Simulation of material flow coupled with die analysis in complex shape extrusion

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Abstract. The paper presents recent studies in simulation of thin profile extrusion technology with the emphasis on interaction between the material flow and the state of the tooling set. To take into consideration die deflection and 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 paper explains the background for this model and some tests to verify its accuracy. Practical implementation of this model at several die making and extrusion companies has shown it to be of higher accuracy compared to the results of rigid die simulation.

Introduction

Extrusion is a precise technology to produce finished products of complicated shape with perfect surface quality while the tolerances of the profile are within hundredths of millimetre. Consequently such technology requires a precise simulation tool. Our recent studies have shown that in many cases the die deflection may have crucial influence on the material flow pattern and accuracy of finish geometry of the profile. Using these research results we have developed a model that takes the die deformation into consideration. It is especially difficult when we approach the bearing zone where the displacement of the tool surface sometimes is comparable with dimensions of the profile geometrical features. To tackle such relatively large displacement a special method has been developed. By these means our model [1] is now able to simulate coupled mechanical problem in the system “material flow domain – assembled die set” even in case of very thin profiles produced in complicated and relatively “flexible” dies. The next logical step ahead was taking into consideration the transient temperature in the tooling set that in turn also may influence the material flow pattern. The proposed approach is illustrated in the paper by several case studies.

QForm-Extrusion is a special-purpose program for aluminium profile extrusion simulation that has been developed by QuantorForm Ltd. The numerical model is based on Lagrange-Euler approach. The simulation starts in Euler domain that represents the space that is completely filled with the material prior to the start of the process. On the other hand the free end of the profile is represented by Lagrange model and this part of simulation domain increases in length very quickly after the die 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 also been done within the International Extrusion Benchmark Tests in 2007, 2009 and 2011 (see, for example, [3, 4]) by means of comparison of the simulation results with precisely measured experimental parameters.

The coupled numerical model formulation

The extruded material is considered as incompressible rigid-plastic continua and elastic deformations are neglected. The system of governing equations includes:

equilibrium equations:

$$\sigma_{ij,j} = 0 , \tag{1}$$

compatibility conditions:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}), \tag{2}$$

constitutive equations:

$$\sigma'_{ij} = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij} , \tag{3}$$

incompressibility equation:

$$v_{i,i} = 0 , \tag{4}$$

and expression for flow stress:

$$\bar{\sigma}=\bar{\sigma}(\bar{\varepsilon},\dot{\bar{\varepsilon}},T) , \tag{5}$$

where σ_{ij} and $\dot{\varepsilon}_{ij}$ – components of stress and strain-rate tensors, v_i – velocity components, σ'_{ij} – deviatoric stress tensor, $\bar{\sigma}, \bar{\varepsilon}, \dot{\bar{\varepsilon}}$ – effective stress, strain and strain-rate, respectively, T – temperature.

In Eq. 1–5 summation convention is used. Comma denotes a derivative with respect to the axis following it. The indexes i and j for three-dimensional problems vary from 1 to 3 and repeated subscript means summation.

Energy balance equation for thermal problem in a workpiece is

$$\rho c\dot{T} = (kT_{,i})_{,i} + \beta\bar{\sigma}\dot{\bar{\varepsilon}} , \tag{6}$$

where β – heat generation efficiency ($\beta = 0.9 \div 0.95$), ρ – density, c – specific heat and k – thermal conductivity. Similar equation but without the last term is valid for the thermal problem in the tools where no heat is generated inside of the body.

The die material is supposed to obey Hook's law

$$\sigma'_{ij} = 2G\varepsilon'^{e}_{ij} , \tag{7}$$

$$\sigma_o = K\varepsilon_V , \tag{8}$$

where G is the shearing elastic module, ε'^{e}_{ij} is the deviatoric elastic strain tensor, σ_o is the mean stress, K is volumetric elastic module, ε_V is the volumetric elastic strain. The system of equations for the tool also includes equilibrium equations Eq. 1 and compatibility equations similar to Eq. 2 but formulated in displacement components.

The deformed shape of the tools is the result of application of the load from the extruded material to the tool surface [5]. 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 of the element size may cause non-convergence problem 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. In our model such mesh optimisation is performed automatically without user intervention [6].

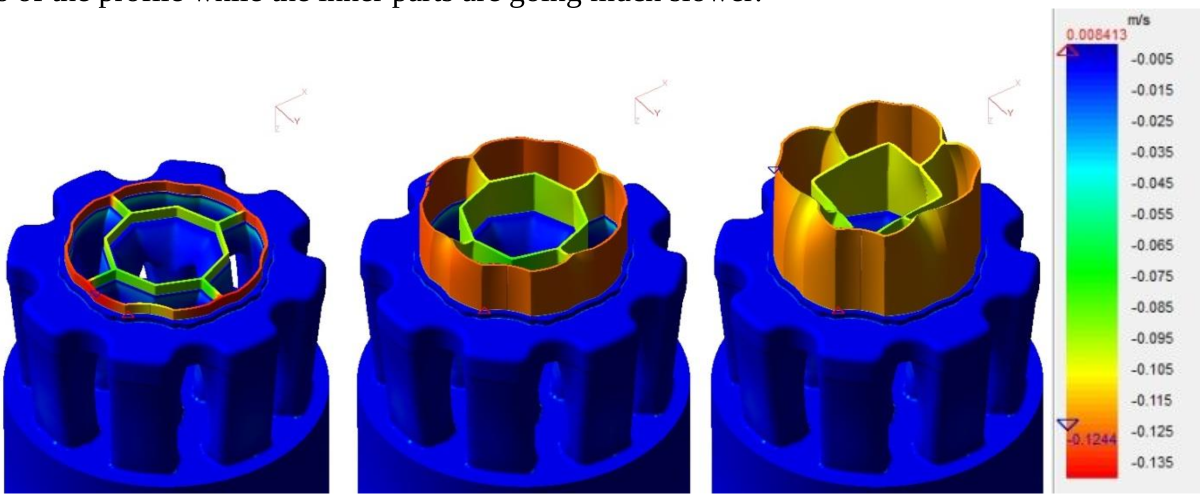
For accurate prediction of the material flow in extrusion process it is also necessary to take into account realistic friction and heat transfer conditions between extruded material and the tooling set. Numerous experimental and theoretical studies show that friction traction on the interface between 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. Consequently depending on the value of the normal contact stress it is necessary to apply different mechanisms of friction as it is explained in our work [7].

The mechanically coupled model realisation

Mechanically coupled simulation requires taking into consideration displacement and distortion of tool surfaces that may have significant influence on the material flow especially in bearing area. Relative linear displacement of the opposite sides of the bearing in many cases may reach half a millimetre or more that is actually comparable with a profile thickness. When the opposite bearing sides shift due to elastic die deformation, the 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 best 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 use the advantage of keeping the bearing geometry as a parametric 3D surface as was explained in our previous work [2]. It allows distinguishing which nodes are placed on the bearing surface and also to take into consideration not only liner displacements of the nodes but also very fine inclination of bearing surface that may vary within just a few angular minutes and create local zones with choke or relief caused by die deformation. Though small, such bearing angle variation may also influence the material flow patterns as has been shown by our simulation practice as well as laboratory tests.

The importance of the mechanically coupled simulation has been shown by the following industrial case study[1]. The simulation of the profile extrusion has been done in two variants, firstly, using "rigid" dies and, secondly, using coupled simulation when the deformation of the die may influence the material flow. Extruded material was AA6063, ram speed 5 mm/s, initial billet temperature 500^{o}C and the die temperature was 430^{o}C. The material flow through the "rigid" die is shown on (Fig.1). It is clearly seen that with such assumption the fastest material flow is in the outer parts of the profile while the inner parts are going much slower.



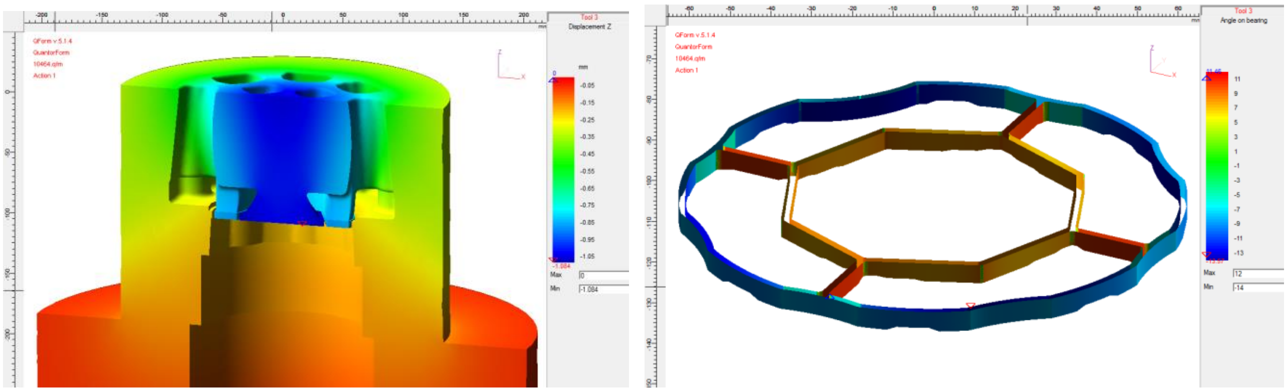
a) b) c)

Figure 1. 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 observations didn't confirm the material flow pattern that was obtained in the variant of simulation with "rigid" dies. The deformation of the dies was most probably the reason for such discrepancy. It is because the die has significant deformation in the bearing area as we can estimate by simulation (Fig. 2a). Actually this die has four outer mandrels that form the outer holes in the profile and one inner mandrel providing the central hole. The axial displacement of the outer and inner mandrels differs significantly causing changing of the contact conditions on respective

[1] Photo courtesy of Mr. Hasim Derman (FF-Ex, Turkey)

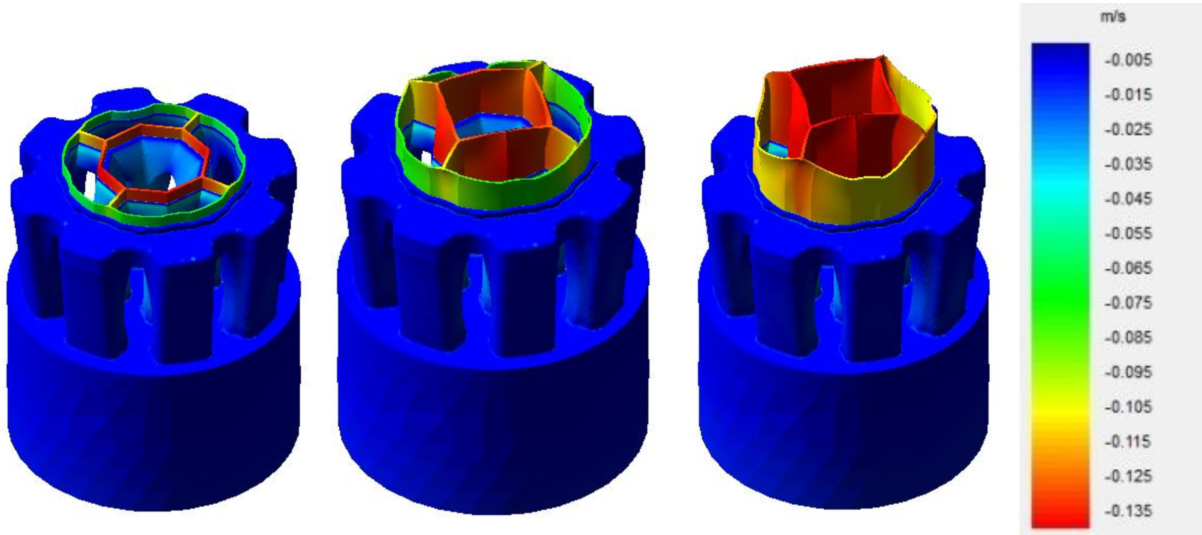
areas of the bearing. Moreover, the die deflection in bearing area causes inclination of the initially straight bearing. This inclination varies in different parts of the profile. The bearing in outer parts of the profile has got choke up to 14 angular minutes while inner parts of the profile have got relief up to 12 minutes. The distribution of the choke and relief on the die bearing is shown on (Fig. 2b) where choke corresponds to negative values and relief is positive.



a) b)

Figure 2. Die deformation: axial displacement in the crosscut of the tooling set (a), inclination of initially straight bearing (b).

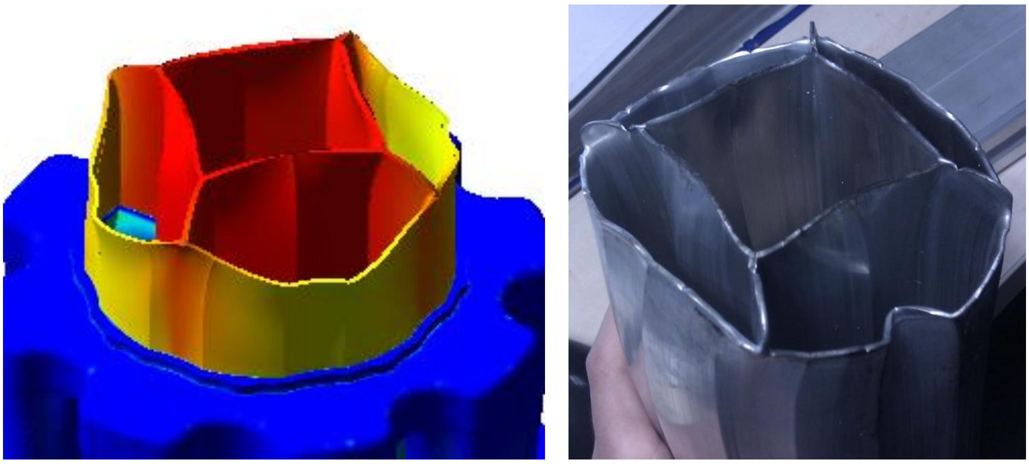
With such relatively big displacement of the tooling set it is clear that coupled simulation is to be implemented and Fig. 3 shows the stages of the front tip formation in this case. It is clearly seen that the material flow pattern has changed to the opposite compared to the extrusion from the “rigid” die simulation.



a) b) c)

Figure 3. Sequential steps of the material flow in case of coupled simulation. The beginning of the process (a), intermediate stage (b) and formation of the profile front tip (c).

Coupled simulation has shown that the inner part of the profile goes faster than the outer parts. This flow pattern is exactly the same as it is in reality (Fig. 4) thus for such kind of profiles with complicated and relatively flexible die set the coupled simulation is the only method to get realistic numerical prediction of the material flow.



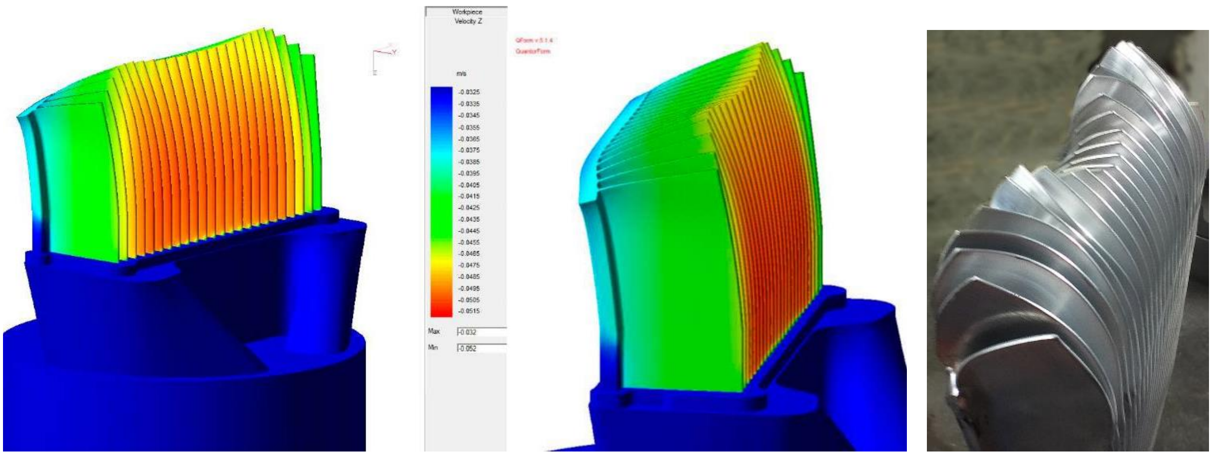
a) b)

Figure 4. 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.

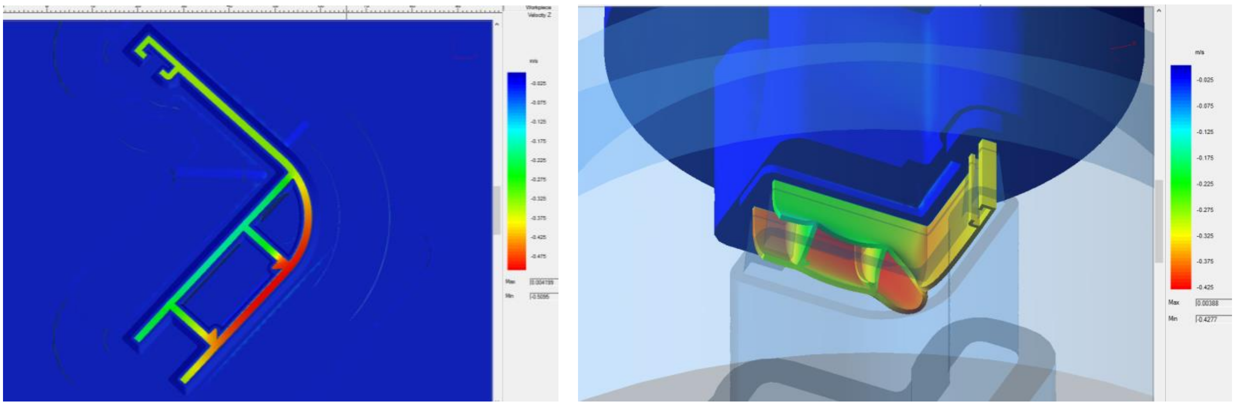


a) b) c)

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

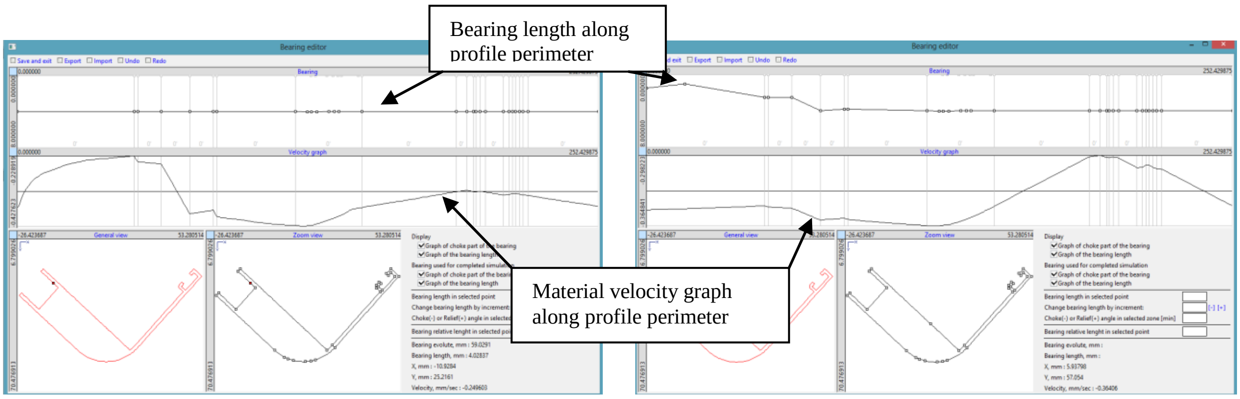
[2] With permission of Thumb Tool & Engineering Co. (USA)

The next industrial example[3] 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 optimisation 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.



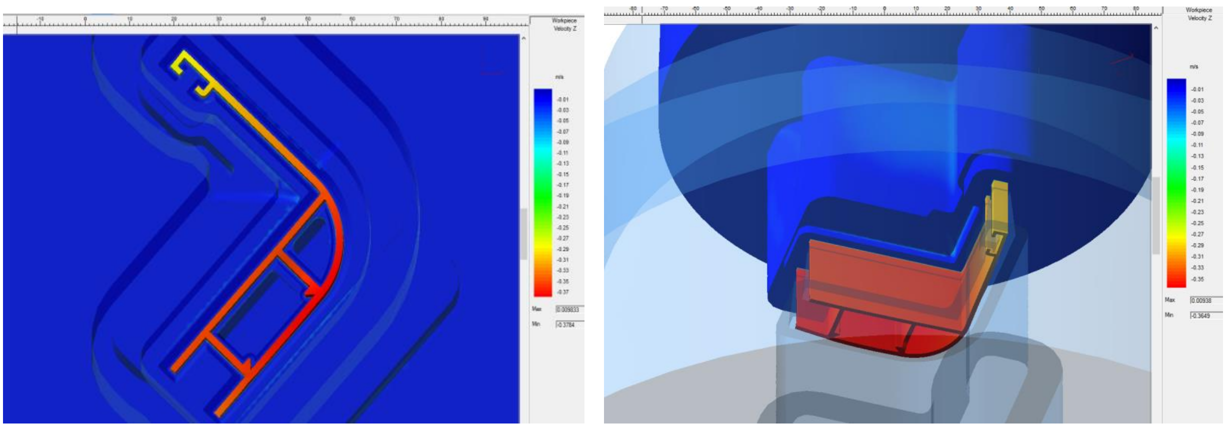
a) b)

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.

[3] The geometry courtesy of COMPES s.p.a., Italy

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.

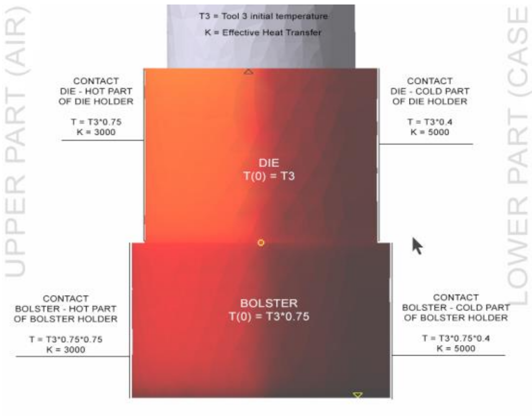
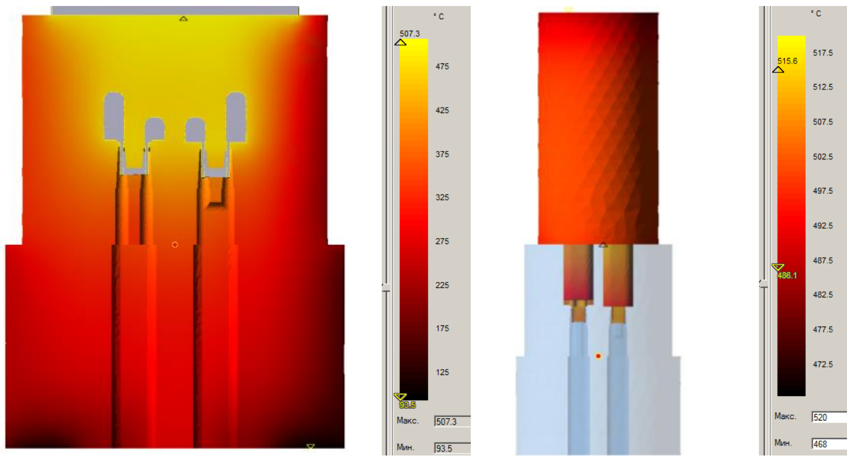


Figure 9. Setting thermal boundary conditions on the die surface.

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 435^0C, while the initial billet temperature was 520^0C. 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 50^0C.



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^{0}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.

Summary

The presented study is focused on analysis of interaction between the material flow and deformation and temperature of the tooling set. A special coupled thermo-mechanical model has been built on the basis of QForm-Extrusion program. Industrial studies have shown good agreement of simulation results with practical observations. The paper shows importance of taking into account fine effects of bearing area displacement and inclination that have significant influence on the material flow in case of complicated hollow dies.

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