tool geometries. This enables one to enlighten dependencies of quantities such as for example the extrusion pressure and temperature as functions of bearing length, profile thickness, weld chamber height, billet temperature, and extrusion speed. In the case of hollow profiles, the tube geometries are particularly adequate to quantify such types of dependencies because of their simplicity.

Experimental Validation

In the example presented here, pressure and temperature have been measured. The measured *pressure data* are:

- ram pressure evolution over the press cycles;
- pressure within the weld chamber, measured by elastic steel capsules' deformation which are being specially inserted for that purpose, as described in a previous paper^[18]. The measured *temperature data* are:
 - the profile exit temperature;
 - the temperature at various positions within the tools. For that purpose the tools have to be instrumented with thermocouples, as schematized in Figure 1.

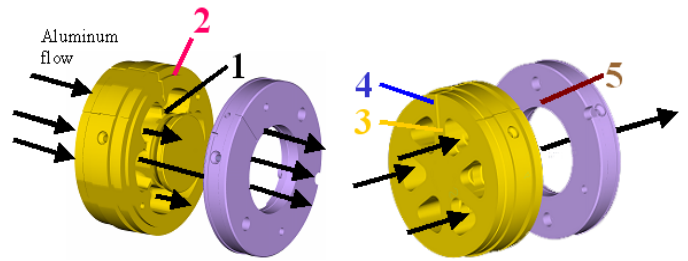


Figure 1. Instrumented tube (\varnothing 250mm) die. Thermocouples are inserted at positions 1 through 5

First, the model results are being checked over a given series of cycles (given tool geometry; given process conditions). Transient measurements are compared with computations (step four of the validation procedure). Figures 2 and 3 respectively show plots of the computed and measured evolution of temperature at locations 1 through 5 in the die (see Figure 1 for reference), and of the ram pressure for four tube extrusion cycles. In the present example the ram speed was varied from 1.7 mm/s (first cycle) up to 3.0 mm/s (fourth cycle). The two intermediate cycles correspond to 2.3 mm/s.

Finally, the model results are being checked by comparison with experiment for different process and geometry conditions (step five of our validation procedure). As an example, the effect of tube thickness on pressure and profile exit temperature is presented in figure 4. The comparison procedure is being repeated for as many different cases as possible (different dies, different process conditions), thus leading to a reliable model calibration. This is a necessary condition for integrating the 3-D FEM within the industrial environment, and for getting reliable and realistic predictions.

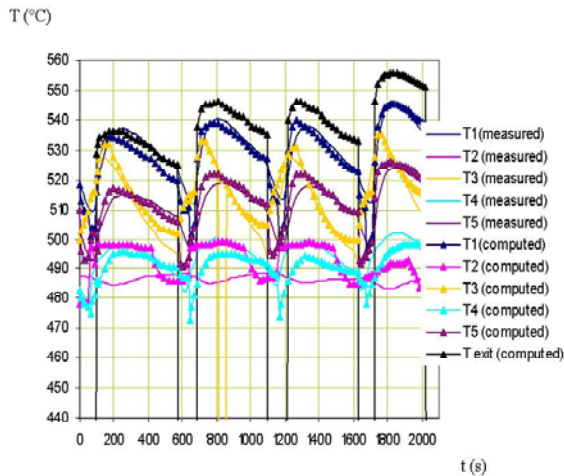


Figure 2. Measured and computed temperatures at various locations in the press. Locations of temperatures gauges are indicated in Figure 1

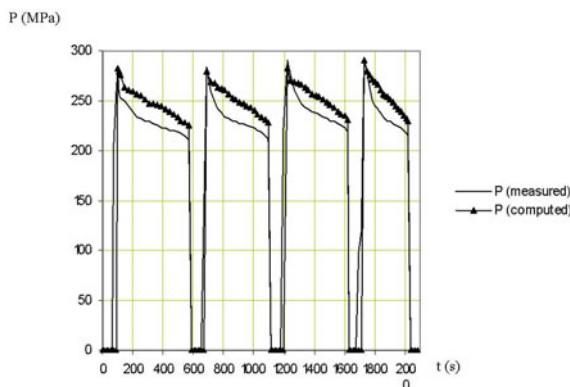


Figure 3. Measured and computed ram pressures

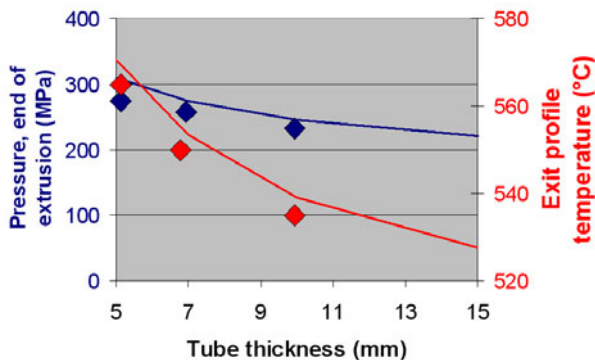


Figure 4. Measured (curves) and computed (dots) profile exit temperature (red) and ram pressure (blue), shortly before the end of typical extrusion cycles.

INTEGRATION OF FLOW SIMULATION IN DIE CONCEPTION

The validation procedure discussed in the precedent section permits continuous improvement of the 3-D model reliability. However, as such, it is not sufficient for integrating a numerical approach in the die conception and fabrication processes on industrial sites, and to obey schedules imposed by production requirements. The main problems are the following:

1. The amount of time needed for the preparation of the 3-D FEM mesh.
2. The computer time needed to solve the 3-D flow problem, especially in the case of complex geometries and multiple extrusion cycles.

To overcome those difficulties, specific methods which we call “*dual grid alternate algorithm*” and “*generalized FEM upper bound method*” have been developed. The aim is to reduce preparation and computational times, thus enabling utilization of 3-D flow simulation in die conception and fabrication.

The Dual Grid Alternate Algorithm

To realize quick meshing (less than one working day) standard CAD integrated mesh generators are often employed. But in the case of extrusion flow simulation, this is not possible *a priori*, because the CAD integrated automatic meshing algorithms do not guarantee the generation of adequate FEM meshes. Indeed, the difficulty is to obtain 3-D meshes of which nodes coincide at the interface between the tooling and aluminum. In fact, one generally cannot avoid meshing the tooling system, because the thermal losses through the die are of crucial importance: ignoring them leads in many cases to overestimate temperature and underestimate pressure and ram force. Therefore, two main regions have to be meshed: the aluminum flow region, and the tooling system.

Commercial mesh generators^[19] can be employed in order to implement meshes which coincide at the interface between both regions. The typical mesh generation time is along the order of one day to two weeks, depending on the geometrical complexity. In the production phase, such an approach is not usually possible because of the tight schedules that are imposed.

To overcome this problem, a so-called “*dual grid alternate algorithm*” was developed. Its principle is the following:

- both the aluminum flow region alone and the full tooling system are meshed separately, employing a standard CAD integrated mesh generator ;

- the connection between both regions is realized through a procedure which we call “*dual grid algorithm*.” At the interface between aluminum and tool, temperature values are automatically interpolated between the nodes of both grids during the FEM computation.

The method has been validated for multiple press cycles by comparison with a standard approach. Employing the dual grid alternate algorithm generally permits a reduction in the mesh generation time to less than one working day.

The Mixed FEM Upper Bound Method.

Although quick meshing is necessary, it is not sufficient for integrating the 3-D numerical approach in the die conception and fabrication processes. The FEM computation of flow problem may take up to several days CPU time on standard work stations, especially in the case of multiple extrusion cycle computations in complex 3-D geometries. As mentioned in the first chapter, as an efficient alternative to heavy FEM-based simulations, the upper-bound method has been employed, in particular three-dimensional geometries^[6]. The upper-bound method, lacks flexibility, and is much too cumbersome to apply in the case of complex 3-D geometries. The upper bound theorem^[12], however, can be employed in view of performing the FEM iterations quickly, for example, by the following procedure:

- compute, by FEM, a “*pseudo velocity field*” obeying the requirements of the upper bound theorem. The pressure field is obtained on the basis of the momentum equation and constitutive viscosity law ;

- perform transient thermal time steps in a decoupled manner.

We call this approach “*mixed FEM upper bound method*,” because it simultaneously takes advantage of both the upper bound theorem and of FEM, thus leading to tractable computational times.

CONCLUSIONS AND PROSPECTS

FEM simulation of 3-D flow and temperature evolution during extrusion cycles is being integrated at production sites for extrusion tool conception and fabrication. The model has been

validated and calibrated by comparison with measurements of pressure and temperature in various process conditions. The development of specific methods and algorithms have allowed reduction in both the geometry preparation time (FEM mesh), and the CPU time, so that the schedules imposed by production can be obeyed. An example of a quickly computed field is given in Figure 5.

Nowadays FEM simulation permits validation, then to optimization of *a priori* given tool concept. Before starting the simulation, an initial tool CAD has to be realized. In future, it will be desirable to integrate flow simulation early in the conception phase, and couple it directly with the CAD design itself.

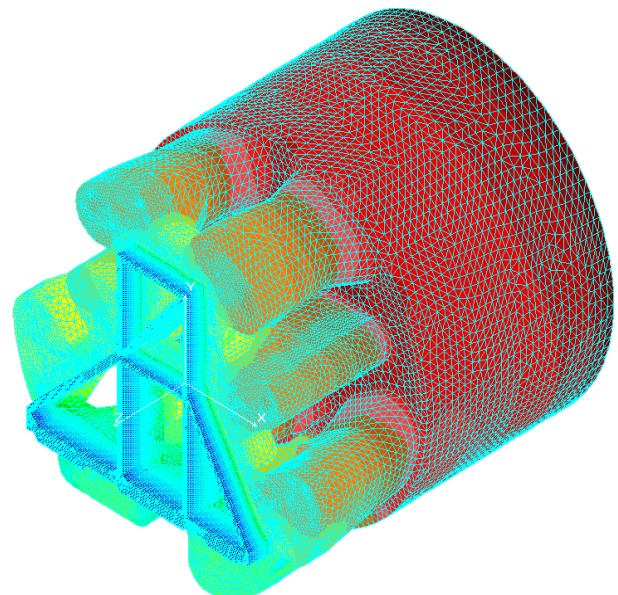


Figure 5. Example of aluminum pressure field into the recipient and die

ACKNOWLEDGMENTS

This development has been funded by the Commission pour la Technologie et l’Innovation (CTI), of which support is gratefully acknowledged, and promoted by Prof. M.O. Deville from EPFL. A. Brunetti and O. Nanchen from Alcan Inc. should also be warmly thanked for designing and installing the measurement devices, as well as collecting the experimental data.

REFERENCES

1. Abtahi S.; “Friction and Interface Reactions on the Die Land in Thin-Walled Extrusion,” Ph. D. Thesis, *Department of Machine Design and*

- Material Technology*, Norwegian Institute of Technology, Trondheim, Norway, 1995.
2. Akeret, R., H. Jung and G. Scharf; "Atlas of Hot Working Properties of Nonferrous Metals," Vol. 1, Deutsche Gesellschaft für Metallkunde (DGM), 1978.
 3. Crochet, M. J.; A. R. Davies and K. Walters, "Numerical Simulation of non-Newtonian Flow," *Rheology Series 1*, Elsevier, Amsterdam, 1983.
 4. Massé, P.; Djinn-Phys User's Guide, *Institut National Polytechnique de Grenoble*, France.
 5. Holthe, K., and S. Tjøtta; "The Heat Balance During Multiple Press Cycles", *Proceedings of the Sixth International Extrusion Technology Seminar*, Vol. 1, 387-392, Chicago, Illinois, May 1996, the Aluminum Extruders Council and The Aluminum Association.
 6. Kakinoki, T., K. Katoh and M. Kiuchi, "Application of the Upper Bound Method to Extrusion Die Design," *Proceedings of the Sixth International Extrusion Technology Seminar*, Vol. 2, 5-9, Chicago, Illinois, May 1996, the Aluminum Extruders Council and The Aluminum Association.
 7. Kobayashi, S., S. I. Oh and T. Altan, "Metal Forming and the Finite-Element Method," *Oxford University Press*, Oxford, UK, 1989.
 8. Lof, J.; "Developments in Finite Element Simulations of Aluminium Extrusion," Ph.D. Thesis, *Department of Mechanical Engineering, University of Twente*, Twente, The Netherlands, 2000.
 9. Polyflow User's Guide, Fluent Inc.
 10. Rubin, M.B. and A. L. Yarin, "On the Relationship between Phenomenological Models for Elasto-Viscoplastic Metals and Polymeric Liquids", *Journal of Non-Newtonian Fluid Mechanics*, Vol. 50, 1993, 79-88. (see also *Journal of Non-Newtonian Fluid Mechanics*, Vol. 57, 1995, 321 (corrigendum)).
 11. Saha, P.K.; "Thermodynamics and Tribology in Aluminium Extrusion," *Wear*, Vol. 218, 1998, 179-190.
 12. Sheppard, T., "Extrusion of Aluminium Alloys," *Kluwer Academic Publishers*, Dordrecht, The Netherlands, 1999.
 13. Støren, S., "The Theory of Extrusion - Advances and Challenges," *International Journal of Mechanical Sciences*, Vol. 35, 1993, 1007-1020.
 14. Van Rens, B.J.E., "Finite Element Simulation of the Aluminium Extrusion Process, Shape Prediction for Complex Profiles," Ph.D. Thesis, Materials Technology Institute, Eindhoven Institute of Technology, Eindhoven, The Netherlands, 1999.
 15. Valberg, H. and T. Malvik, "Metal Flow in Die Channels of Extrusion Investigated by an Experimental Grid Pattern Technique," *Proceedings of the Sixth International Extrusion Technology Seminar*, Vol. 2, 17-28, Chicago, Illinois, May 1996, the Aluminum Extruders Council and The Aluminum Association. .
 16. Zhou, M., L. Li and J. Duszczyc, "3-D FEM Simulation of the Whole Cycle of Aluminium Extrusion Throughout the Transient State and the Steady State Using the Updated Lagrangian Approach," *Journal of Materials Processing Technology*, Vol. 134, 2003, 383-397.
 17. Zienkiewicz, O.C., "Flow Formulation for Numerical Solution of Forming Processes." In: Pittman, J.F.T. ; Zienkiewicz, O.C. ; Wood, R.D. and Alexander, J.M., *Numerical Analysis of Forming Processes*, Wiley, Chichester, 1984, 1-44.
 18. Bourqui, B., C. Moulin, A. Huber, A. Brunetti, and Y. Krähenbühl, "Improved Weld Seam Quality Using 3-D FEM Simulation in Correlation with Practice," *Proceedings of the First EEA Extruders Division Congress*, Brescia, Italy, 2002.
 19. Hypermesh User's Guide, Altair Engineering.