PRACTICAL IMPLEMENTATION OF NUMERICAL MODELING TO OPTIMIZATION OF EXTRUSION DIE DESIGN FOR PRODUCTION OF COMPLEX SHAPE PROFILES

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Abstract

The paper presents the experience of aluminium profile extrusion simulation using QForm-Extrusion program. 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. The program has special interface for fastest die geometry import. The program automatically finds bearing zones and converts them into parametric form allowing modification of bearing design without return to original CAD model. Alterations and optimization can be done by using a special module "Bearing Editor". In turn with simulations the user can modify die design to achieve the most uniform distribution of longitudinal velocity. The simulation also provides comprehensive analysis of the tool stresses and deflection taking into accounts all the components of the tool assembly. Coupled mechanical simulation mode allows to analyse the influence of the die deflection on the material flow and to compensate this effect. To take into consideration the gradient of the temperature across the die and mandrel during the entire process cycle a transient coupled thermo-mechanical model has been built on the basis of QForm-Extrusion program. The software is in use at many die making and extrusion companies showing its high economic efficiency.

Keywords: Extrusion, aluminum, profiles, dies, FEM, simulation.

Introduction

QForm-Extrusion is a special-purpose program for aluminium profile extrusion simulation that has been developed by QuantorForm Ltd. It shares postprocessor with the versatile metal forming simulation program QForm3D but is actually a stand-alone application. The extrusion model is based on Lagrange-Euler approach [1]. The model also includes the assumption that the tool set is completely filled with the material prior to the beginning of the simulation thus the solution is to be found in the domain that is inside of the tooling set. On the other hand the free end of the profile increases in length very quickly after passing through the orifice. Due to non-uniform material flow the profile that leaves the orifice may bend, twist or buckle. The simulation is capable of predicting this undesirable shape deterioration and finding ways to minimize it. Validation of the model has been performed for prediction of load, material flow pattern, profile temperature and die deformation using special model experiments and numerous industrial case studies [2]. Comprehensive analysis of the program accuracy has been also done within the International Extrusion Benchmark Tests in 2007, 2009 and in 2011 (see, for example, [3, 4]) by means of comparison of the simulation results with precisely measured experimental data. The numerical formulation of the model as well as methods of solving coupled problem are described in our works [5-7].

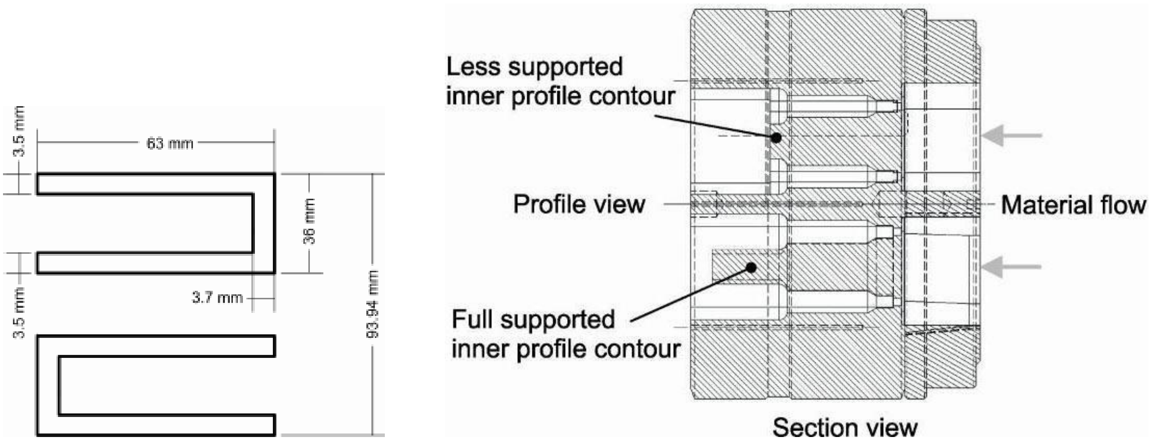
Verification of the model using laboratory experiments

The numerical model described above has been tested to find out the influence of the die deformation on the material flow. Die deflexion is difficult to measure thus especially dedicated laboratory tests are to be performed. One of such tests has been done as a case study for the Extrusion Conference and Benchmark ICEB 2009 and it has been reported in [8] where the data summary and experimental results can be found. Using these source data we have done the simulation for two cases considering the assumption of rigid and deformable dies. The profiles sketch and the tooling set drawing are shown in (Fig. 1).

As seen from the drawings both profiles are identical and are placed using rotational symmetry on the die plate. Thus there are no reasons for the material to flow differently through both orifices except it may be caused by different deformation of the die within them. This may happen because one of the tongues intentionally has been done with longer support than the other. In (Fig. 1, b) these two tongues are marked as “less supported” and “fully supported” ones. The experiment has shown the difference in the displacement of the tongues about 0.5 mm with respect to each other that potentially may cause the difference in material flow [8]. The displacement distribution on the die surface obtained by our simulation using the presented model is in (Fig. 2). It is clearly seen that both tongues deform differently. Moreover, each tongue has different displacement on its container side that is close to bearing area comparing to its outlet side where the experimental measurement of the deflection has been actually done. Meanwhile overall deflection of the die is probably less important than local distortion of the bearing that actually controls the material flow (Fig. 2 c).

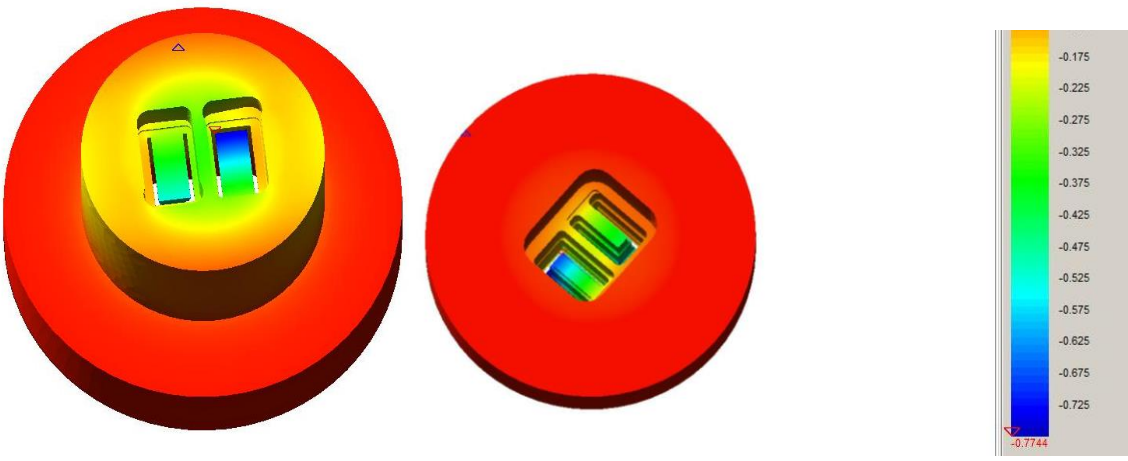
Opposite sides of the bearing have different displacement and they slightly shift with respect to each other. The result of this deformation is variation of the bearing angle and change of “effective” bearing length. This alteration of actual bearing shape may influence the material flow conditions in both channels that in our case are different due to different tongue support.

To check how effectively the coupled numerical model of extrusion may detect the influence of the die deformation on the material flow the test described above has been simulated two times, i.e. once using the rigid die and secondly with elastically deformable die using the coupled model. In the first case with the rigid die both profiles flow similarly with just slight bent towards each other. It is important to notice that in this case there is no bend of the profile in its symmetry plane (see Fig. 3 a).



a. b.

Fig 1**.** The scheme of the profiles used for the test (a) and crosscut of the die done through the tongues showing different support conditions (b). Both pictures are taken from [8].



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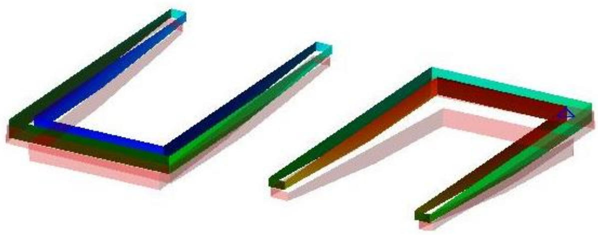
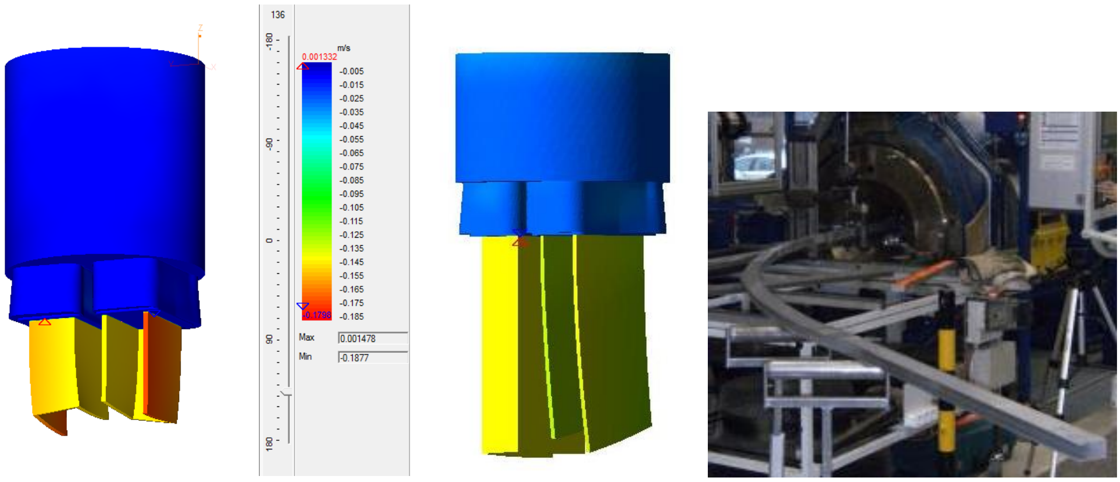


c.

Fig. 2. The axial displacement of the die in mm shown from the container side (a) and from the outlet side (b) and local displacement of the bearing area (c). Colour scale shows the value of the displacement while pink contour in (c) is the deformed shape of the bearing magnified for better visibility.

When the simulation has been performed using the deformable die the profile with less supported tongue bents in the plane parallel to its legs towards its bridge (Fig. 3 b). The same bending direction of the profile going from the orifice with less supported tongue has been reported by the authors of the experimental work [8] (compare pictures on Fig. 3 b and c) even though it is difficult to estimate their correspondence quantitatively because no information about the bending radius is available. Nevertheless we can conclude that die deformation may cause some effect on material flow and taking it into account in simulation by means of coupled modeling provides higher accuracy of the numerical results.



a. b. c.

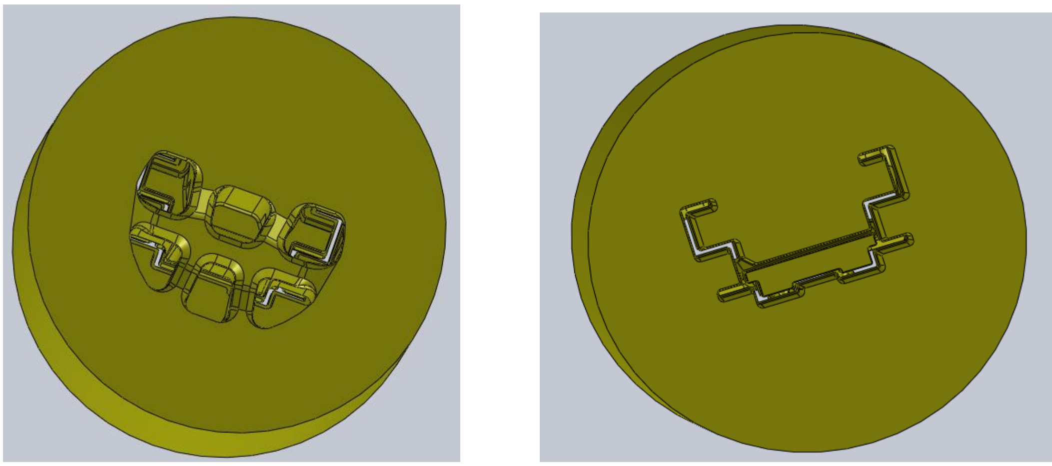
Fig. 3. Simulation of the test extrusion: with the rigid die both profiles go straight (a); with deformable die one profile bends in direction parallel to its legs (b); photo of the experiment [8] with one profile bending (c).

The die deformation and material flow in industrial case study

The effect of die deflection on material flow may not always be significant and probably in many cases the simulation with the assumption that the die is rigid provides sufficient accuracy for practice. Meanwhile in cases when the die has long tongues or it is designed for complex hollow profiles when mandrels are supported by narrow and relatively flexible bridges the die deformation may be critical. In such cases it is impossible to achieve the accuracy required by practice without use of coupled modelling as it is illustrated by the following industrial case study.

Let us consider extrusion through the die shown on (Fig. 4)[1]. This is profile with rectangular central hole and two structural stepped open sides.

[1] With kind permission of COMPES, Italy



a. b.

Fig. 4. The die for production of the profile shown from container (a) and exit (b) sides.

The simulation model as it is seen in the program is shown on (Fig. 5). It includes the material flow simulation domain and then respectively the die, the mandrel and the bolster assembled together.

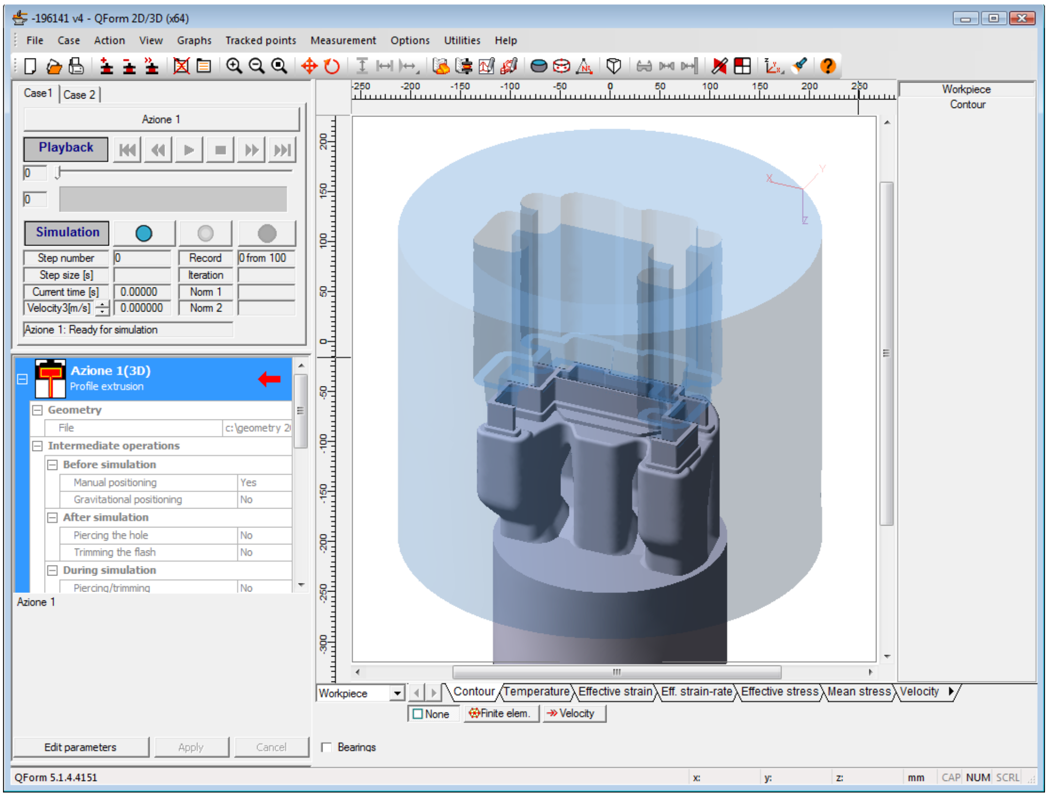
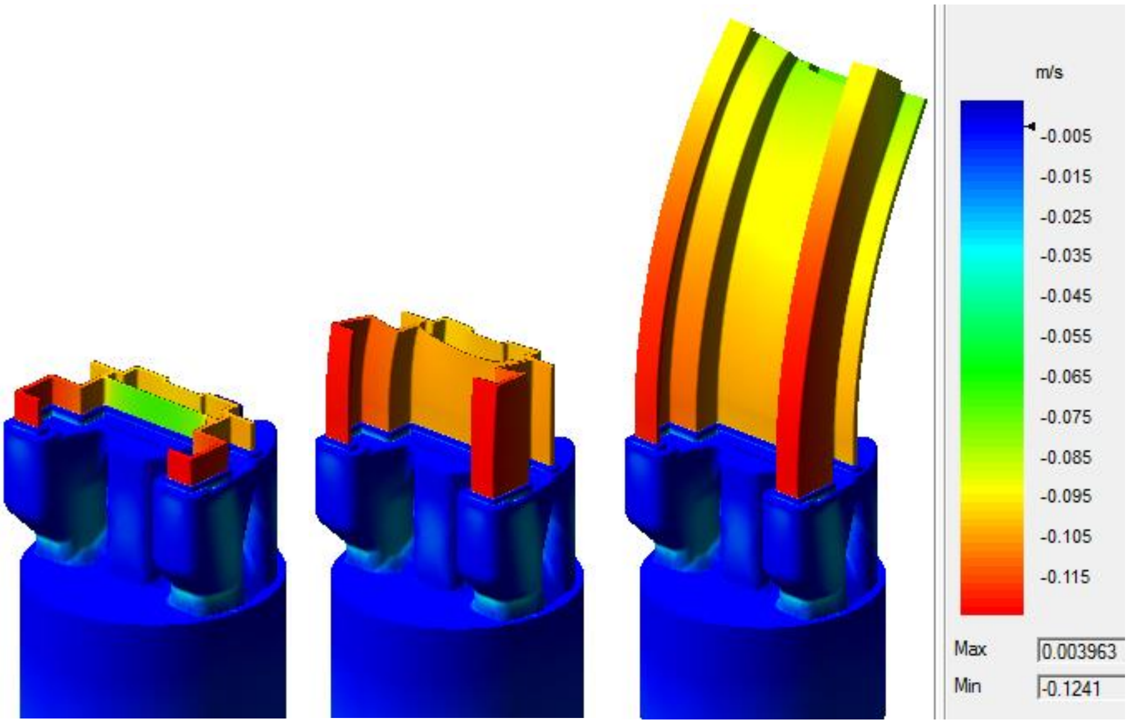


Fig. 5. The simulation setup in QForm-Extrusion with the die set while no container is shown. The material flow domain consists of 341405 nodes while tool set model consists of 241071 nodes

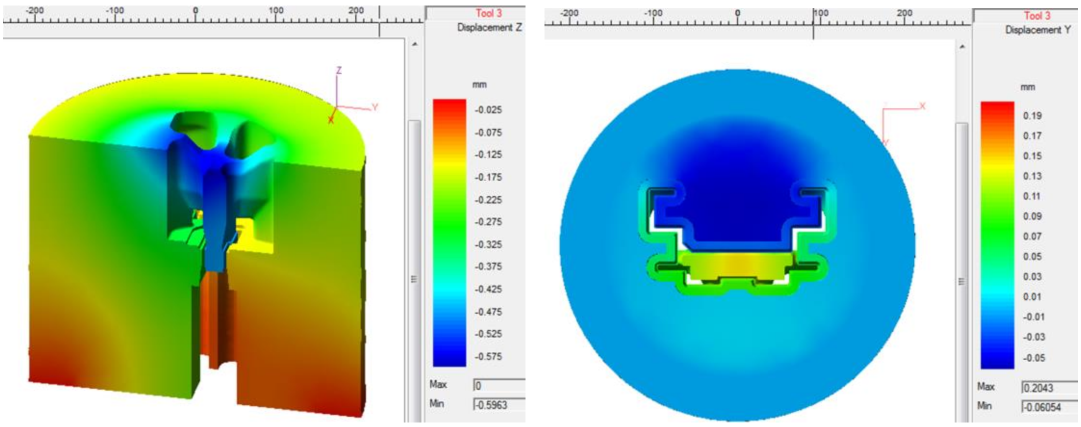
The simulation has been done for two variants, firstly, using “rigid” dies and, secondly, using coupled simulation when the dies deformation may influence the material flow. Extruded material was AA6060, ram speed 8 mm/s, initial billet temperature 480°C, the die temperature 400°C. The material flow through the “rigid” die is shown on (Fig.6). The central rib goes slower than the opened sides of the profile. This materials flow causes to considerable bending of the profile that is shown in the Fig. 6c.



a. b. c.

Fig. 6. Sequential steps of the material flow simulation in case of “rigid” dies. The beginning of the process (a), intermediate stage (b) and formation of the profile front tip (c).

The experimental observation didn’t confirm the material flow pattern that was obtained in the variant of simulation with “rigid” dies. The most probably the deformation of the dies was the reason of such discrepancy. Simulation of the tool set has indicated the considerable displacement of the central part of the mandrel in the extrusion direction. The spider displacement reaches 0.575 mm in the extrusion direction Z (Fig.7). The movement of the spider in Z and Y directions become the reason of the inclining of the bearing walls. So in some aria we have got choked bearing and in other parts relieved bearing as shown in the Fig.8. So around the central rib the bearing become relieved that caused to increasing of the exit velocity of the profile in the central part during extrusion.



a. b.

Fig. 7. Distribution of axial (a) and lateral (b) displacement in the crosscut of the tooling set

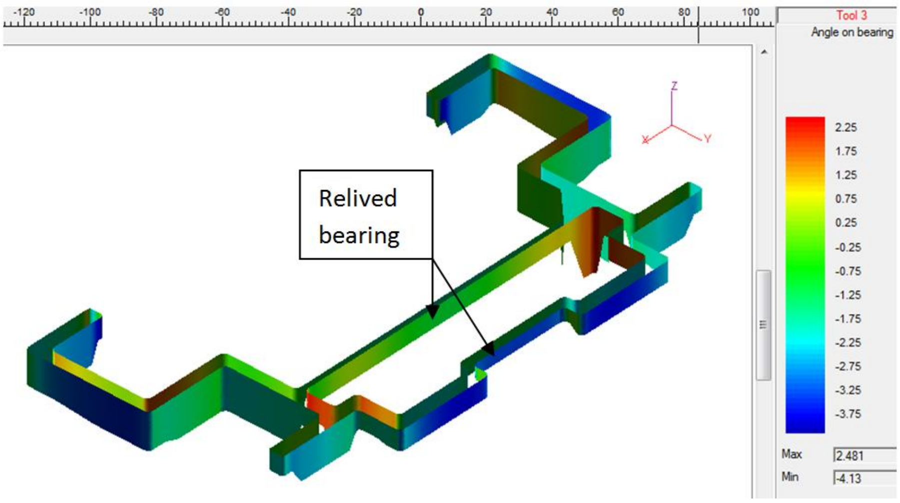
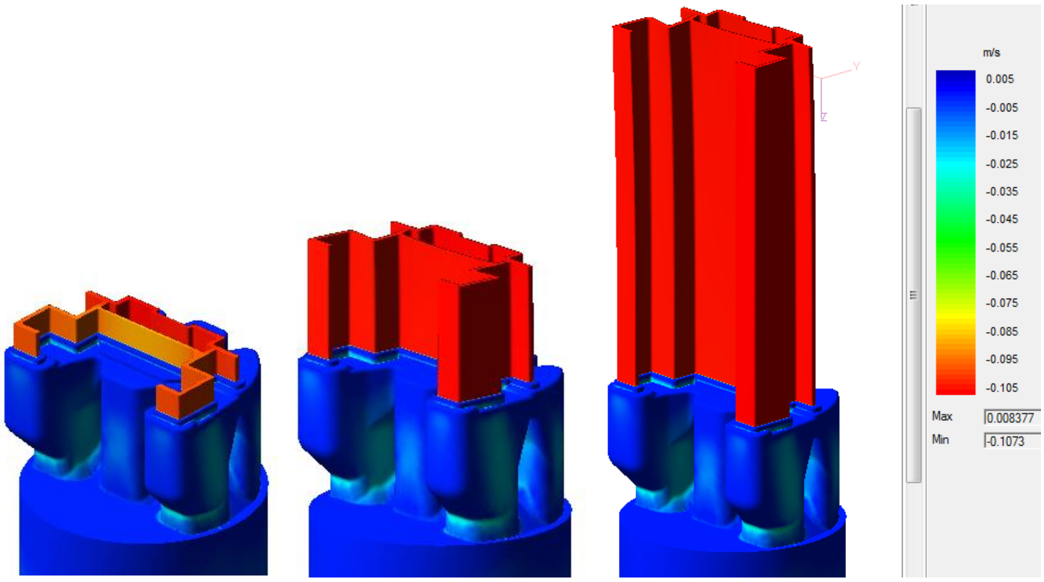


Fig. 8. Distribution of the inclination of initially straight bearing that was induced by elastic deformation of the die. The central part of the profile has got relived bearing.

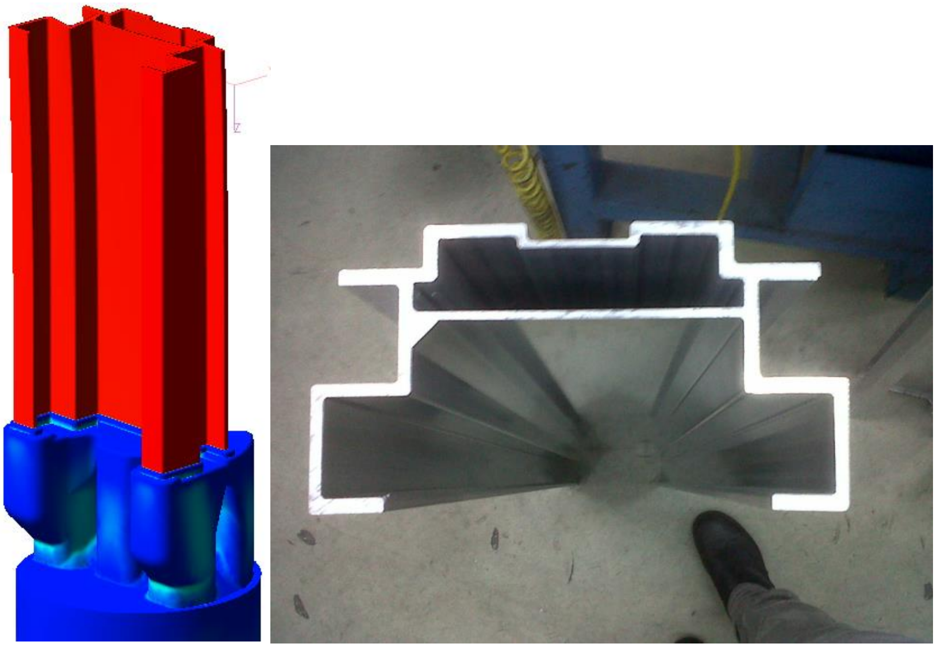
The material flow in coupled simulation depends on deflection of the die and mandrel and it has very big influence on the material flow. (Fig. 9) shows the stages of the front tip formation in coupled simulation. It is clearly seen that the material flow pattern has changed comparing to one in “rigid” die simulation.



a. b. c.

Fig. 9. Sequential steps of the material flow simulation in case of coupled simulation. The beginning of the process (a), intermediate stage (b) and formation of the profile front tip (c).

The simulation of the material flow with taking into account the elastic deformation of the tool set (coupled simulation) has shown that the central part of the profile started to flow with same velocity like the fastest side parts of the profile and exit velocity of the profile has become uniform. This flow pattern is exactly the same as it is in reality. In the Fig. 10 are shown the simulated profile with coupled approach and front tip of the profile from the practice. The simulated material flow is identical the reality.



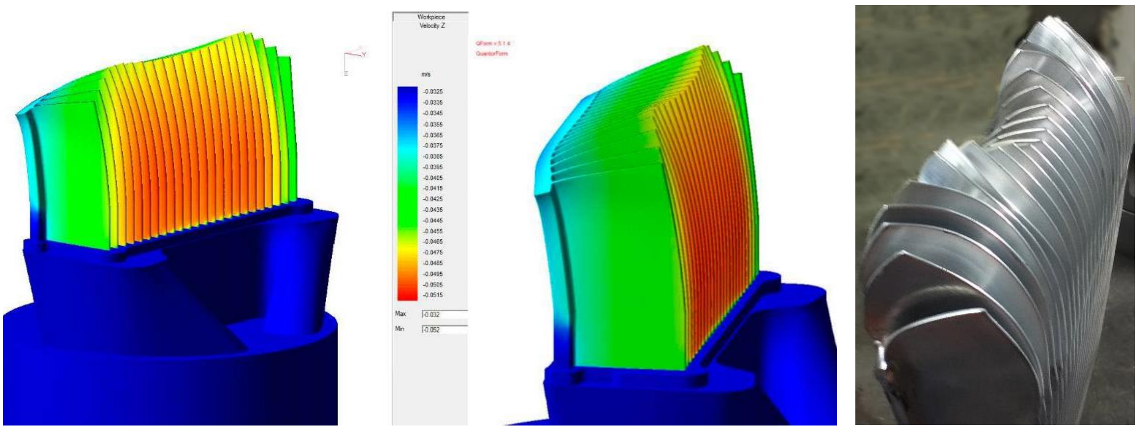
a. b.

Fig. 10. Front tip of the profile in coupled simulation (a) and in reality (b).

Another recent industrial case study[2] is an extrusion of heat sink profile with 24 ribs that results in a numerical model containing about one million nodes (Fig 5a,b). When running this simulation with “rigid” dies it was not possible to get a realistic distribution of the front tip shape that in practice is the evidence of the velocity distribution.

With the facilities explained above it has become possible to obtain the correct material flow pattern that has the following specific features:

- The thin ribs are going faster than the thick back of the profile.
- The velocity in the ribs is not equally distributed along the profile width but has two characteristic maximum “waves” that are clearly seen in the simulation screenshots as well as in the real profile tip in the photo (Fig 5c).
- The fastest ribs are at about a quarter of the total width of the profile from its ends. The slowest ribs are at profile ends. The second slowest ribs are in the center.
- The shape of the ribs in the simulation is less articulated than in the photo. It is because the simulation starts with fully filled die while real tip shapes are also influenced by the material flow during die filling.



a. b. c.

Figure 5. The shape of the front tip of the profile: (a) and (b) two different views obtained in simulation (axial velocity distribution) and (c) is the photo of a front tip in industrial extrusion

The next industrial example shows the importance of coupled simulation when making optimisation of the bearing design. The initial coupled simulation has been performed with constant bearing length. The velocity distribution and profile tip shape are shown on Fig.6. The constant bearing has given significant velocity non-uniformity that resulted in a distorted profile. The velocity distribution along the profile perimeter inside the bearing is shown in Fig. 7. In the case of a uniform bearing, the velocity variation is Vmax/Vmin= 0.43/0.23=1.87 as shown by the graph on Fig. 7a. After optimization the velocity has become more uniform and its variation has been reduced to Vmax/Vmin= 0.36/0.30 = 1.2. Such moderate variation of the velocity becomes even smaller when the material leaves the bearing due to influence of the profile end.

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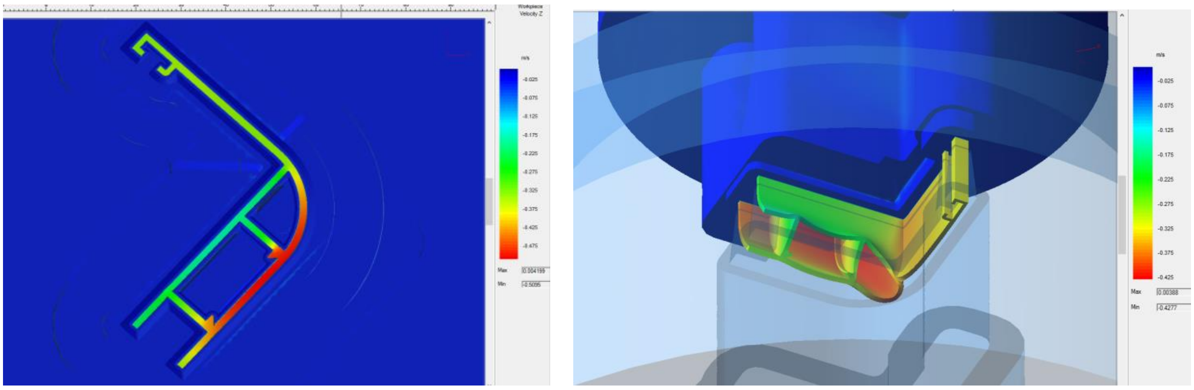
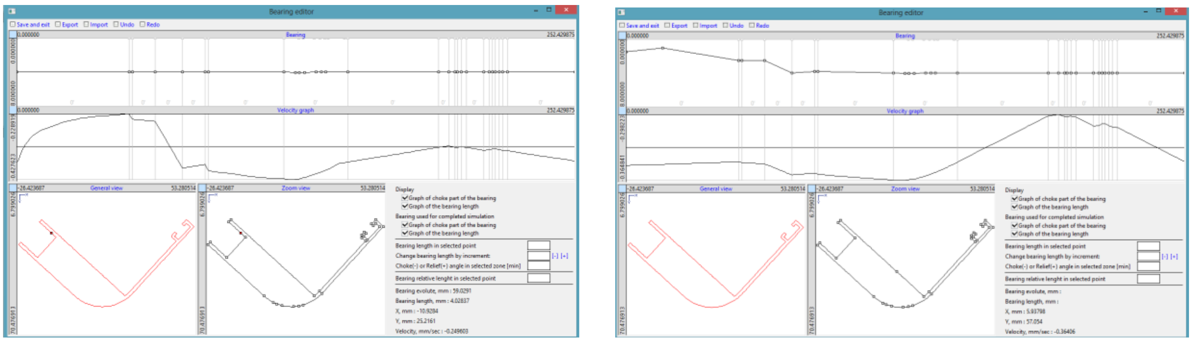


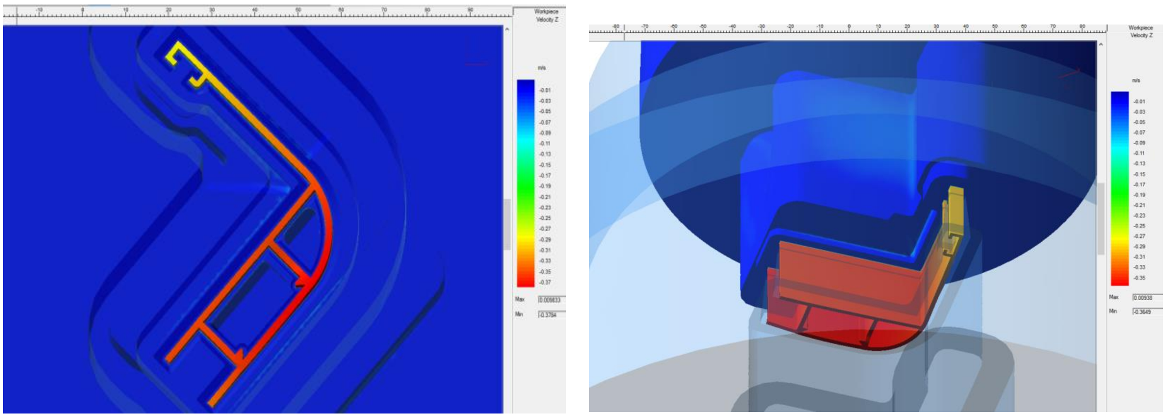
a. b.

Figure 6. The velocity (a) and shape of the front tip (b) in coupled problem with uniform bearing.



a) b)

Figure 7. The bearing length and velocity graph along the profile outer perimeter in coupled simulation: (a) constant bearing length; (b) optimised bearing length.



a. b.

Figure 8. The velocity (a) and the front tip (b) after second iteration of the bearing design.

Coupled thermal problem in the die and deformed material.

In addition to solving coupled mechanical problem in the system "tooling set – deformed material", further development has added the capability to simulate coupled thermal problems. This is performed by sequential solving of the thermo-mechanical problem in the

Euler material flow domain and thermo-mechanical problem in the tools using the actual boundary conditions on their contact surfaces. Thanks to the method of mesh generation implemented in QForm Extrusion, both meshes (in the die and material flow domain) can share the same nodes and triangular elements on their adjacent surfaces. This helps to arrange coupling of the solutions in both bodies in the most effective way.

The principal scheme of a tool set prepared for coupled thermal simulation is shown on Fig. 9. The system allows specifying varying boundary conditions and different values of heat transfer coefficient K and temperature T for an angular sector along the lateral surface of the die. This may result in uneven temperature distribution between opposite halves of the die and may cause a difference in the material flow due to the temperature gradient in the extruded material even in geometrically symmetrical die.

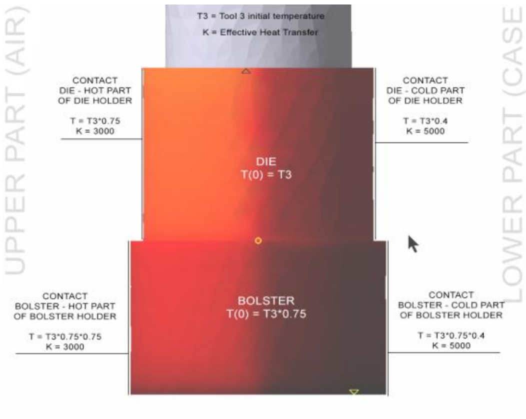
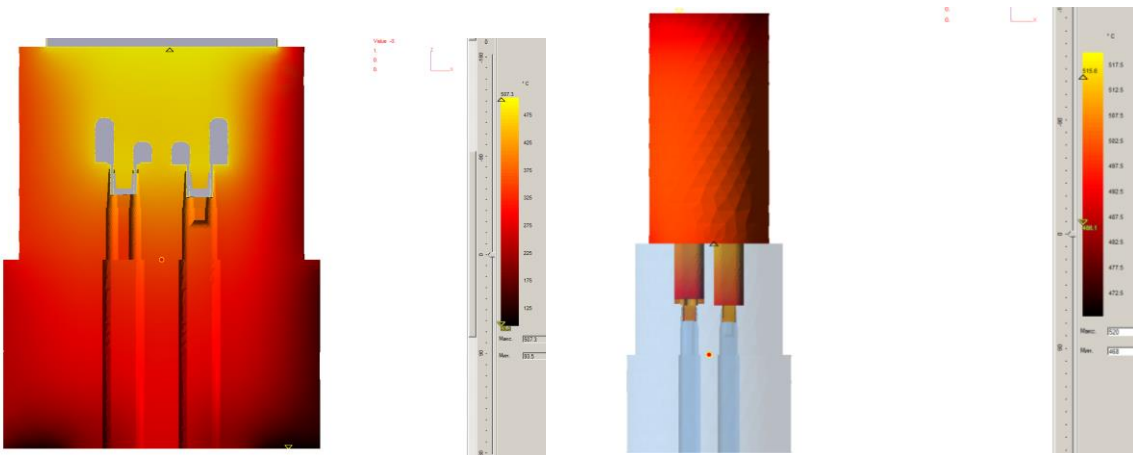


Figure 9. Setting thermal boundary conditions on the die surface.

Below is an example of die temperature distribution in a tooling set used for the benchmark test in Bologna [3]. Initial temperature of the die was supposed to be uniform and equal to 435C, while the initial billet temperature was 520C. The total process time included initial die filling time of about 5 seconds and then 45 seconds of a quasi-steady-state extrusion process. The die had lateral support applied to its sides at 180 degrees while the rest of its lateral surface was exposed to air. The bolster also had contact with a pressure ring that had a constant temperature of 50 C.



a. b.

Figure 10. Temperature distribution in the die crosscut (a) and on the surface of the extruded material (b) after 50 seconds of the extrusion process obtained in coupled simulation.

The temperatures obtained in the simulation are in good agreement with experimentally measured temperatures even though the thermal boundary conditions were not identical. The variation between the temperatures obtained experimentally and in simulation was within 5-10 C in different points. Further research that will be done in the near future will take into consideration more precise setting of the conditions including the time elapsed after setting the tooling set in the press.

Conclusions

1. Numerical model used in QForm-Extrusion program has been enhanced to include coupled simulation of the material flow and die deformation during extrusion process.
2. A special coupled thermo-mechanical model has been built on the basis of QForm-Extrusion program
3. The die deformation causes geometrical changes in the bearing area and by these means it may influence the material flow.
4. The model has been tested using the laboratory experiments with available measurements of die deflection and profile shape and good accuracy of numerical prediction has been observed.
5. Industrial case study has shown very good agreement between practice and coupled simulation in terms of the material flow pattern and formation of front tip of the profile while "rigid" die simulation has shown unacceptable results.

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