Fluid-Structure Interaction in Aluminum Extrusion

Introduction

In massive forming processes like rolling or extrusion, metal alloys are deformed in a hot solid state with material flowing under ideally plastic conditions. Such processes can be simulated effectively using computational fluid dynamics, where the material is considered as a fluid with a very high viscosity that depends on velocity and temperature. Internal friction of the moving material acts as a heat source, so that the heat transfer equations are fully coupled with those ruling the fluid dynamics part. This approach is especially advantageous when large deformations are involved.

This model is adapted from a benchmark study in Ref. 1. The original benchmark solves a thermal-structural coupling, because it is common practice in the simulation of such processes to use specific finite element codes that have the capability to couple the structural equations with heat transfer. The alternative scheme discussed here couples non-Newtonian flow with heat transfer equations. In addition, because it is useful to know the stress in the die due to fluid pressure and thermal loads, the model adds a structural mechanics analysis to the other two.

The die design is courtesy of Compes S.p.A., while the die geometry, boundary conditions, and experimental data are those of Ref. 1.

Note: This model requires the Chemical Engineering Module, the Heat Transfer Module, and the Structural Mechanics Module. In addition, the model uses the Material Library.

Model Definition

The model considers steady-state conditions, assuming a billet of infinite length flowing through the die. In the actual process, the billet is pushed by the ram through the die and its volume is continuously reducing.

Figure 3-34 shows the original complete geometry with four different profiles. To have a model with reasonable dimensions, consider only a quarter of the original geometry. The simplification involved in neglecting the differences between the four profiles does not affect the numerical scheme proposed. Figure 3-35 shows the resulting model geometry.

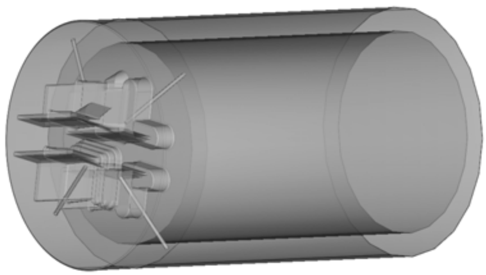

Figure 3-34: Original benchmark geometry.

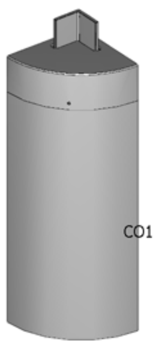

Figure 3-35: Quarter of the original geometry considered in the model.

MATERIAL PROPERTIES

The documentation associated with the benchmark (Ref. 1) serves as the data source for properties of the two main materials: AISI steel for the die and the container (the ram here is not considered) and aluminum for the billet.

Structural Analysis

Because only the steel part is active in the structural analysis, consider a simple linear elastic behavior where the elastic properties are those of the material H11 mod (AISI 610) that can be found in the COMSOL Multiphysics Material Library.

Heat Transfer Analysis

The documentation associated with the benchmark suggested to use for aluminum and for steel the following properties:

ALUMINUM	VALUE	DESCRIPTION
K_{al}	210 N/(s·K)	Conductivity
ρ_{al}	2700 kg/m^3	Density
C_{pal}	2.94 N/(mm^2·K)/ρ_{al}	Specific heat

STEEL	VALUE	DESCRIPTION
K_{fe}	24.33 N/(s·K)	Conductivity
ρ_{fe}	7850 kg/m^3	Density
C_{pfe}	4.63 N/(mm^2·K)/ρ_{fe}	Specific heat

Non-Newtonian Flow

The properties of the aluminum were experimentally determined and then checked using literature data for the same alloy and surface state. However the benchmark proposes an experimental constitutive law, suited for the structural mechanics codes usually used to simulate such processes, in the form of the flow stress data. For this model this requires a recalculation of the constitutive law to derive a general expression for the viscosity. The equivalent von Mises stress, σ_{eqv}, can be defined in terms of the total contraction of the deviatoric stress tensor as

$$\sigma_{eqv} = \sqrt{\frac{3}{2}\tau:\tau}$$

or, using $\tau = 2\eta\dot{\varepsilon}$ where $\dot{\varepsilon}$ is the strain rate and η is the viscosity, as

$$\sigma_{eqv} = \sqrt{6\eta^2\varepsilon:\varepsilon} \qquad (3\text{-}1)$$

Introducing the equivalent strain rate

$$\dot{\phi}_{eqv} \equiv \sqrt{\frac{2}{3}\varepsilon:\varepsilon}$$

Equation 3-1 can be expressed as

$$\sigma_{eqv} = 3\eta\dot{\phi}_{eqv}$$

The strain rate tensor is defined as (Ref. 2)

$$\dot{\varepsilon} = \frac{\nabla \mathbf{u} + (\nabla \mathbf{u})^T}{2} = \frac{1}{2}\dot{\gamma}$$

Equation 5-26 on page 142 in the *Chemical Engineering Module User's Guide* states that the shear rate $\dot{\gamma}$ is defined as

$$\dot{\gamma} = |\dot{\gamma}| = \sqrt{\frac{1}{2}\dot{\gamma}:\dot{\gamma}}$$

so that

$$\phi_{\mathrm{eqv}} = \frac{1}{\sqrt{3}}\dot{\gamma}$$

The flow rule

$$\sigma_{\mathrm{eqv}} = \kappa_{\mathrm{f}}$$

states that plastic yielding occurs if the equivalent stress, σ_{eqv}, reaches the flow stress, κ_{f}. The viscosity is defined as (see Ref. 2 for further details)

$$\eta = \frac{\kappa_{\mathrm{f}}}{3\phi_{\mathrm{eqv}}}$$

The organizers of the benchmark propose specific flow-stress data expressed in terms of a generalized Zener-Hollomon function

$$\eta = \frac{\operatorname{asinh}\left(\left(\frac{Z}{A}\right)^{\frac{1}{n}}\right)}{\sqrt{3}\alpha\dot{\gamma}}$$

where $A = 2.39 \cdot 10^8\ \mathrm{s}^{-1}$, $n = 2.976$, $\alpha = 0.052\ \mathrm{MPa}^{-1}$, and

$$Z = \frac{1}{\sqrt{3}}\dot{\gamma}e^{\left(\frac{Q}{RT}\right)}$$

with $Q = 153$ kJ/mol and $R = 8.314$ J/(K·mol).

SOURCES, INITIAL CONDITIONS, AND BOUNDARY CONDITIONS

Structural Analysis

Because the model geometry is a quarter of the actual geometry, use symmetric boundary conditions for the two orthogonal planes. On the external surfaces of the die, apply roller boundary conditions because in reality other dies, not considered here, are present to increase the system's stiffness.

The main loads are the thermal loads from the heat transfer analysis and pressures from the fluid dynamics analysis.

Heat Transfer Analysis

For the billet, use a volumetric heat source related to the viscous heating effect.

The external temperature of the ram and the die is held constant at 450 °C. The ambient temperature is 25 °C. For the heat exchange between aluminum and steel, use the heat transfer coefficient of 11 N/(s·mm·K). Also consider convective heat exchange with air outside the profiles with a fixed convective heat transfer coefficient of 15 W/(m^2·K).

Apply initial temperatures as given in the following table:

PART	VALUE
Ram	380 °C
Container	450 °C
Billet	460 °C
Die	404 °C

Non-Newtonian Flow

At the inlet, the ram moves with a constant velocity of 0.5 mm/s. Impose this boundary condition by simply applying a constant inlet velocity. At the outlet, a normal stress condition with zero external pressure applies. On the surfaces placed on the two symmetry planes, use symmetric conditions. Finally, apply slip boundary conditions on the boundaries placed outside the profile.

Results and Discussion

The general response of the proposed numerical scheme, especially in the zone of the profile, is in good accordance with the experience of the designers. A comparison between the available experimental data and the numerical results of the simulation shows good agreement.

On the basis of the results from the simulation, the engineer can improve the preliminary die design by adjusting relevant physical parameters and operating conditions. For this purpose, the slice plot in Figure 3-36 showing the temperature field inside the profile gives important information. Furthermore, the combined streamline and slice plot in Figure 3-37 reveals any imbalances in the velocity field that could result in a crooked profile. A proper design should also ensure that different parts of the profile travel at the same speed. In Figure 3-38 you can see von Mises equivalent strain in the steel part considering the thermal load and also the pressure due to the presence of the fluid.

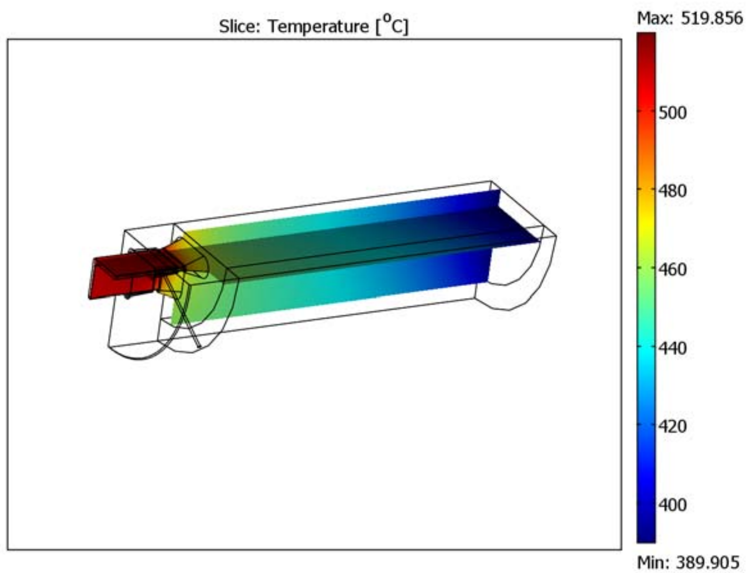

Figure 3-36: Temperature distribution in the billet.

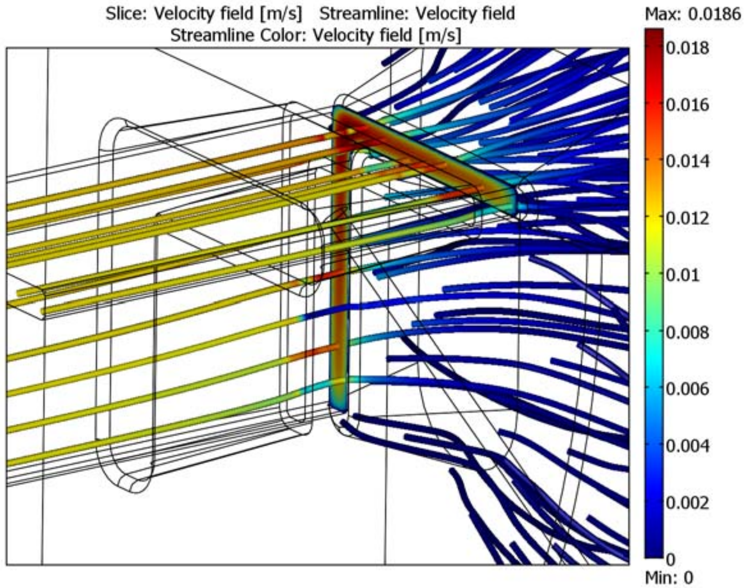

Figure 3-37: Velocity field and streamlines at the profile section.

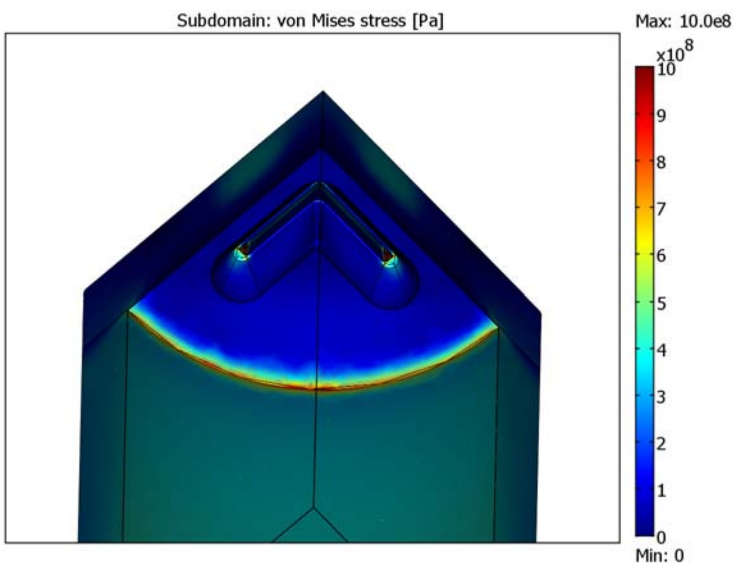

Figure 3-38: Equivalent von Mises distribution in the container.