Automated Extrusion Die Design Integrated with Simulation

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ABSTRACT -- The paper presents recent studies in simulation of profile extrusion technology, with an emphasis on the interaction between the material flow and the die design. The simulation is based on an Euler-Lagrange approach that couples the Finite Element (FE) model of the material flow with the deformation and temperature distribution of the die. This means that elastic deformation of the die influences the material flow, while the die distortion itself is dependent on the contact pressure from the material. Such a coupled solution is obtained through several iterations combined with automated remeshing of the flow domain, due to significant distortion of the initial mesh in the bearing area. As soon as the simulation shows some problems like unbalanced material flow, it is necessary to modify the die geometry either in the bearing area, portholes, or welding chamber. Such modification can be done faster and easier with an automated system of 3D extrusion die design that is based on parametrisation of the basic features of the die and mandrel shapes. The modified shape of the die is exported to the simulation program where we can estimate how efficiently it improves the material flow, and after several iterations, obtain a completely straight profile.

INTRODUCTION

Accurate prediction of material flow in an extrusion with complex thin profiles requires taking into consideration many parameters of the process such as material properties and friction conditions, as well as the temperature distribution in the material and the die. In our previous works, we have developed a Finite Element (FE) numerical model based on a Lagrange-Euler approach that is realized in the program QForm-Extrusion. [1, 2] The extruded material is considered as an incompressible rigid visco-plastic continuum, and its elastic deformations are neglected. The system of governing equations is presented in the literature. [1] The die material is subject to small elastic-plastic deformations.

When the simulation starts, the chamber and bearing area are already filled with material that is represented by the Euler domain (Figure 1a), and the free end of the profile exiting the bearing and extending beyond the die orifice is represented by the Lagrange model. The FE mesh inside the domain is built using tetrahedral elements, and the quality of the mesh is critical to obtain accurate results. Mesh of insufficient density or with too steep a gradient of element size may cause non-convergence problems and deteriorate the quality of the solution. 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. In our model, such mesh optimization is performed automatically without any user intervention. Figure 1b shows the mesh in the simulation domain, with automatic densification in the bearing area.

For accurate prediction of material flow in the extrusion process, it is also necessary to take into account realistic friction and heat transfer conditions between the extruded material and the tooling set, particularly in the bearing area. 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. [3, 4] Consequently, depending on the value of the normal contact stress, it is necessary to apply different mechanisms of friction in sticking and sliding zones of the bearing, and to detect the position of this transition depending on process parameters, as explained in the literature. [5]

TESTING THE MATERIAL FLOW MODEL

The balanced material flow through the die is a key factor to produce profiles of sound quality. The numerical model used in a simulation must be accurate enough to predict undesirable velocity variations that cause profile shape deterioration and provide tools to find ways to minimize them. Validation of our model has been performed for prediction of the load, material flow pattern, profile temperature, and die deformation, using special laboratory experiments and numerous industrial case studies. Estimation of the program accuracy partially has been done within the International Extrusion Benchmark Tests in 2007, 2009, 2011, 2013, and 2015, by means of comparison of the simulation results with measured experimental parameters.

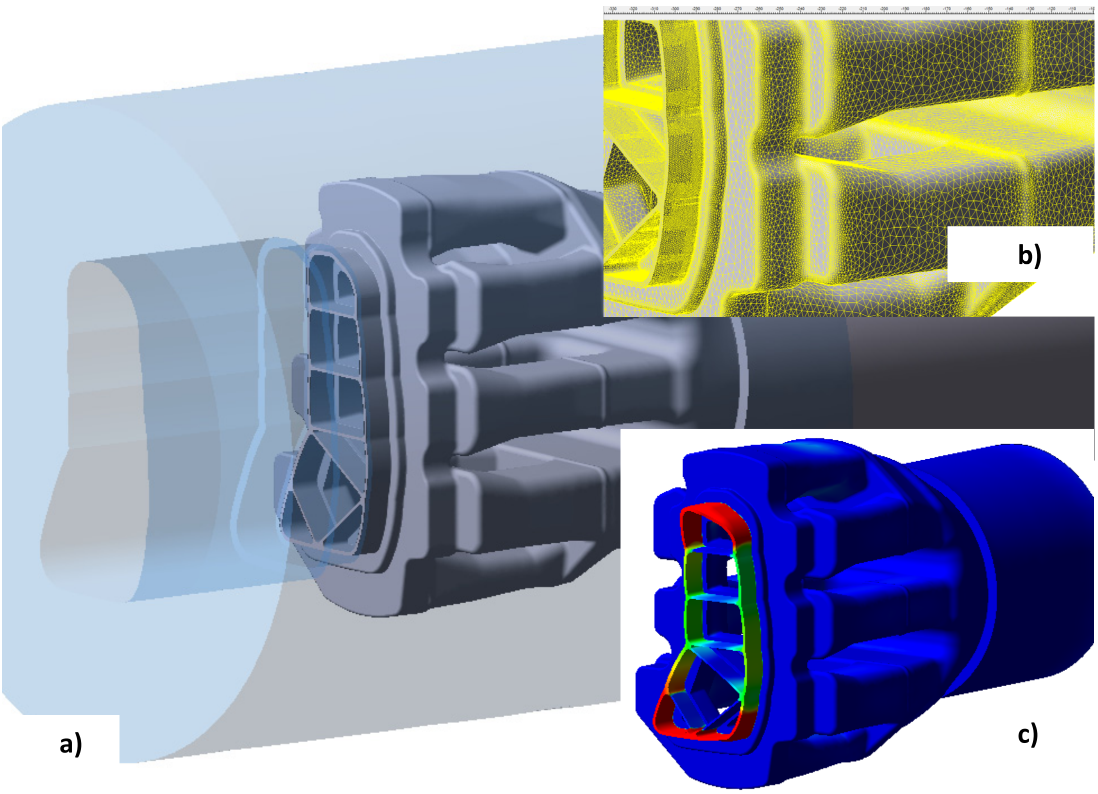
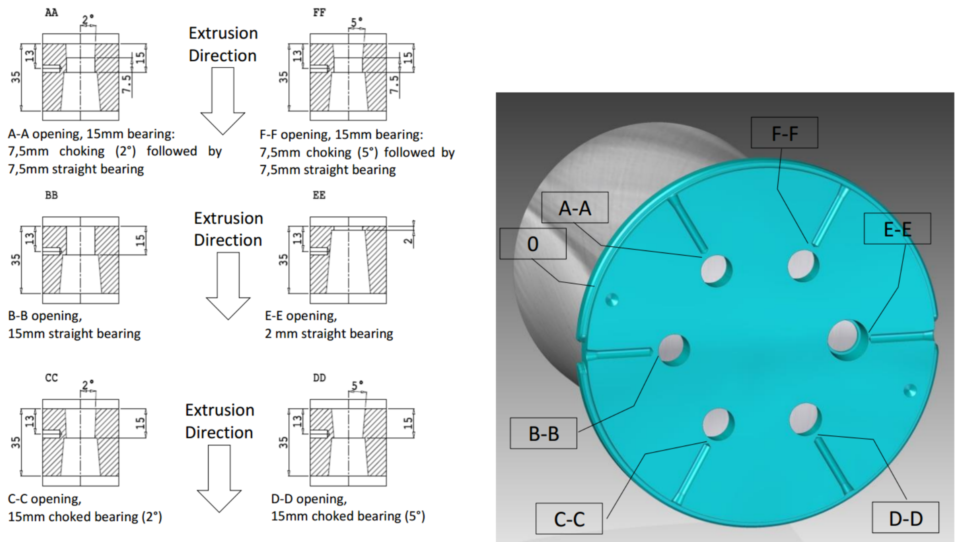


Figure 1. a) Material flow domain and tool set for profile extrusion simulation; **b)** the fragment of FE mesh with automatic mesh densification in transitions and bearing area; and **c)** the material flow obtained in simulation with the fastest flowing material in red zones.

One of the recent examples of such model validation is the International Benchmark Test 2015. The scope of the test was to analyze how the length of the bearing and its choke angle may influence the velocity of the material flow through the identical holes, and how accurately the numerical model can predict it. The test extrusion was performed through six round holes of the same diameter 15mm with straight 2mm, and 15mm bearings, and also bearings with choke of two degrees and five degrees extended to different lengths (7.5mm and 15mm, respectively). The bearing drafts and general view of the die are shown in Figure 2. The material was AA6060 alloy, average billet temperature was 500^{o}C, and ram velocity 4mm/s, while other parameters and tooling set sizes can be found in the literature. [6]



a) **b)**

Figure 2. **a)** Draft of six different bearing designs; and **b)** general view of the die with six holes marked with the same letters. [6]

The comparison of experimental results from literature [6] and our simulation results are shown in Figure 3. It proves good qualitative (the same ranking of the velocities in different holes) and quantitative agreement between them (not more than nine percent discrepancy). It is interesting that increasing of the choke from two degrees to five degrees does not slow down the material flow, but causes slight increasing of the speed (compare pairs of bars FF - AA and DD – CC, respectively).

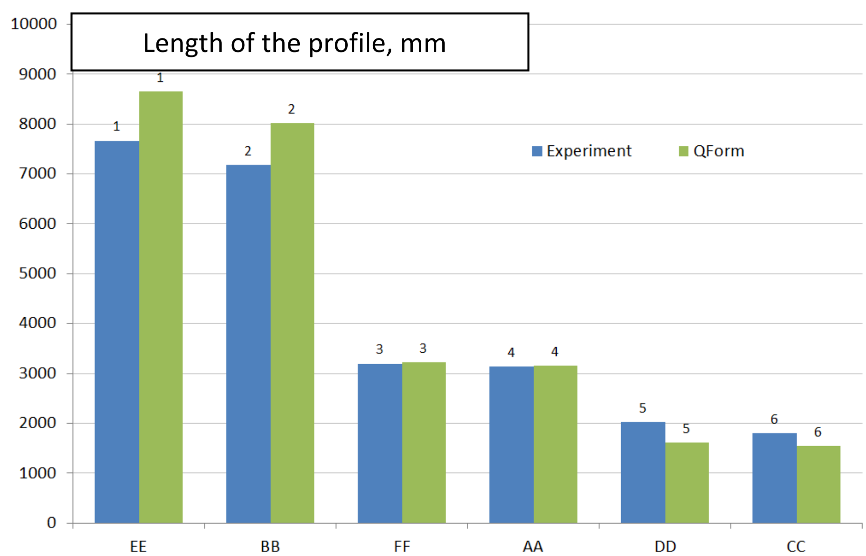
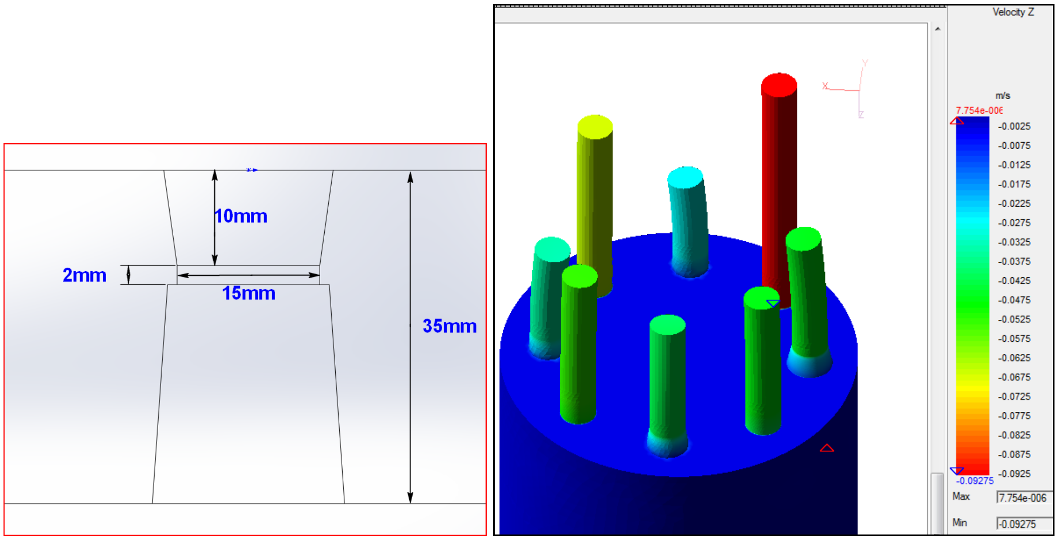


Figure 3. Experimental (blue bars) and calculated (green bars) lengths of the profiles, extruded through different holes marked with letters.

These interesting results motivated us to investigate more comprehensively how the choke angle may influence the material flow velocity. We designed a die and simulated the extrusion through eight equal round holes (diameter 15mm) with the same length of the straight part of the bearing (2mm) and the same length of the choke part of the bearing (10mm), but having a varying choke angle from 10 angular minutes to 12 degrees (Figure 4a). The angle variation in all the holes is shown in Table 1. The material, billet temperature, and other parameters of the process are the same as presented in the above example from the Benchmark Test in 2015.



a) **b)**

Figure 4. **a)** The draft of the bearing with straight and choke parts; and **b)** the bars of different length obtained in simulation through the die with eight holes.

Table 1. The choke angle in bearings of eight-hole dies.

Hole No	1	2	3	4	5	6	7	8
Choke angle, minutes.	0	10	30	60	120	240	480	720
Choke angle, degrees	0	0.17	0.5	1	2	4	8	12

In the simulation, all extruded bars have different velocities and different respective lengths (see Figure 4b). Here, we can observe a very interesting effect. The increasing of the angle from a straight bearing to two degrees (120 minutes) choke slows down the velocity in the holes (Figure 5), but any further increasing of the choke angle above two degrees causes an opposite effect, and the velocities of profiles increase.

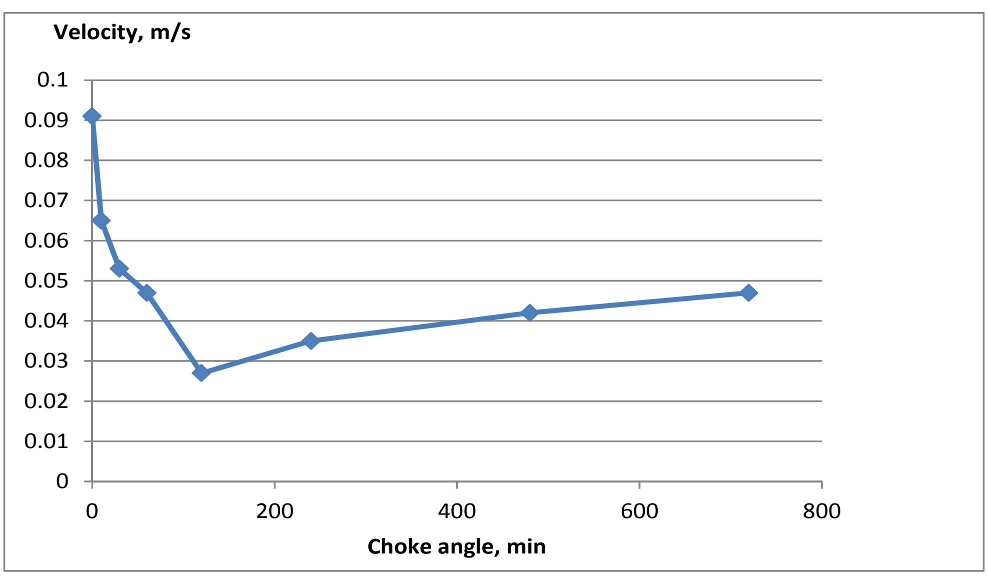
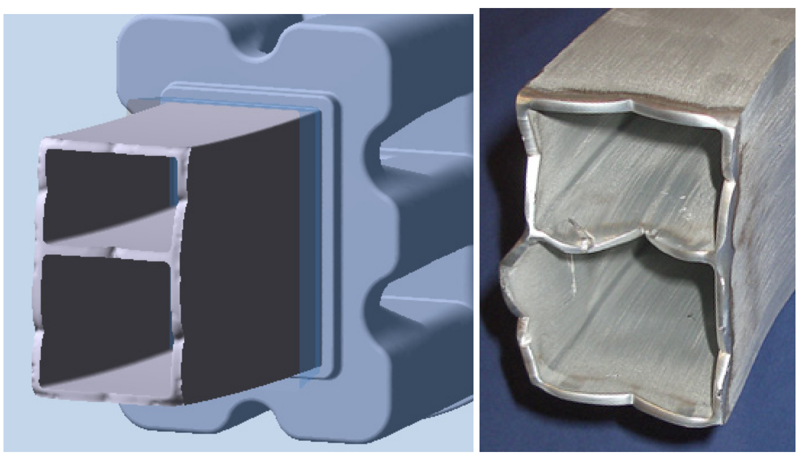


Figure 5. Velocity variation, depending on the choke angle in the holes in angular minutes.

These results clearly show that the biggest effect of the choke is at small angles (within 30 minutes), while further choke increase is less effective, and has no positive effect above two degrees. Very intensive influence of a small (within only few minutes) choke angle on the material flow velocity also explains why it is so important in simulation to take into consideration the deflection of the dies. Due to elastic deformation the initially straight bearing may tilt, causing a small choke or relief that in turn may drastically change the material flow pattern, as explained below in the presented paper.

Another method of verification of the numerical model in terms of material flow balance is comparing the front tip shape of a real profile with the predicted front tip in simulation. The die filling at the initial stage of extrusion is not a steady-state process. That is why the transitional processes both in material flow and temperature distribution are to be taken into account. This can be done by introducing time as a parameter in our Euler model. Using this approach, it is possible to calculate the shape of the front edge of the profile tip, as the material has been passed through the die during the filling stage. It means that when calculating the length of the profile at its front end, we integrate the actual velocities along the trajectories of the points tracked back to the container. This method approximates the history of the material flow during the very first stage of the extrusion, when the material fills the inner space in the die. Figure 6a shows the front tip shape obtained by simulation using this transitional approach based on the Euler model, compared to experimental results (Figure 6b). The parameters of the process and the die geometry are from the literature. [7] It is clearly seen that the new method creates the shape that has the same characteristic "waves" on the profile edge as the real extrusion tip, and approximates its shape more accurately.



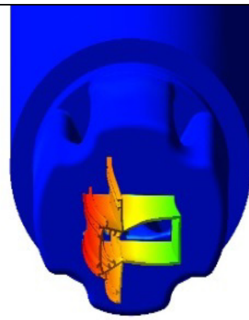
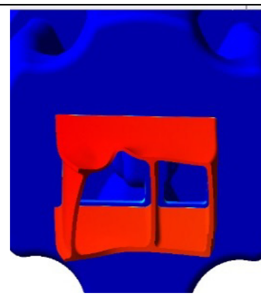
a) **b)**

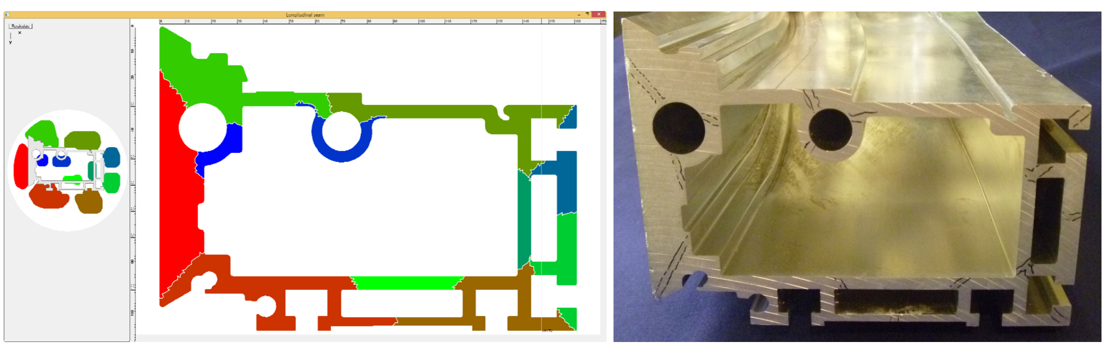
Figure 6. a) The front tip of the profile predicted in simulation using transitional approach in Euler domain; and **b)** the photo of a real profile. [7]

The comparison of front tip obtained in simulation and experimentally has been done in hundreds of industrial cases, and its analysis still requires a method for quantitative estimation of the accuracy. Currently, we can just compare them qualitatively by indicating the fastest and slowest parts of the profile that give us information about the material flow balance that can be used for successful die re-design or correction. Table 1 contains several simulated and practical front tip shapes, as well as basic parameters of the extrusion process. As we can see from these examples, the simulation shows a front tip shape very close to reality, and it gives us a clear understanding of the material flow balance, and helps us to understand how to modify the die design.

When extruding hollow profiles, we have zones where metal from different portholes is welded. The location of these seams may be important for the aesthetic look of the finished product, as well as for its strength, especially for highly-stressed parts. The accuracy of the prediction of seam welds is another good indication of the quality of a numerical model, and an experiment from International Benchmark Test 2015 has been used to check the accuracy of seam weld prediction. The process data and die geometry can be found in the literature. [8] It is important to say that experimental determination of seam weld positions is often a difficult task. In the case of a perfect weld, the material can be completely and homogeneously recrystallized, and then only the band of larger grains can indicate the seam weld. Sometimes, a darker line of precipitation can be seen in the seam weld. The experimental location of seam welds has been done by means of microstructural analysis by the organizers of the benchmark test. [8] The simulation and experimental results are shown in Figure 7. It is clear that locations of seam welds are the same in both pictures, which shows good accuracy of the material flow in the numerical model.

Table 2. Comparison of the profile tips extruded in industry and simulated.

Technological parameters	Simulation of the material flow	Extruded tips in industry
Extrusion temperature 480℃ Ram velocity 5mm/s		
Extrusion temperature 480℃ Ram velocity 5mm/s		



a) b)

Figure 7. **a)** Location of the seam welds in simulation shown by merging colors; and **b)** in the actual profile. [8]

THE MECHANICALLY-COUPLED MODEL OF EXTRUSION

In many cases, the assumption that the die can be considered in simulation as a rigid body is not correct. The die deformation may have significant impact on the material flow. Mechanically-coupled simulations take into consideration the displacement and distortion of tool surfaces, especially in the bearing area. In many cases, the relative linear displacement of the opposite sides of the bearing may reach half a millimeter or more, that may actually be comparable to the profile thickness. When the opposite bearing sides shift due to elastic die deformation, tiny finite elements within the profile inevitably become critically distorted, and further use of the initial finite element mesh in the material flow domain becomes impossible. In our model, this problem is solved by remeshing the simulation domain to provide good mesh quality in iterations of the coupled simulation.

To build a practically usable coupled model, this remeshing is to be performed completely automatically, without any user's intervention. In our approach, we take advantage of keeping the bearing geometry as a parametric 3D surface, as was explained in our work. [9] This allows the program to distinguish which nodes are placed on the bearing surface, and also takes into consideration not only the linear displacements of the nodes, but also very fine inclination of bearing surfaces that may vary within just a few angular minutes, creating local zones with choke or relief caused by die deformation. Though small, such bearing angle variation may significantly influence the material flow patterns, as has been shown by simulation practice as well as laboratory tests.

The importance of the mechanically-coupled simulation has been shown by the following industrial case study[1] shown in Figure 8. This realistic front tip shape was not possible to get when running this simulation with just a "rigid" die model (Figure 8a), while the mechanically-coupled simulation has shown the same flow pattern as in reality (Figures 8b and 8c).

a) **b)** **c)**

Figure 8. **a)** The shape of the front tip of the profile when using a "rigid" die model; **b)** photo of the real profile; and **c)** the front tip obtained in coupled simulation.

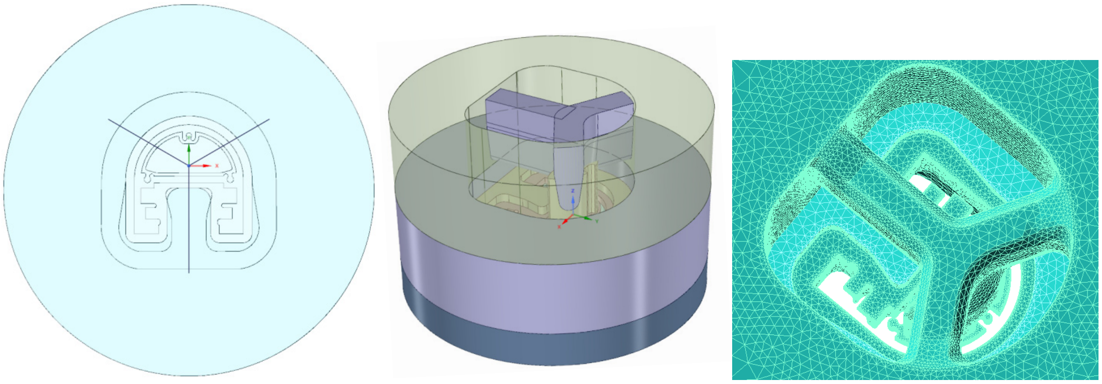
DEVELOPMENT AND CORRECTION OF PARAMETRIC DIE DESIGN

When trying to implement extrusion simulation in industry, we faced one more problem. Many die makers still develop their products using 2D drawings, and do not have full 3D models of the tooling set. Moreover, not every CAD model of a die can be successfully used for simulation. Only a sound solid body with exact fitting of surfaces can be used for mesh generation; otherwise, the model should be manually repaired using special programs for cleaning up the geometry that is time consuming.

In this situation, it is quite natural to make the next step and develop the software tool for creation and modification of die geometry, and combine this software with simulation for virtual error-free die design. With this in mind, we have developed a system called QForm-Extrusion Die Designer (QExDD) that automates the die design routine, and significantly speeds up the process of developing new dies. This system has been developed as an OEM application powered by SpaceClaim™, and has a special interface to the simulation program.

In the Figure 9, the main steps of the die geometry preparation are shown. Starting with a 2D drawing of the main features of a die set (Figure 9a) we create a parametric 3D design of the tool set that includes the mandrel with webs and core, and the die plate and backer as separate solid bodies that later are automatically merged in a single solid body to be used for simulation (Figure 9b). In the last step, we import prepared solid geometry in a simulation program where it creates the FE model (Figure 9c).

[1] With permission of Hasim Derman, Ffex, Istanbul, Turkey.



a) **b)** **c)**

Figure 9. **a)** Creating the die model and flow domain with: the initial 2D drawing; **b)** a complete solid 3D model of the die set; and **c)** an FE model of the die.

Let us illustrate how this integrated approach can be used for die design optimization using the same profile as in Figure 9. The extruded material is AA6061 alloy, tool material H13, billet temperature is 450°C, die temperature is 400°C, and the ram velocity is 5mm/s. The initial bearing configuration has been automatically created at the first stage of the die design using some empiric algorithms. This bearing design comes together with the die model, resulting in respective configuration of the bearing zone in the FE model (Figure 9c). At the stage of flow domain, creating the initial bearing design can be visualized and modified in *Bearing Editor* (Figure 10). In other words, it can be modified without returning back to the CAD system.

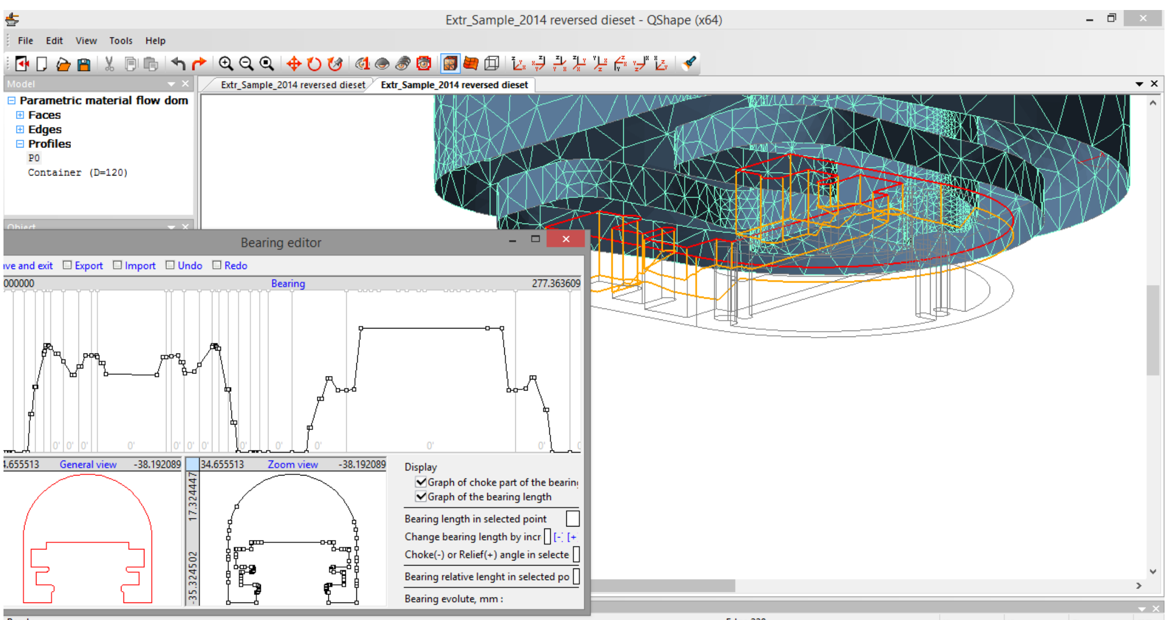


Figure 10. Parametric representation of the material flow domain with the curve of bearing length placed on the bearing surface (on the right); and a drawing of the bearing as a graph along its perimeter (on the left).

After the first simulation attempt with the initially created die and bearing designs, we see that the material flows much faster to the "legs" of the profile than to its rounded side (Figure 11). Such large disproportion can be explained by too much material going from the portholes to the leg parts of the profile. It is clear that the initial design is unsuccessful.

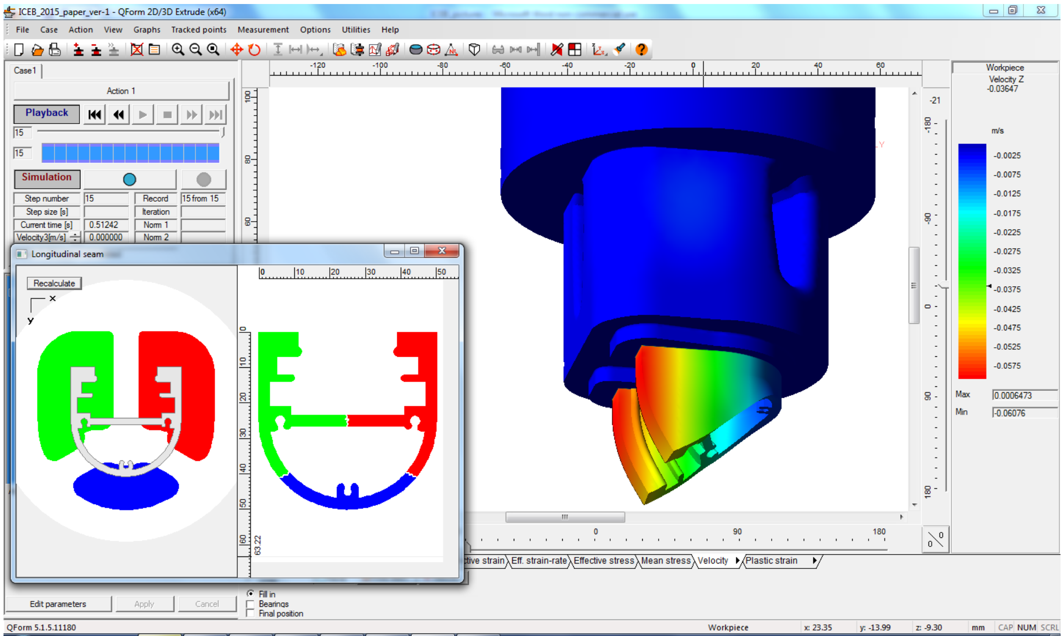
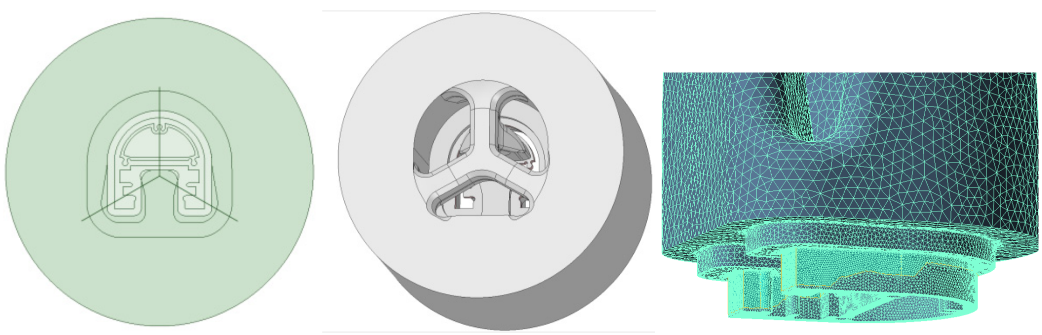


Figure 11. The material flow obtained with the initial porthole design. The location of portholes over the profile and seam weld locations are shown in boxes in the lower left corner.

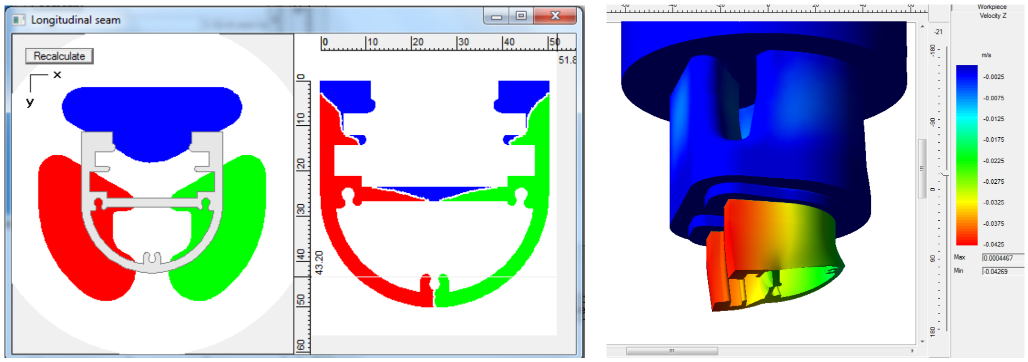
Then we changed the location of the webs to reduce the amount of the material going to these leg areas by simply rotating the lines that specify the location of the webs, as shown in Figure 12a. Then by re-playing all subsequent steps of the design process, we get a solid model of the die set with the opposite orientation of the webs (Figure 12b), and respectively, its FE model of the flow domain (Figure 12c).



a) **b)** **c)**

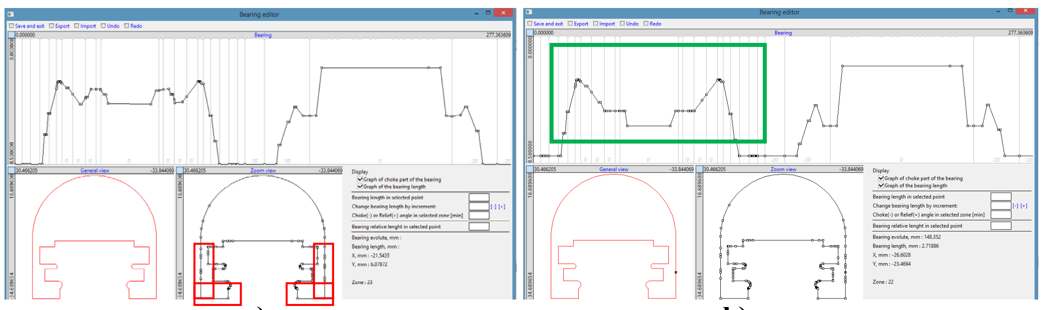
Figure 12. **a)** Second variant of the web design as a drawing; **b)** as a complete 3D model; and **c)** as a material flow domain with the mesh ready for simulation.

After the simulation of this second design variant the authors have got a more balanced material flow, as shown on Figure 13. Even though the legs of the profile still go faster than its rounded side, now such velocity variation can be eliminated by proper modification of the bearing. As we see from the drawing of the bearing, there is no way to increase the bearing length. Thus, a choke has been applied to these areas and this modification has been implemented on the outer surfaces of the legs, where it is easier to make (Figure 14a).



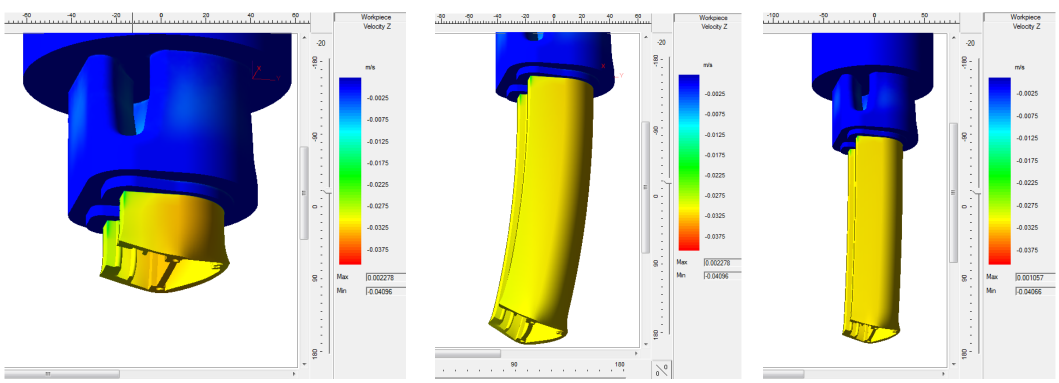
a) **b)** **c)**

Figure 13. Second variant of porthole design: **a)** the portholes placement over the profile; **b)** seam weld locations; and **c)** material flow pattern and velocity distribution.



a) **b)**

Figure 14. **a)** Bearing design as it was generated by QExDD, but with choke angle applied to the legs area within red boxes; and **b)** modified bearing design in the green box after the third simulation attempt.



a) **b)** **c)**

Figure 15. The material flow after implementing choke in the legs area as a third attempt of simulation: **a)** at the beginning of material flow; **b)** extending of the profile; and **c)** the fourth simulation variant with bearing design, as seen in Figure 14b.

Running the simulation with this modified bearing design, the authors immediately see the effect. At the beginning of simulation, the legs and the rounded part of the profile flow with the same speed, while the inner profile web goes slightly faster (Figure 15a). To be sure that the design is really effective, the authors proceeded with the simulation for a longer length and found that the profile has a slight bend toward the legs (Figure 15b). That is why one more iteration of the bearing design has been done, as shown on Figure 14b in the area highlighted by the green box. Then finally, the material flow has become straight, as is clearly seen even for the much extended profile length (Figure 15c). It is important to notice that all simulation has been done in coupled mode, which means that the material flow has been simulated concurrently with the deformation of the die.

SUMMARY

1. Mechanically- and thermally-coupled approach to extrusion simulation is essential to provide good accuracy of the results, in terms of prediction of material flow, load, temperature, and die stress.

2. The validation of the numerical model has been done using laboratory experiments and industrial trials.

3. The comparison has shown good quantitative correspondence of the velocity between the simulation and the experiment, in orifices having different bearing designs.

4. The effectiveness of the method of automated die design combined with simulation has been illustrated by an industrial case study of a hollow profile with massive legs.

5. The die geometry has been created and then successfully modified in three iterations, to provide balanced material flow.

REFERENCES

1. Biba, N., Vlasov, A., and Stebunov, S., "The Simulation of the Extrusion Process Using QForm3D," *Extrusion Workshop 2007, and 2nd Extrusion Benchmark*, Bologna, Italy, Sept. 20-21, 2007.

2. Stebunov, S., Lishnij, A., Biba, N., Belotti, S., and Fazzini, P., "Development and Industrial Verification of QForm-Extrusion Program for Simulation Profile Extrusion," *Conference proceedings of the Extrusion Workshop Latest Advances on Extrusion Technology and Simulation*, Dortmund, Germany, Sept. 16-17, 2009, pp. 41-42.

3. Valberg, H., "Experimental techniques to characterize large plastic deformation in unlubricated hot aluminium extrusion," *Proceedings of International Conference, Latest Advances in Extrusion Technology and Simulation in Europe and Extrusion Benchmark*, Bologna, Italy, 2007, pp. 9-12

4. Abtahi, S., "Friction and Interface Reactions on the Die Land in Thin-Walled Extrusion," *Ph. D. Thesis*, Norwegian Institute of Technology, Trondheim, Norway, 1995.

5. Biba, N., Stebunov, S., and Lishnij, A., "Influence of contact friction conditions on thin profile simulation accuracy," *Progress in Extrusion Technology and Simulation of Light Metal Alloys*, Bologna, Italy, 2011, pp. 35-42.

6. *Scientific and Industrial Benchmark Settings and Results*, 5th International Conference on Extrusion and Benchmark, Florence, Italy, May 12-16 2015, pp. 131-141.

7. *Scientific and Industrial Benchmark Settings and Results*, International Conference on Extrusion and Benchmark, Dortmund, Germany, September 16-17, 2009, p. 147.

8. Scientific and *Industrial Benchmark Settings and Results*, 5th International Conference on Extrusion and Benchmark, Florence, Italy, May 12-16, 2015, pp. 175-184.

9. Stebunov, S., Biba, N., Vlasov, A., and Maximov, A., "Thermally and Mechanically Coupled Simulation of Metal Forming Processes," *Proceedings of the 10th International Conference on Technology of Plasticity*, Aachen, Germany, 2011, pp 171-175.