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Influence of Contact Friction Conditions on Thin Profile Simulation Accuracy in Extrusion

Sergey Stebunov[1,a], Nikolay Biba[2,b] and Andrey Lishnij[1,a]

[1]QuantorForm Ltd. 115088 P.O. Box 74, Moscow, Russia

[2]Micas Simulation Ltd., P.O. Box 4190, Stouport On Severn, Worcestershire, Dy13 0WU, UK

[a]info@qform3d.com, [b]nick@qform3d.com

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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 such as sticking and sliding and transient zones between them. 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.

Introduction

The further development of the extrusion simulation model has been done within the program QForm-Extrusion for the needs of the aluminium industry [1]. The software includes Lagrange-Euler model for simulation at a steady state stage [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 inside of the tool does not change. 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. The goal of the simulation is to predict this undesirable shape deterioration and to find ways to minimize it. The developed approach for profile extrusion simulation has shown good results at the Benchmark tests in Bologna [4] and Dortmund [2].

Meanwhile some cases of the most complex profiles with thin walls may have had slightly less accuracy in the results than are usually observed in our simulation practice and this has highlighted the necessity for more profound investigation. Experimental and theoretical studies show that the 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 [5]. To get the precise results of the material flow we took into account the variation of the effective choke angle and the actual thickness of the profile. To get these values the material flow problem was coupled with the simulation of the tool deformation.

Description of friction model implemented in the program

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.

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. 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. In this area we can distinguish three zones with different friction models:

- 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.
- The sliding zone where deformation friction decreases.
- 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 [6]. Thus for every point along the profile perimeter the following parameters may influence the extent of the zones:

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

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 the program 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 and actual profile thickness 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.

The presented method of friction realisation in the 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. More detailed description of the model can be found in our work [7].

Elastic deformation of the bearing zone in the die

The further analysis of the conditions in the bearing zone has been aimed towards finding the mechanism how the elastic deformation of the dies may influence the effective choke angle and how the profile thickness may vary due to the die deformation.

Fig.1 shows the elastic deformation of the die for simultaneous extrusion of two thin flat profiles of the same dimensions with the thickness 3.6 mm and the width 45 mm from AA6063. The half of the die is considered. The contact pressure that has been calculated by extrusion simulation has been applied as a boundary conditions for simulation of elastic deformation of the die cap. It was found that the small elastic deformation of the die causes significant changes of the choke angle in the bearing. It is also very important that the angle variation is very dependent on the bearing lengh. The angle of elastic inclination of the bearing surface is more than three times bigger in the case of the bearing length 12 mm comparing to the bearing length 6 mm.

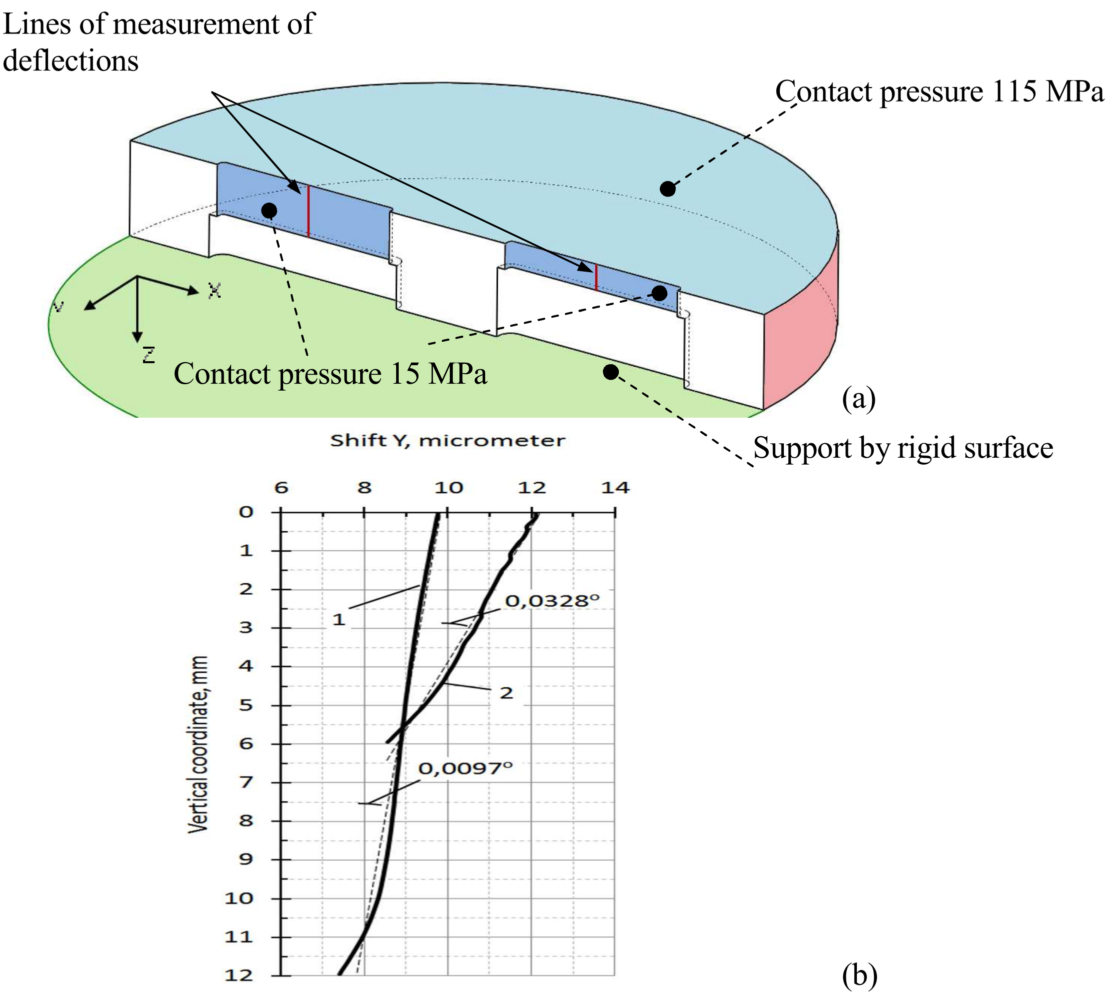


Fig.1 The boundary conditions (a) and the die deflection (b) in Y direction (Shift Y). Changing shape of the vertical line: 1- bearing 12 mm, 2 – bearing 6 mm; ——— calculation, ------- approximation

These results show that in many real industrial profiles we can expect significant variation of the actual bearing choke angle when the bearing length is varied along the profile perimeter. Thus to get the precise results of the material flow we have 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 the program includes the influence of the elastic deformation of the tooling set on the effective angle and the profile thickness. It is possible to use some pre-set values for them or get it from coupled solution of the tool deformation.

Elastic deformation of assembled tooling set

Typical set of the extrusion tools for solid and hollow profiles looks like the following sequence of the components: mandrel, die ring, die, backer, bolster, sub-bolster, pressure ring. Currently simulation of the complex assembled die set in the program is performed using the following simplifications:

- The contact die stress due to material flow in the rigid die is found by Lagrange –Euler approach and then it is used to simulate the stress and deformation of the tooling set.
- The assembled tooling set is considered as a merged solid body. The small relative radial displacement of the parts of the tooling set is considered as negligible. It is known that the tooling set is preloaded before extrusion process that reduces the radial movement of the dies.
- The coupled thermo-mechanical problem is not considered.

To estimate possible inaccuracy of such simplified approach for die strain and stress prediction several test simulations have been done. Such test simulations have been performed for the extrusion of hollow rectangular profile from AA6061. The contact pressure on the die surface varies from 50 to 420 MPa. The boundary conditions are shown in the Fig. 2.

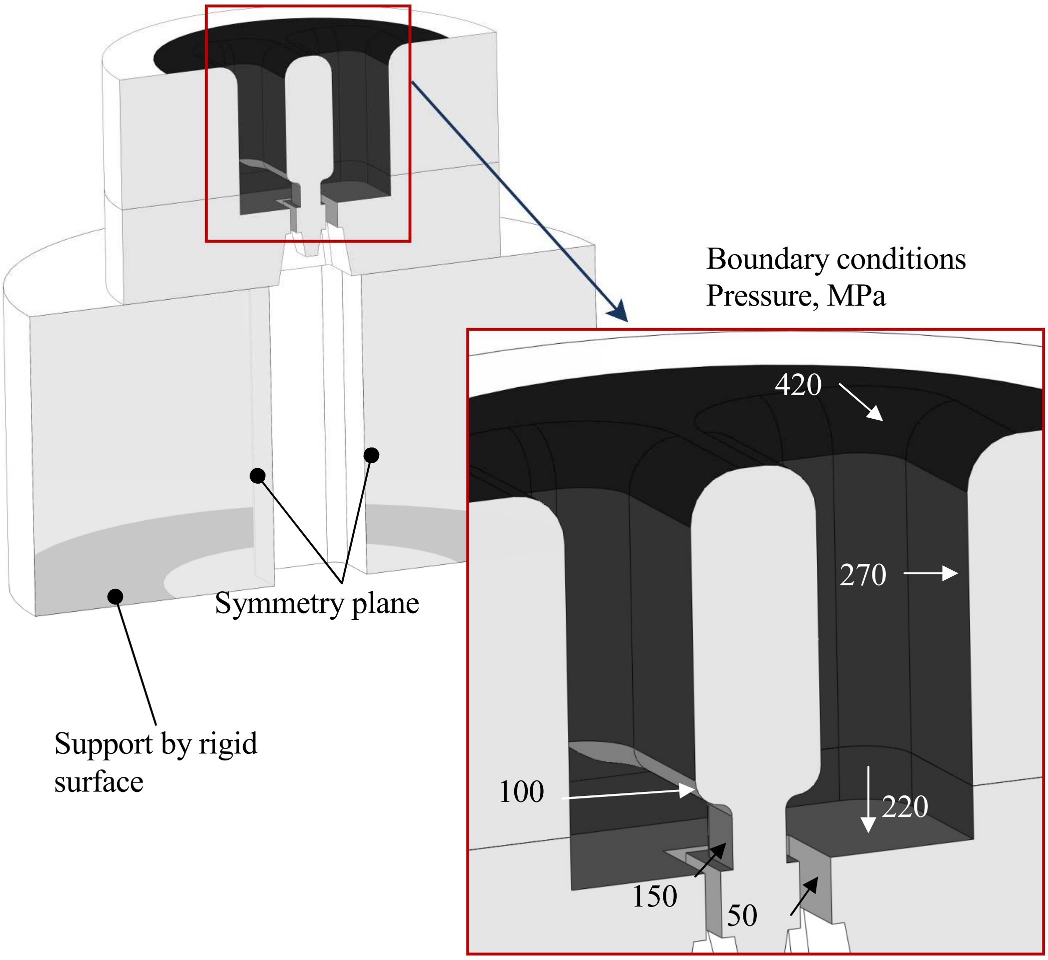


Fig.2 Die set simulation for extrusion of rectangular hollow profile made of alloy AA6061. Boundary conditions are shown

In the Fig. 2 is shown the half of the tooling set with specified plane of symmetry. It is supposed that the tooling set has a support by rigid surface along the contact with the pressure ring. The values of the contact pressure in MPa are shown in the zoomed fragment on the respective surfaces. In the Fig. 3a,b are shown the vertical and horizontal displacement for assembled tooling set. In the Fig.3c,d are shown the vertical and horizontal displacement for the merged single solid die. The solid die was simulated with the same boundary conditions as the assembled tooling.

The goal was to analyse how relative displacement of the tooling assembly parts may influence the deformation and inclination of the bearing surface. For this purpose two variants of assembled tooling set and a tooling set merged in a single solid body have been simulated. The die stress simulation that is shown in Fig.3 has been done by COSMOSWorks[1] that has the facilities to consider complex assemblies of the parts. The contact stresses were taken from the results of extrusion simulation through a rigid die by QForm-Extrusion.

[1] © Dassault Systemes

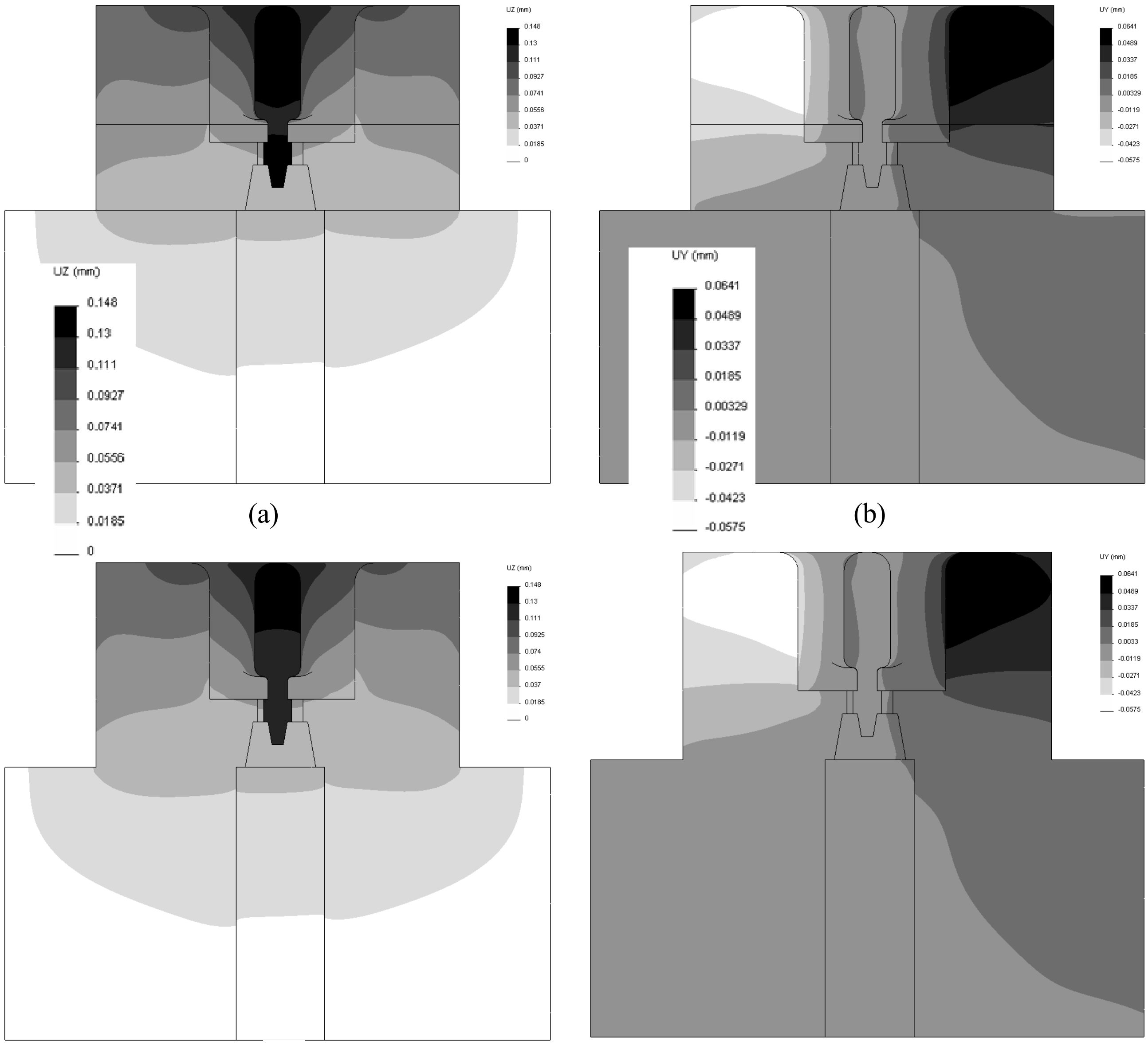
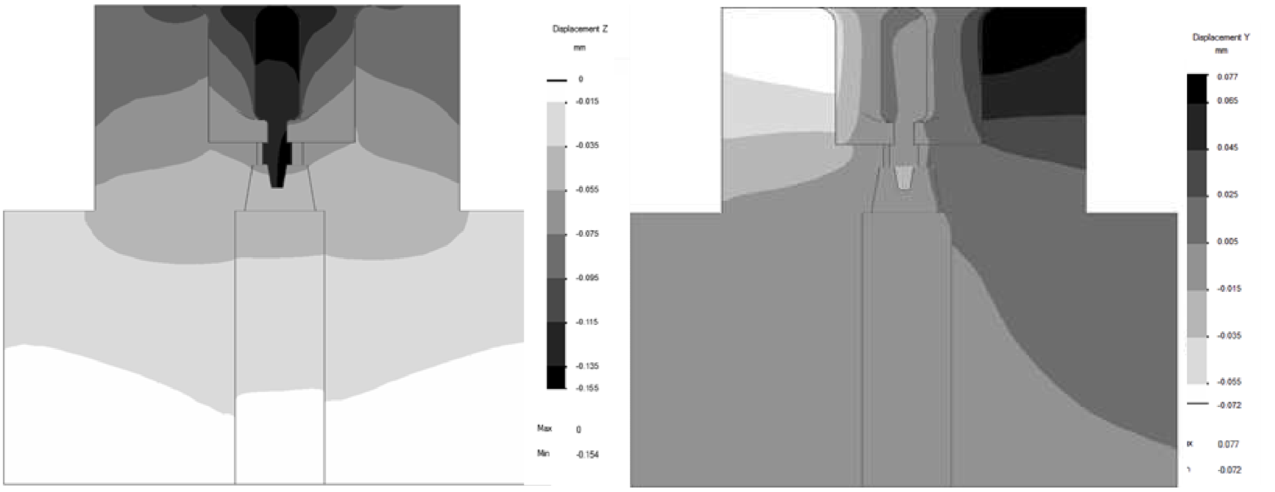


Fig.3 Die set simulation for extrusion of hollow rectangular profile from alloy AA6061; a,b – vertical and horizontal displacement of the assembled die set; c,d – vertical and horizontal displacement of the solid die set

The maximum vertical and horizontal displacement that are calculated for both schemes have the difference not more that 1%. Fig. 4 shows the vertical and horizontal deflection in the tooling set simulated by QForm-Extrusion. The distribution of the strain and stress simulated by COSMOSWorks and QForm-Extrusion are in qualitative and quantitative agreement (see Fig. 3,4). The quantitative difference is not more than 2%.



a. b.

Fig. 4 Vertical (a) and horizontal (b) displacement in mm of the die for extrusion hollow rectangular profile simulated by QForm-Extrusion.

The procedure of decoupled simulation of the profile extrusion in QForm-Extrusion includes the geometry modification using the results of the die stress and strain analysis. After the domain modification the program simulates the material flow again using Lagrange–Euler approach. This decoupled method of simulation of the contact problem between the profile and die set provides taking into account the influence of the elastic deformation of the tooling set on the changing dimensions of the die orifice and that is the most important the actual bearing choke. This development of the simulation of the contact problem provides considerable increasing of the accuracy of the extrusion simulation especially for very thin whole profiles. Verification of the realized algorithms has been performed by comparison of the simulation results with industrial and laboratory experiments.

Model verification by simulation of industrial cases

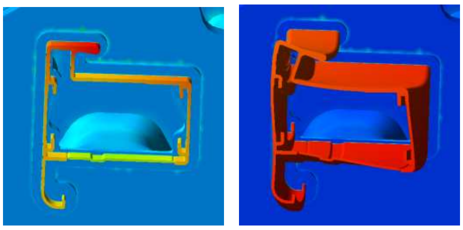
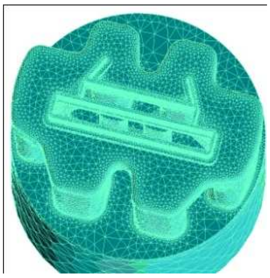
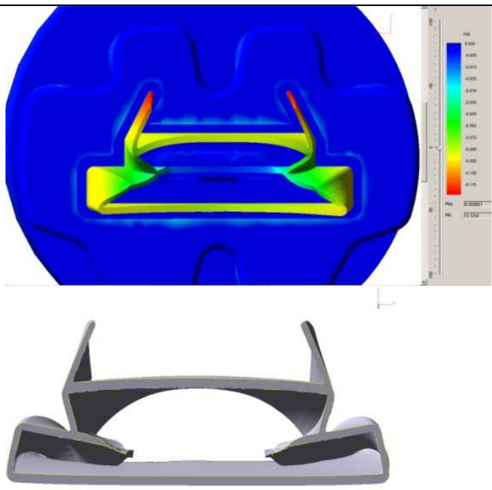
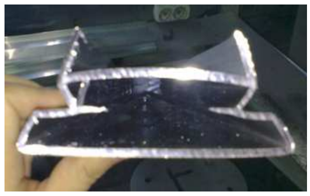
Industrial verification of the model was done using a wide range of solid and hollow profiles of different complexity with various extrusion ratios that are produced by Ekstek-Nord Ltd. (Belaya Kalitva, Russia). More than 15 profiles were investigated and two of them are presented in Table 1.

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 1-2 in the Table 1. It is important to point out that 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.

TABLE 1. Some examples of industrial tests for hollow profiles (with permission of Ekstek-Nord Ltd.)

Profile No	The simulation domain with finite elements mesh	The profile shape and the velocity distribution	Photo of the real profile tip
1			
2			

The experimental and simulation results are in good agreement for Profile 2 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.

On the other hand the variation of the friction model in the bearing area does not significantly influences the extrusion load. Its main reason is relatively small area of the bearing zone with respect to the total contact area of the material. This means that the load cannot be used as a criterion of the friction model accuracy and experimental observation of the material flow in different parts of the profile is the only available way to verify the model.

Thus we can say that 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 thermo and mechanical simulation of the material flow and dies set.

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