Finite Element Modelling of Complex Thin Profile Extrusion

N. Biba[a], A. Lishny[b], S. Stebunov[b]

[a] *QuantorForm Ltd., 20 Church Road, Worcester, WR3 8NX, United Kingdom*
[b] *QuantorForm Ltd., P.O. Box 74, Ugreshskaya Street, 2, Moscow, 115088, Russia*

Abstract. The paper presents the development of the Finite Element model for simulation of thin aluminium profile extrusion of both solid and hollow shapes. The analysis has shown that the material flow in simulation is very dependent on the friction model. Experimental and theoretical studies show that friction traction on the interface between the tool and the deformed material can be represented as a combination of adhesive friction force and the force that is required to deform surface asperities. In aluminium extrusion we can clearly distinguish two different areas with respect to friction conditions. The first area covers the inner surface of the container, feeding channels and pockets. Here the contact pressure is very high and the deformation friction factor is close to 1. The second area is the bearing. In this area we deal with combinations of different friction models in sticking, sliding and transient zones. The sticking zone has predominantly deformation friction. It is situated at the entrance to the bearing and may extend when the bearing has a choke angle. Thus the lengths of these zones are also dependent on variation of the choke angle and actual thickness of the profile. To get these values the material flow problem is to be coupled with the simulation of the tools deformation. A series of experiments with specially designed tools have been done to investigate how the bearing length and choke angle may influence the extension of different friction zones and by these means vary the material flow pattern. The friction models have also been tested with industrial profiles of complex shapes and have shown good correspondence to reality.

Keywords: Metal forming, FEM, software, simulation, extrusion, aliminium, thin profiles.

INTRODUCTION

QForm-Extrusion is a special-purpose program for aluminium profile extrusion simulation that has been recently developed by QuantorForm Ltd. The software includes Lagrange-Euler model for simulation at a steady state stage [1, 2]. The Lagrange-Euler model is based on the assumption that the tool set is already completely filled and the domain of the material flow on the inside of the tool does not change. Thus the finite element mesh on the inside of the tool represents the space domain subject to simulation. This means that the mesh here is immovable while the material flows through it. The advantages and drawbacks of this method were analysed in monograph [3] where different types of elements were used to get the solution. This approach allows the program not to remesh the domain inside the tools but just to calculate the velocity of the nodes within it. On the other hand after passing through the orifice the free end of the profile increases its length very quickly with the progress of deformation. Due to non-uniform material flow the profile that leaves the orifice may bend, twist or buckle. The goal of the simulation is to predict this undesirable shape deterioration and to find ways to minimize it. Validation of the model was performed for load prediction, material flow pattern and temperature distribution using special model experiments and industrial practice. The developed approach for profile extrusion simulation has shown good results at the Benchmark tests in Bologna [4] and Dortmund [2].

SIMULATION OF EXTRUSION ON THE BASIS OF LAGRANGE-EULER APPROACH

The most important stage from a practical point of view is the quasi steady-state stage when the product shape and its properties are formed. During the quasi steady-state stage some parameters such as temperature and load may vary but this variation does not influence material flow considerably and in many cases it can be neglected.

Generally the source data for extrusion simulation include:

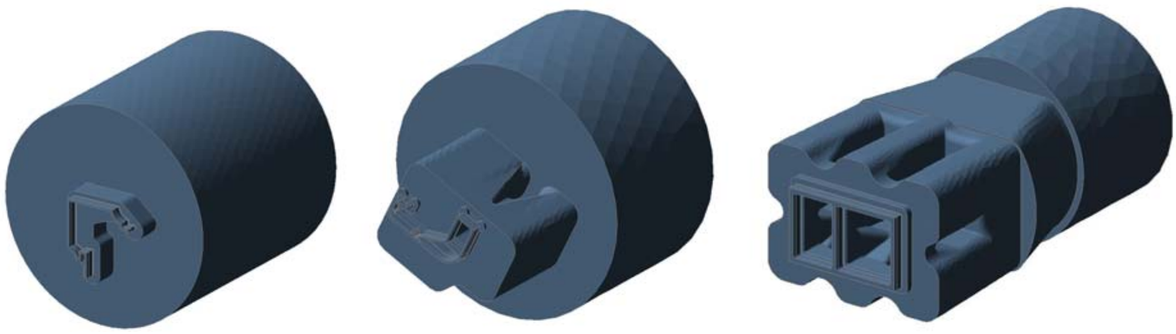
- The geometric models of the die set originally created in some Computer-Aided Design system.
- The properties of the extruded material (the flow stress and thermal properties).
- The conditions on the contact surface of the extruded material with the tools (friction, heat transfer coefficient, and temperature of the tools).
- The process parameters (initial temperature of the billet, extrusion speed and pulling force).

Simulation of the extrusion process is performed within a so-called simulation domain. The simulation domain 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. Let us consider typical die tooling arrangements for extrusion of solid and hollow profiles and how the tools are to be used to create the simulation domain.

The die set for solid profile extrusions generally includes the feeder, the die, the backer and the bolster. Sometimes there may be no feeder at all or the feeder and the die can be made as a single tool. In the case of a hollow profile extrusion, the tooling set includes the die mandrel, the die cap, the backer and the bolster. Semi hollow tooling design can be done according to open die or closed die scheme depending on the profile specifics.

In both cases the tooling set is eventually assembled with the container. Thus the extruded material fills the space inside the container and has contact only with the feeder and the die in case of a solid profile and with the die cap and the mandrel in case of a hollow profile extrusion. The other parts of the die assembly (the backer and the bolster) have no direct contact with the material and are not used to create the simulation domain. Their design and properties are only taken into account when simulating the die stress and deflection.

The simulation domain of typical solid and hollow profile extrusion is shown in Fig. 1 where we can distinctly see the volume of material that fills the container, the feeder with the pocket and the die respectively. In extrusions of profiles with large overall dimensions, the volume of the material inside of spreader is also to be included into the simulation domain as shown in Fig.3,c.



(a) (b) (c)

FIGURE 1. The simulation domain of a typical solid profile (a), hollow profile (b) and profile with spreader (c).

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 may cause non-convergence problems 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. While it is enough to have 2-3 elements across the extruded profile as it leaves the die, it is necessary to have at least 10 element layers across the deformation zone. Thus the finite element mesh is to be created iteratively adapting its density to the solution behaviour such as the velocity gradients at the entrance to the die orifice.

DESCRIPTION OF FRICTION MODEL IMPLEMENTED IN QFORM-EXTRUSION

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. Thus the expression for friction traction in general can be written as follows:

$$T = T_a + T_d\,. \tag{1}$$

Where

T is the total friction traction,

T_a is the force required to break the adhesive links

T_d is the force required to deform the asperities.

The adhesive friction component is caused by molecular links of different nature between the body surfaces and is dependent on the material's physical properties. The deformation component is required to deform the asperities and depends on the roughness of the surfaces, flow stress of the deformed material, contact normal pressure and sliding velocity. At high contact pressure the deformation component T_d is predominant while when the normal pressure is small the adhesive component is relatively more influential.

Let us express the adhesive friction stress τ_a as a product of some adhesive friction factor m_a and shearing flow stress S:

$$\tau_a = T_a / A = m_a \cdot S. \qquad (2)$$

Where A is the area of the contact.

Let us use constant friction law for deformation friction:

$$\tau_d = T_d / A = m \cdot S \qquad (3)$$

where m is conventional friction factor that takes into account only the deformation component of friction.

Thus the total friction stress τ can be represented as

$$\tau = (m_a + m)\, S \qquad (4)$$

In the case of aluminium forming, according to some sources, m_a can vary between 0.05 and 0.1 because of good adhesion of aluminium to steel. In aluminium extrusions we can clearly distinguish two different areas with respect to friction conditions. The first area covers the inner surface of the container, feeding channels and pockets (Fig.2,a). Here the contact pressure is very high and the deformation friction factor is close to 1. Due to additional effect of the adhesive friction the total friction traction can be bigger than shearing flow stress. This means that the metal sticks to the surface of the tooling set and sliding takes place inside the deformed material by intensive shearing deformation.

The second contact area is the bearing area that can be visible in Bearing Editor of QForm-Extrusion program (Fig. 2,b). In this area we can distinguish three zones with different friction models:

1. The sticking zone with predominantly deformation friction. It is situated at the entrance to the bearing and may extend when the bearing has a choke angle.
2. The sliding zone where deformation friction decreases.
3. The zone where the material may separate from the die due to small normal contact stress.

Relative dimensions of these zones depend on several parameters and may vary along the profile perimeter. The division of the bearing into zones and some of the relations between them have been experimentally proved by S. Abtahi [5]. Thus for every point along the profile perimeter the following parameters may influence the extent of the zones:

- Actual (effective) choke angle A_b
- Actual thickness of the profile R_p
- Velocity of the profile flow V_m.

The effective choke angle is the algebraic sum of the choke angle as it was originally manufactured in the die and the angle of the bearing surface inclination that appears due to tool deformation. The profile thickness also may vary due to the die deformation.

Thus to get the precise results of the material flow we need to take into account the variation of the effective choke angle and the actual thickness of the profile. To get these values the material flow problem is to be coupled with the simulation of the tool deformation. Now the friction model developed in QForm-Extrusion includes the influence of the elastic deformation of the tooling set on the effective angle and the profile thickness.

Such a complicated friction model cannot be expressed analytically thus it is realised as an iterative semi empiric algorithm. Firstly we simulate the material flow and solve the die deformation problem. Then we calculate effective choke angle A_b and actual profile thickness R_p at every point of the bearing perimeter and solve the material flow problem again. For every zone in every point of the bearing perimeter we calculate the friction stress depending on velocity, normal contact stress and flow stress.

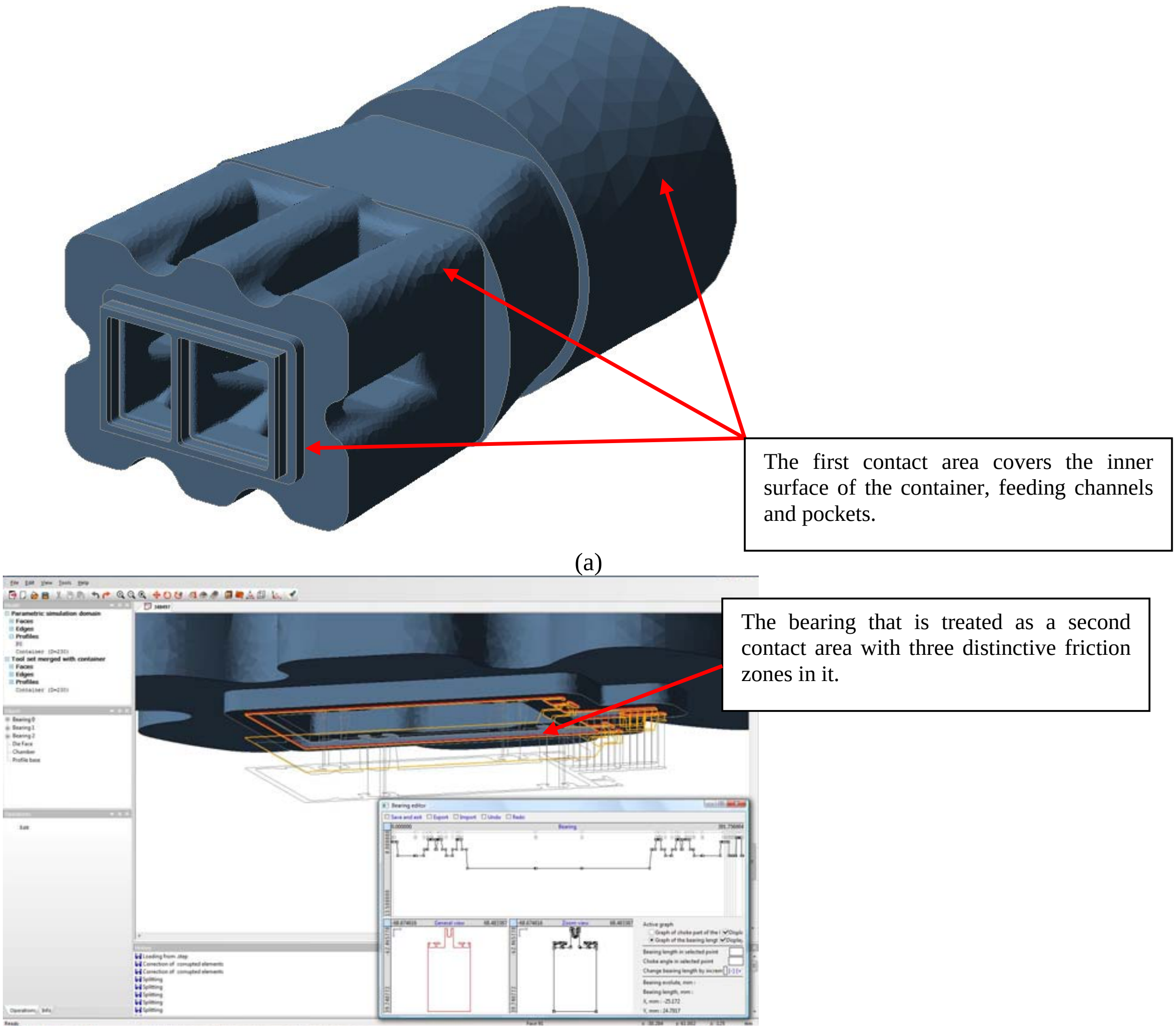


FIGURE 2. The first contact area (a) and second contact area as it is presented in the Bearing Editor of QForm-Extrusion program (b) on the surface of the simulation domain.

The presented method of friction realisation in our extrusion simulation program is quite universal and allows taking into account all the parameters of the friction phenomenon. It takes into consideration both the physical model of friction as well as the geometrical aspects caused by the die deformation. Now these parameters are calculated and the model works in full scale.

MODEL VERIFICATION BY SIMULATION OF INDUSTRIAL CASES

Industrial verification of the model was done using a wide range of solid and hollow profiles of different complexity with various extrusion ratios that are produced by Ekstek-Nord Ltd. (Belaya Kalitva, Russia). More than 15 profiles were investigated and three of them are presented in Table 1.

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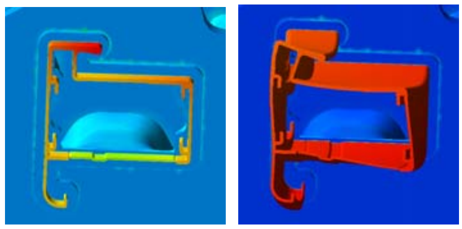
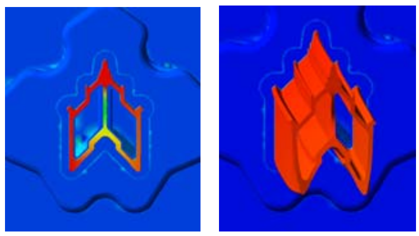
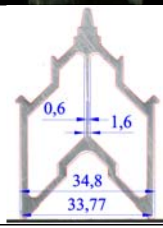
<table>
<caption>**TABLE 1.** Some examples of industrial tests for hollow profiles (with permission of Ekstek-Nord Ltd.)</caption>
<tr><th>Profile No</th><th>The simulation domain with finite elements mesh</th><th>Simulation results (the beginning and the end)</th><th>Photo of the real profile tip</th></tr>
<tr><td>1</td><td>
The bearing (enlarged)
</td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td>

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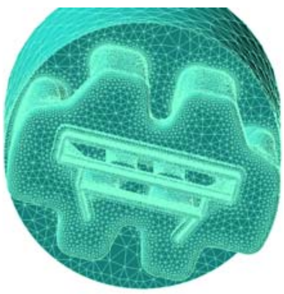
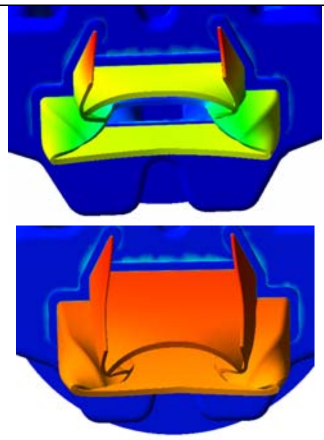
<tr><td>3</td><td></td><td></td><td></td></tr>
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It is impossible to measure the velocity distribution along the profile contour in a real extrusion. Thus the only way is to compare the shape of the front tip of a real profile with the shape of its front end predicted in simulation. The shape of the front tip in both cases clearly shows inequality of the velocity in different parts of the profile. There were several goals of such industrial investigation:

- Testing and improving the methods of the geometry data transfer from industrial system of die design into the simulation program.
- Estimation of the accuracy of the simulation.
- Use the results of the tests for further development of the numerical model and the software.

The results obtained in these tests have shown very good correspondence between the simulation and real extrusion as can be seen by comparing the shapes of the front tips for the profiles 1-3 in the Table 1. It is important to point out that the relative velocities of different parts of the profile may change with the progress of the extrusion process. For example, the lower web of Profile 1 at the beginning of the process is the slowest segment of the product but during the process it starts to flow faster than the other parts of the profile causing the shape formation very similar to one observed in the experiment.

The example of Profile 2 shows that the die design does not provide uniform material flow and the slowest segment is the central web of the profile. Even though with the extrusion progress the velocity difference becomes smaller it is still big enough to fulfill product quality requirements and definitely the die is to be redesigned to provide more material flow into its central part. The experimental shape of the front tip is very similar to one obtained in the simulation.

The experimental and simulation results are in good agreement for Profile 3 as well. Simulation and experiment both have shown the fastest flow of the vertical ribs of the profile causing specific shape deterioration. To correct this initial die design it is necessary to increase the cross-sectional area of the central feeding channel and to modify the length of the bearing along the profile.

Thus industrial verification has shown that the model provides accurate prediction of the material flow in extrusion of the complicated thin wall profiles that is sufficient for majority of practical applications. Further model development direction is coupling of the friction model and elastic deformation of the dies.

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