Development and Industrial Verification of QForm-Extrusion Program for Simulation of Profile Extrusion

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Introduction

QForm-Extrusion is a special-purpose program for aluminum profile extrusion simulation newly developed by QuantorForm Ltd. The software includes two discreet models. The Lagrange model is for transient simulation at the first stage of the process while the Lagrange-Euler model is for simulation at a steady state stage.[1,2] At the first stage, the finite element mesh follows the material flow and by these means precisely traces the progress of the die filling. In the case of hollow profiles, the material flow separates at the bridges that support the mandrel and then merges again in welding zones and very clearly shows the details of the material flow. The simulation of the transient stage of extrusion is by means of the Lagrange model, which operates quite quickly at the beginning but then slows down when the material reaches the die orifice where further simulation with this model becomes ineffective.

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. Thus the finite element mesh in the inside of the tool represents 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 analyzed in monograph,[3] where different types of the elements were used to get the solution. This approach allows the program to not remesh the domain inside of the tools, but to just calculate the velocity in the nodes within it. On the other hand, after the die orifice, the free end of the profile increases its length very quickly. Due to non-uniform material flow the profile that leaves the die orifice may bend, twist, or buckle. The simulation goal is to predict this undesirable shape deterioration and to find ways to minimize it. To simulate this stage of the extrusion process both the Lagrange and the Lagrange-Euler models are coupled together in QForm. Validation of the model was performed for load prediction, material flow pattern, and temperature distribution, using special model experiments and in industrial practice. The developed approach for profile extrusion simulation has shown good results at the Benchmark test in Bologna.[4]

Simulation of Extrusion on the Basis of Lagrange-Euler Approach

From a practical point of view the most important part of extrusion is the quasi steady-state stage, when the product shape and properties are formed. During the quasi steady-state stage of the extrusion process some parameters (temperature and load) may vary, but this variation does not influence material flow considerably and can be ignored. Generally the source data for simulation includes:

- The geometric models of the tools originally created in a CAD system, which is then converted into finite-element representation
- The properties of the extruded material (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)

QForm-Extrusion is a finite-element simulation program specially developed for modeling and optimization of profile extrusion. This program is a 64-bit application that allows dealing with up to 500,000 nodes on PCs with up to 16 GB of RAM and runs simulations in parallel on up to 8 CPUs. It includes a special module, QShape, to import CAD models of extrusion tools and to generate FE mesh inside the tools and to create the simulation domain. Within QShape, Bearing Editor allows modification of bearing design, i.e., the bearing length and choke angle along the bearing evolute. The mesh generation in the program is completely automated and does not require any user's interference. The program also includes pre- and post-processors and provides different kinds of visualization results and analysis.

Mesh Generation in the Domain

Proper setting of tooling geometry is vital to get successful simulation. As is well known from extrusion practice, there are three basic types of extrusion dies: solid dies, semihollow dies, and hollow dies, which produce solid profiles, semihollow profiles, and hollow profiles, respectively. Meanwhile for simulation purposes we distinguish the types of die design in slightly different way (Figure 1):

- Flat dies for making solid profiles
- Hollow and semihollow dies with flat die surface
- Dies that have non-flat die surface

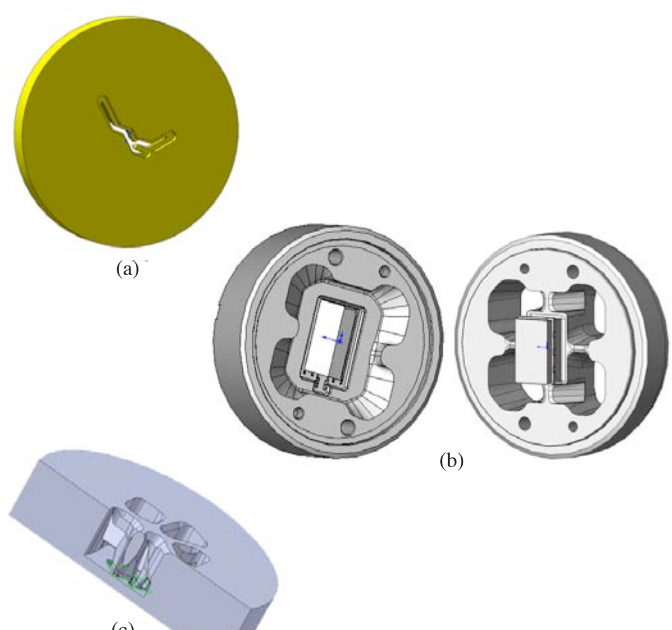


Figure 1. Different types of dies for extrusion of aluminum profiles: (a) flat die for solid profiles; (b) mandrel die for hollow profiles; (c) die with stepped chamber of bearing.

Simulation of the extrusion process is performed within the so called "simulation domain." This is the volume of the extruded material that fills the container and the inner space of the die up to the exit from the bearing land. The domain is to be created using models of the tools. In general the domain can be created in three different ways:

• For flat solid dies, it is created using two-dimensional drawings of the profile, the chamber, and the container. The domain initially has the bearing of constant length that later can be modified using the Bearing Editor.

• All 3D solid models of the tooling set are preliminarily merged into a single body in a CAD system as shown in Figure 2a. The domain is created by means of import of the 3D die geometry from CAD system into QShape and subsequent conversion into finite element representation. Then QShape creates the domain as shown in Figure 2b-c.

• The domain is created using the tools as separate parts, created in CAD, and then joined together directly in QShape program.

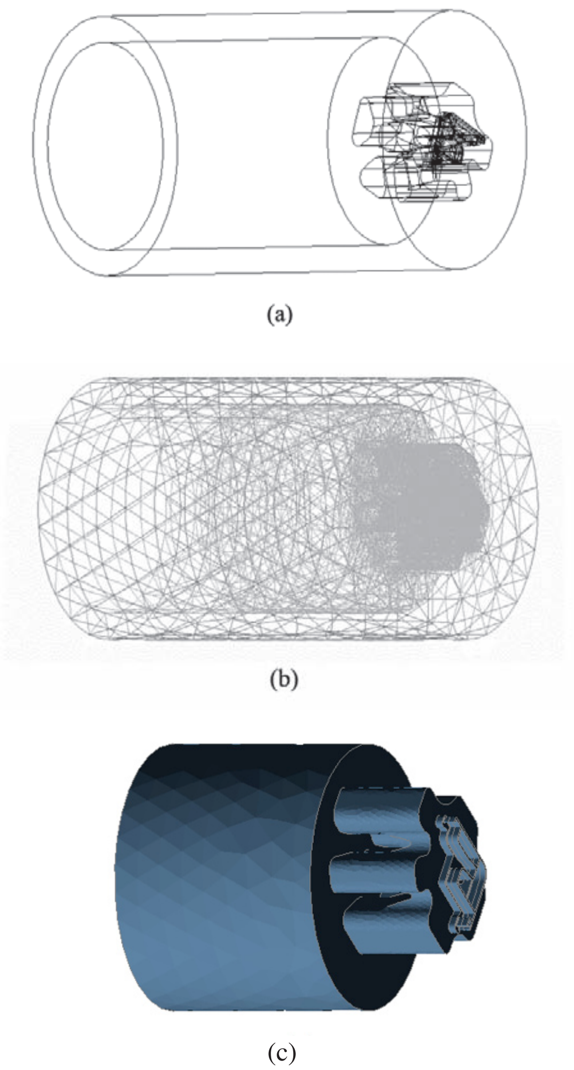


Figure 2. Die set merged with the container to form a single solid body for subsequent creation of the simulation domain inside it: (a) CAD model; (b) finite element model of the tooling set; (c) simulation domain automatically generated inside of the tooling set.

Currently the second option for domain generation is realized in the program while the other options are to be added soon. The most critical stage of the domain creation is automatic recognition of the bearing zone and converting this part of the die design into parametric representation. Parametric representation of the bearing is necessary for its interactive modification without going back to the CAD system. After such parameterization, the geometry of the bearing is represented not by finite elements but by means of splines and can be easily modified in the program. Particularly it is possible to change the bearing length and choke angle to provide desired material flow. It is also important to have parametric representation of the bearing when dealing with the dies to produce several similar profiles at a time. Any modification of the bearing of a single die must be automatically repeated for all the others. The last stage is generation of the finite element mesh inside the domain. As soon as the domain is created the program automatically sets proper boundary conditions over its surface and provides simulation of extrusion process to the profile length specified by the user (Figure 3).

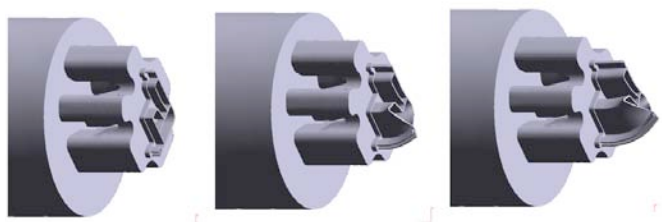


Figure 3. Several steps of profile extrusion simulation using the simulation domain shown in Figure 1.

It is important to mention here that the sequential stages of simulation domain creation just described can be automated and an interface to other CAD/CAM programs for die design and manufacturing can be developed on request.

The mesh inside the domain is built using tetrahedral elements, while the profile's exit from the die orifice is approximated by prism elements. The quality of the finite element mesh is critical to obtain accurate results. Insufficient mesh density or its over-sized gradients may cause a non-convergence problem and deteriorate the quality of the simulation (Figure 4). This is especially critical if the mesh has improper density distribution at the entrance into the bearing where the most intensive deformation takes place. When the extruded profile leaves the die, it is enough to have two to three elements across the profile, while in the deformation zone it is necessary to have not less than ten element layers. Thus the finite element mesh is created iteratively, adapting it to solution behavior such as the velocity gradients at the entrance to the die orifice.

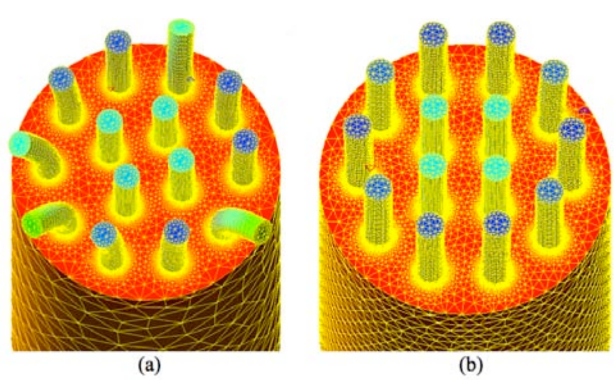
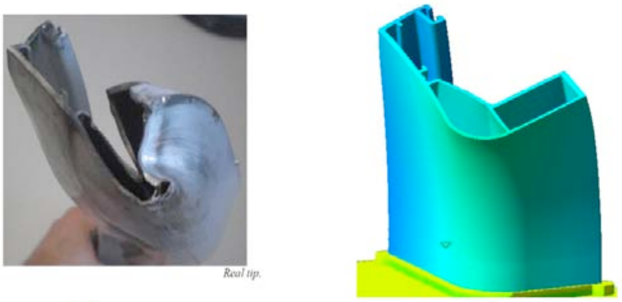


Figure 4. The influence of the finite element mesh quality on the material flow: (a) insufficient mesh adaptation causes fluctuation of the material flow; (b) optimal adaptation provides accurate simulation.

Bearing Editor

Bearing Editor is a part of the QShape program and is intended for interactive modification of bearing design. To show how it can be used, consider the simulation of extrusion of hollow angular profiles. The first attempt of the simulation has shown the same deformation of the front tip of the profile as in real extrusion (Figure 5). The reason for such shape deterioration is a much lower metal velocity in the "corner" of the profile that in its legs. Bearing Editor displays the evolutes of the bearing length of all contours of the profiles (outer and inner ones) and shows them as graphs (Figure 6). Moreover after completing the simulation, Bearing Editor displays the evolute of the velocity profile on the same graph as the evolute of the bearing length, which shows how they correspond to each other (Figure 7). For this particular angular profile, the initial reduction of the bearing length in the corner area of the profile was not enough to equalize the velocity (Figure 8b). With further reduction, the velocity profile, as well as the front end of the profile, becomes uniform when it leaves the die orifice (Figure 8b).



(a) (b)

Figure 5. Comparison of real front tip (a) and its shape obtained by the simulation (b) for hollow angular profile.

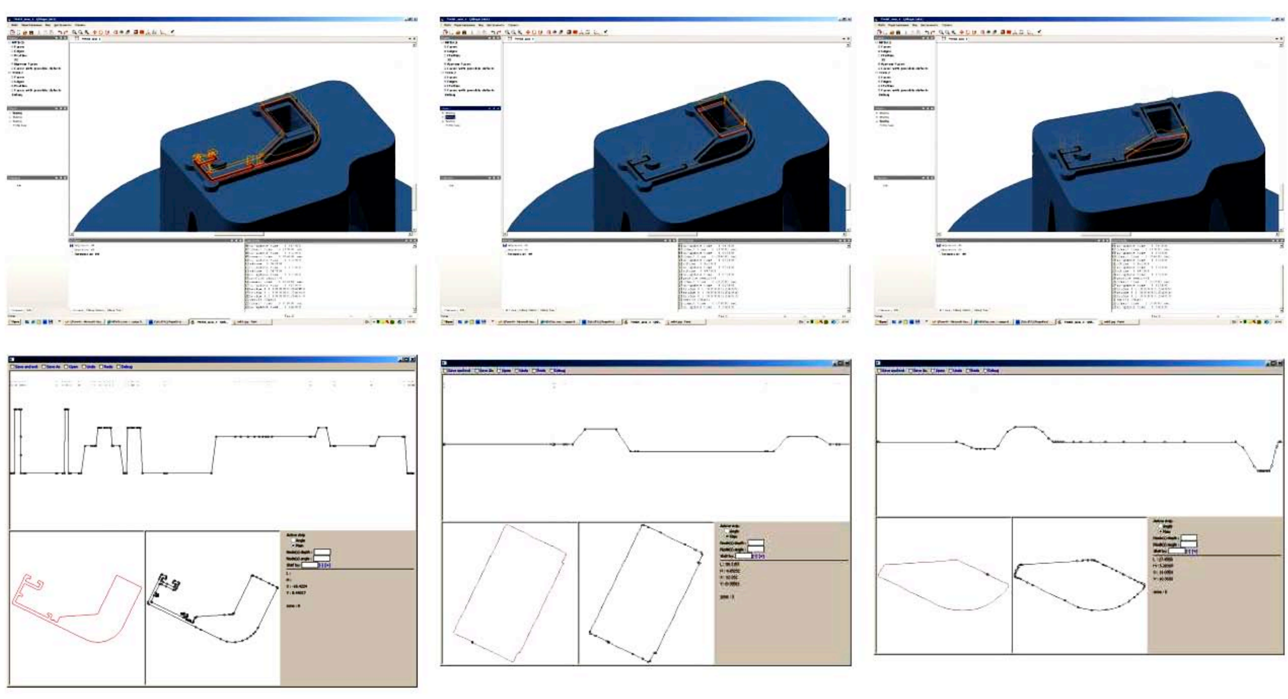
Model Verification by Simulation of Industrial Cases

Industrial verification of the program was done using a wide range of different solid and hollow profiles of different complexity with various extrusion ratios produced by COMPES S.p.a. More than 20 profiles were investigated. It is impossible to measure the velocity distribution along the profile contour in real extrusion, thus one must compare the shape of the front tip of an real extruded profile with the shape of the simulated prediction of the front end. There were several goals of such industrial investigation, which include:

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

The results obtained in these tests were divided into three groups. The first group shows very good correspondence between simulation and real extrusion, for example, profiles No. 1 and No. 2 in Table I. Meanwhile, some profiles show a less exact but still acceptable correspondence, as in profile No. 3, and yet other profiles show poor correspondence between simulation results and the real profile, as with profile No. 4.

These results were analyzed and the reason for the inaccuracies was found to be insufficient mesh density in the zones of the most intensive deformation of the material at the entrance to the bearing zone. When the program was supplied with additional optimization of the mesh density the correspondence of the simulation results to real extrusion was significantly improved as seen in the second simulation for the profile No. 4 (Table I). On the other hand increasing the mesh density causes extention of the overall problem size that essentially requires hundreds of thousands of nodes for industrially produced profiles of complicated shape. To fit this demand QForm-Extrusion



(a) (b) (c)

Figure 6. The evolutes of outer (a) and inner (b, c) bearings of a hollow angular profile displayed in Bearing Editor.

Figure 7. Graph shows the evolutes of the bearing length (1), profile velocity distribution (2), and average profile velocity shown as a line (3).

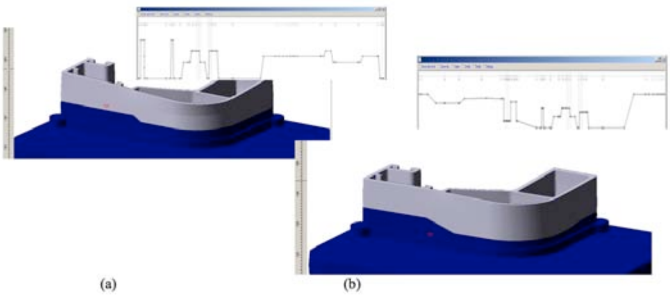


Figure 8. Two subsequent stages of bearing length optimization: (a) insufficient variation of the bearing length; (b) bearing length variation provides uniform velocity distribution.

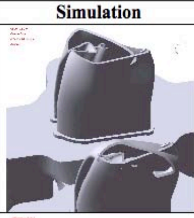
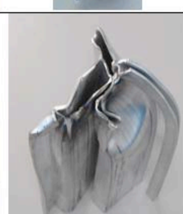
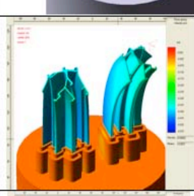
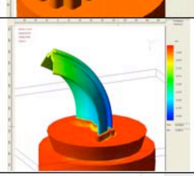
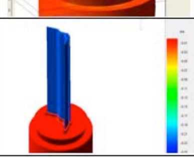
Profile #	Results evaluation	Simulation	Photo of the profile tip
1	Good correspondence between simulation and experiment		
2	Good correspondence between simulation and experiment		
3	Acceptable correspondence between simulation and experiment		
4	Poor correspondence due to insufficient quality of the mesh		
	Good correspondence after improvement of mesh density distribution		

Table I. Some examples of industrial tests for different profiles.

provides highly efficient facilities for mesh generation, solving of the system of equations, and parallel computation techniques to speed up the simulation.

Conclusion

QForm-Extrusion is a special-purpose finite-element simulation program based on Lagrange-Euler approach for the use in industrial environment. The program has a module for data import from CAD systems that allows interactive modification of bearing design and that can also be used for bearing design optimization. The program provides automated simulation of the material flow through the die orifice and shows where the shape of the front end of the profile can be compared with front tip in real extrusion. Industrial tests of the program have provided vital information on the effectiveness of this approach and supplied the data for further development of the model. After improvement of the algorithms, the program has shown very good correspondence of simulation results with real extrusion for a wide range of the profiles, which means it can be successfully used for die design development and extrusion technology optimization in industry.

Editor's Note: For more information, contact S. Stebunov by email at: info@qform3d.com.

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