QUANTITATIVE EVALUATION OF PORTHOLE DIES DESIGN PRACTICES BY MEANS OF FE ANALYSES

Tommaso Pinter - Alumat & Almax Mori, Italy
Barbara Reggiani - University of Bologna, Italy

Abstract

During the last decade, finite element simulations have became a very useful technology for tool designing, especially in such cases, like in the extrusion process, where on-plant die trials are expensive and sometimes of difficult interpretation.

However, even if good die-design practices are well known by the leading industry players, quantitative evaluations of commonly adopted die-design solutions are seldom available in literature.

This contribution presents the preliminary results of a new approach for porthole dies design optimization by means of finite element analysis using HyperXtrude® software.

Introduction

Since the last years, in the extrusion context, finite element (FE) codes are becoming the most important tools for process and product optimization.The current state of the numerical simulation applied to the extrusion process has been exploited by an extrusion benchmark conference in several past editions (1,2). As a result, a generally significant increase of codes accuracy was found in the prediction of process load, material flow and temperature evolution.

Accurate finite element simulations can be performed to study the material flow, temperature distribution, process loads, and tools performance (3,5). By means of the numerical simulations, process parameters can be optimized in order to enhance the product properties and, more in general, to increase productivity at a relatively low cost.

Nowadays, die-makers are called to produce higher productivity tools without compromising knock-off rates. One of the main aspects to be considered while designing a porthole extrusion die is the geometry of legs and ports in the mandrel plate. In fact, the mandrel geometry modifies locally the strain (ε) and the strain rate ($\acute{\varepsilon}$) levels thus influencing the required ram force for a given ram speed, the stress on the legs (and consequently their performance), the pressure in the welding chamber and the temperatures.

In order to quantitatively evaluate the effects of the best practices adopted in the design of porthole extrusion dies, a new methodology and its preliminary results are presented and discussed in this contribution.

Experimental activities and 3D model validation

A 51.5 mm outer diameter and 2 mm wall thickness tube made of ZM21 magnesium alloy was extruded at 1 mm/s ram speed on a 8 '' billet container direct extrusion press with a maximum capacity of 2100 tons.

The 500 mm length billets were preheated at a temperature of 440 °C in a single cell oven with vacuum atmosphere. A temperature of 440 °C was chosen also to preheat the porthole die.

The container was heated to 420 °C by a controlled heating system. Due to only small changes of +/-5 °C before and after extrusion, the container temperature was considered to be constant over the entire process.

The porthole die was designed taking into consideration the requirement of an uniform strain increase from die inlet down to die bearings in order to avoid local concentration of stress. Once defined the geometry of legs, welding chambers and bearing areas, FE simulations were performed to define the optimal number of legs in order to minimize the required ram force without compromising the mandrel stability; ports shape and number of legs were then optimized in order to reduce the resistance to flow. A three legs die was chosen as shown in Fig. 1.

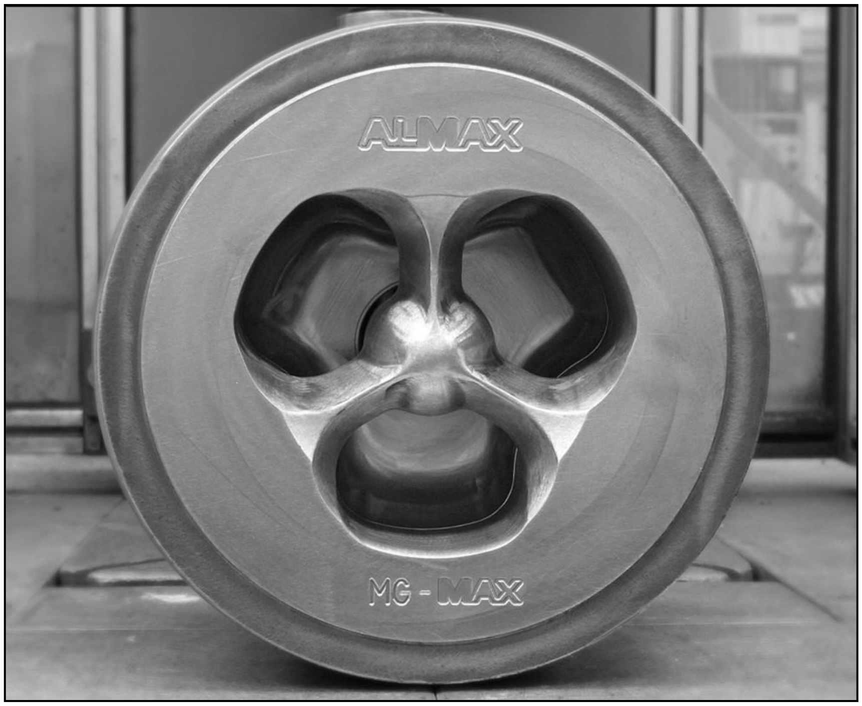

Figure 1: Front picture of the porthole die used for the experimental activities.

Transient simulations were performed by means of HyperXtrude® using the geometry shown in Fig. 1. HyperXtrude® is a FE code based on the fluid-dynamic formulation that adopts an ALE approach; this allows to simulate a realistic load-stroke curve due to the progressive decreasing of the billet-container friction by means of the moving boundaries technique. The same process parameters used for the experimental activity were used as boundary conditions for the numerical simulations (data are protected by an I.P. agreement).

In order to perform reliable and accurate FE simulations, a correct definition of the flow stress dependence on thermo-mechanical parameters is an essential prerequisite (6). The inverse sine hyperbolic relationship (7,8) is widely used for modelling the flow stress behaviour of magnesium alloys (9). The FE simulations were run using the material constants shown in Table 1 (10). A HTC (Heat Transfer Coefficient) value of 3000 W/m^{2}K was imposed both at the die-workpiece and at the container-billet interfaces.

Alloy	**n**	**Q_{HW} [J/mol]**	**A [sec^{-1}]**	**α [MPa^{-1}]**
ZM21	3.95	164000	1.06E+12	0.024

Table 1: Constitutive parameters used for the model validation.

A good correspondence between numerical and experimental results was achieved. As shown in Fig. 2, the load-stroke history and the maximum load were predicted in close agreement with experimental results.

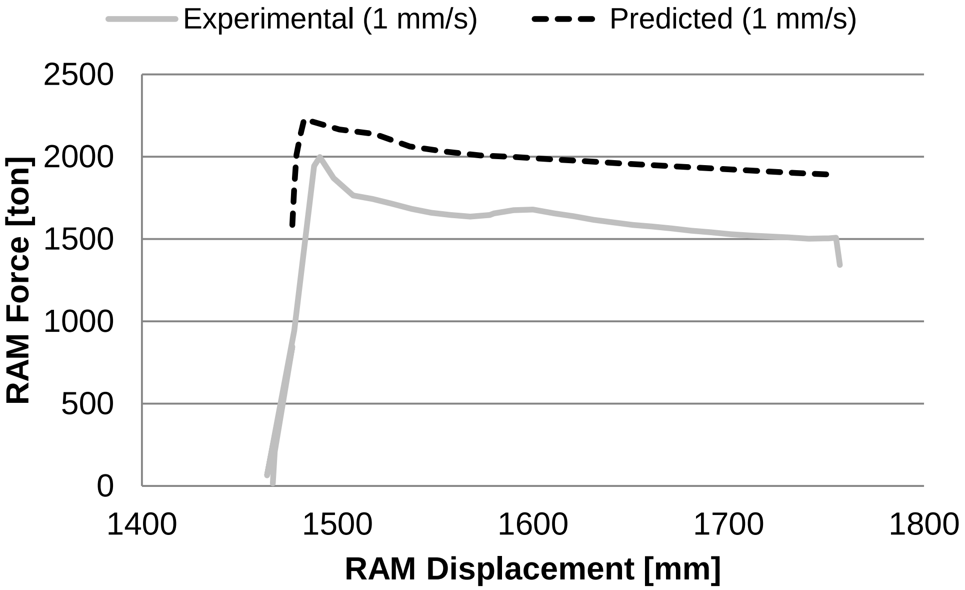

Figure 2: model validation by means of ram force.

Numerical Investigation

Accurate FE simulations were performed to investigate the material flow and the tool performance with the final aim to evaluate different porthole die design solutions. Among the many topics of interest, the design of leg chamfer geometry and mandrel inlet were chosen for their capacity to influence significantly the material flow.

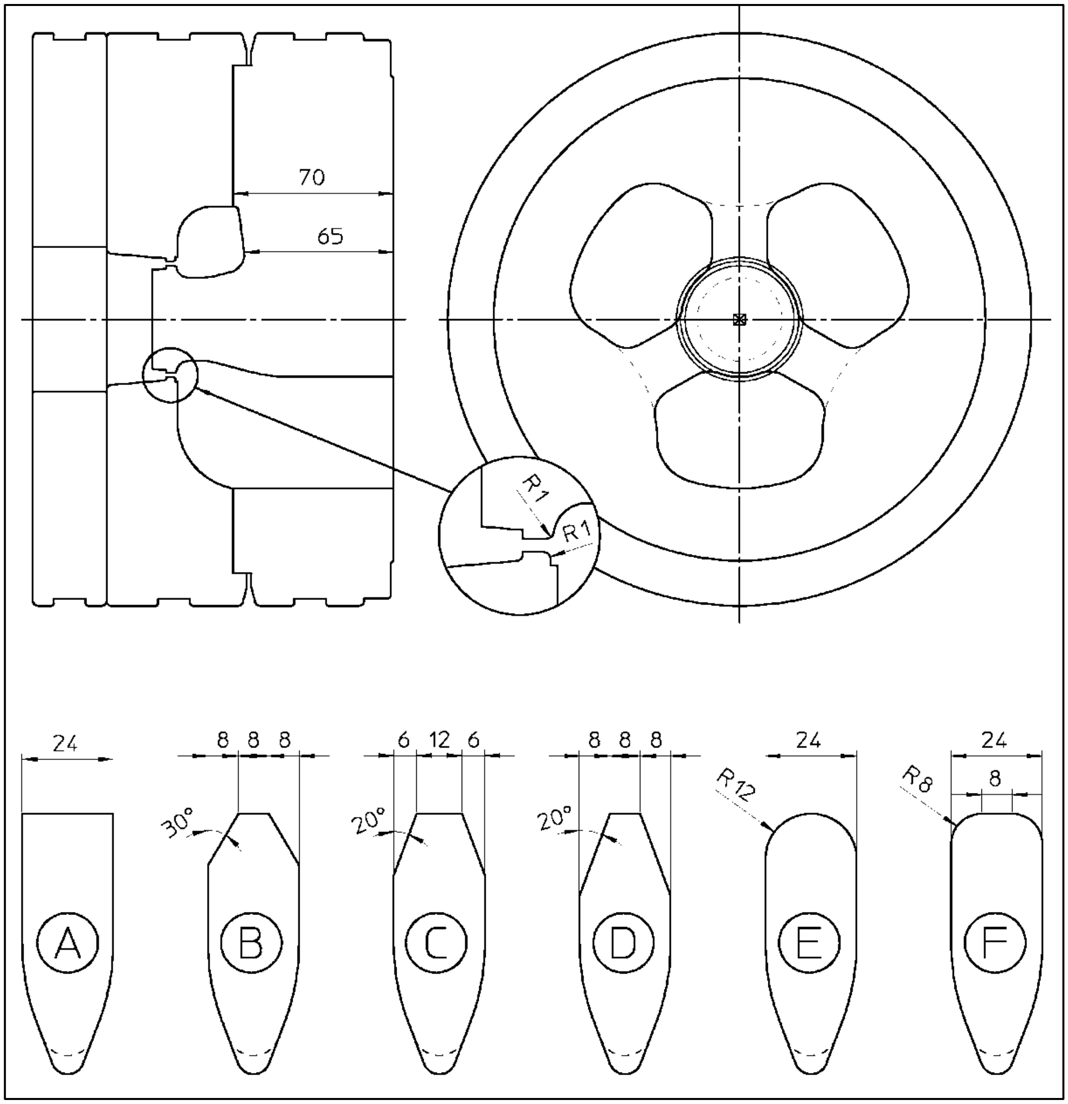

Figure 3: Base die design and geometries of the six chamfers investigated by means of steady state simulations.

A steady-state simulations plan was defined in order to compare different leg geometries for the same process conditions.

Fig. 3 shows the basic die design and the six different leg geometries investigated. In all cases, a radius of 1 mm was placed on the bearings.

A uniform 440 °C preheating temperature was used for die and workpiece, while the ram speed was settled at 1 mm/s for all the simulations.

Attention was paid to the preparation of the six FE models in order to minimize the influence of the workpiece model architecture on the numerical results. In particular, an identical size of the tetra-elements was adopted for each model in the different workpiece sections. Numerical results are summarized in Fig. 4 in terms of ram force and extrudate temperature at 50 mm from the die back for all the chamfers geometries investigated.

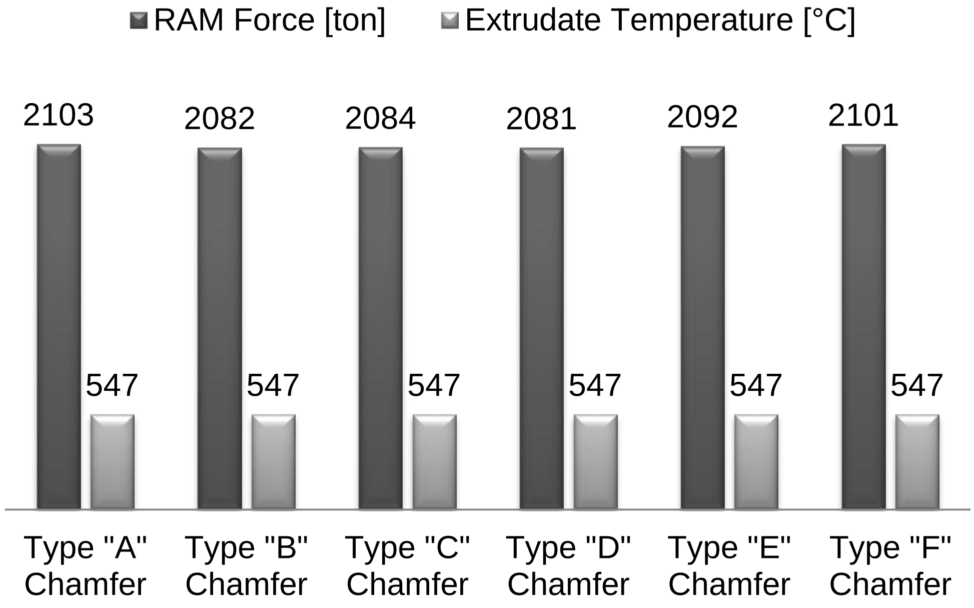

Figure 4: numerical result for the 6 geometries investigated.

It can be noticed that the different chamfers geometries produced a not significant variation in terms of ram force; predicted differences in the ram force were all in the range of +/-1 %. In addition, FE simulations did not predict any difference in the extrudate temperature. The adoption of chamfers does not influence significantly the extrudate temperature.

The steady state simulations cannot predict any relevant difference between type "A" and type "F" leg design in terms of required ram force; even if the best choice seems to be the type "D" chamfers, results demonstrate that chamfers geometry has a very modest influence on the resistance to flow for the die geometry analyzed in this paper. On the basis of the previous considerations, a second set of tool geometries was investigated by means of steady-state simulations in order to quantitatively evaluate the effect of different porthole die design practices on material flow and tool stress. Thus, starting from the design "D" in Fig. 2, a 12 mm conical lowering (solution "X" in Fig. 5), a 5 mm undercut on ports (solution "Y" in Fig. 5) and a 2 ° relief (solution "Z" in Fig. 5) were added one by one.

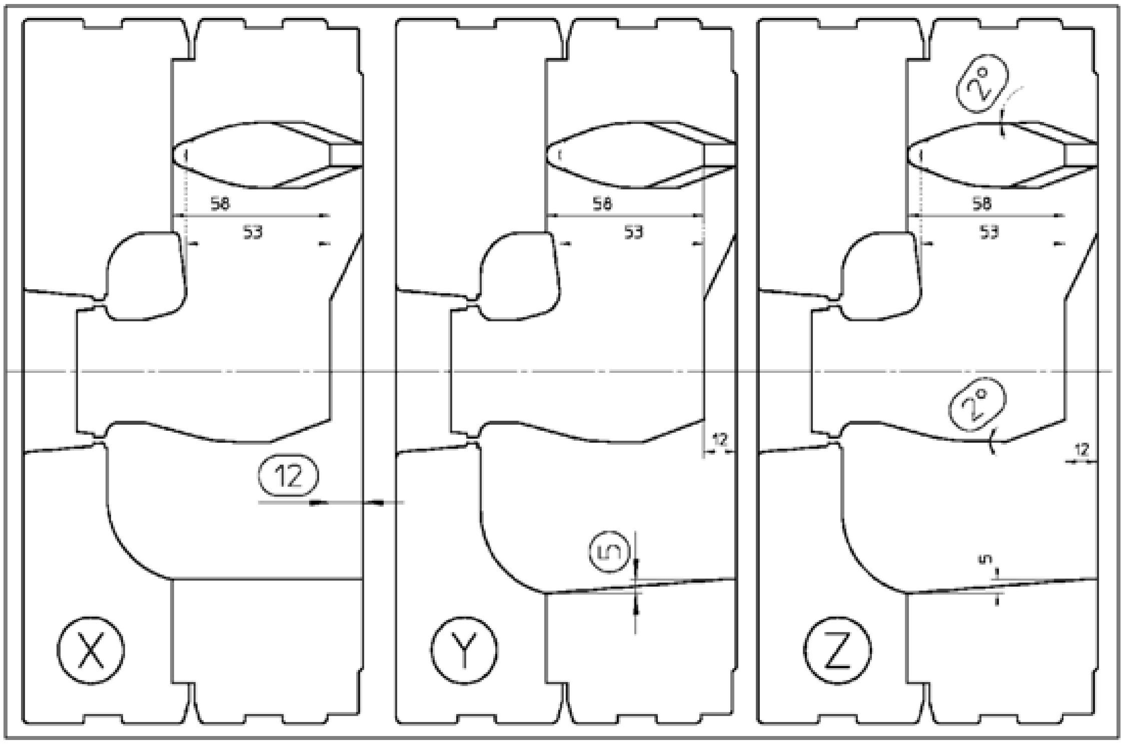

Figure 5: Die designs investigated in the second set of steady-state simulations.

Results are summarized in Fig. 6 in terms of ram force and profile temperature for the most interesting geometries investigated. The chart shows the step-by-step reduction of the ram force and exit temperature by means of summing different design solutions one to the other.

Starting from a standard type "A" geometry, the ram force was reduced of a 3 % adopting type "Z" geometry. Fig. 6 demonstrates that the improvement given by adding a single design enhancement is not relevant; only the sum of several best practices can reduce the resistance to flow of a porthole die.

An additional consideration is that adding a relief on legs and central mandrel can reduce the resistance to flow more than manufacturing the mandrel ports with an undercut. Finally it must be noticed that removing the radius at the bearings can increase significantly both the extrudate temperature and the ram force; this is probably due to the capacity of the radius to reduce locally the strain rate.

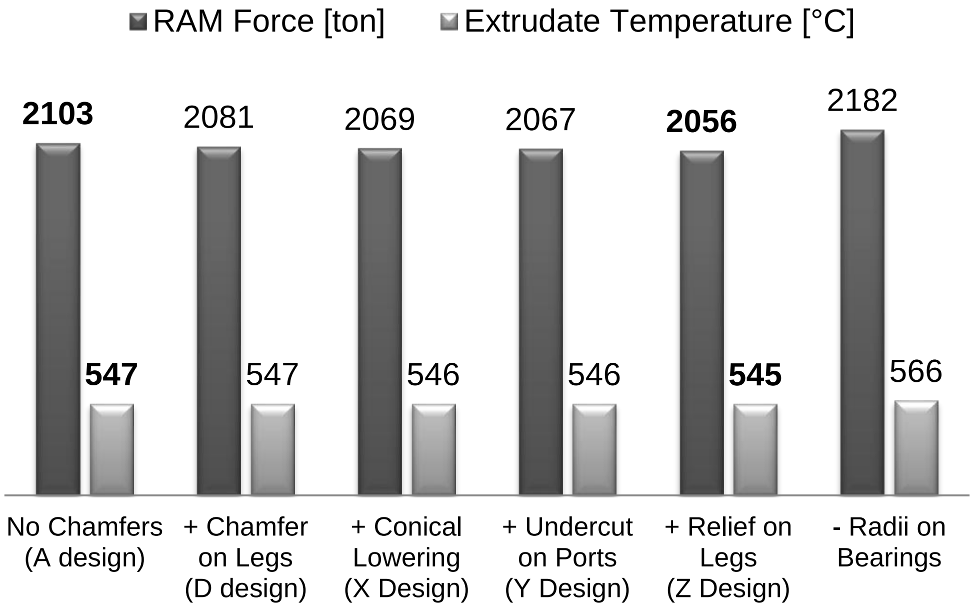

Figure 6: Numerical results in terms of ram force and extrudate temperature. A 1mm radius on bearings (Fig. 2) is more effective in reducing the RAM force than the sum of enhancements "D", "X", "Y" and "Z".

After the preliminary analyses, transient simulations were performed for type "D" and "X" designs in order to comprehend the effect of the conical lowering on the pressure at the contact between workpiece and the central part of the mandrel; Fig. 8 shows the point chosen for the measurement of the predicted workpiece pressure.
The evaluation of the stress on the die was performed using the "Tool Deflection Analysis" module of HyperXtrude®; a working temperature of 440 °C, a Young modulus of 160 GPa and a Poisson's ratio of 0.3 were settled in the linear-elastic material model.
Fig. 7 shows a comparison between the time history of the pressure on mandrel during the ram acceleration. A mandrel lowering at the inlet implies less ram force during extrusion and less load on the legs. However it must be noticed that the predicted pressure reduction is small and in the specific case of type "X" design is equal to 2.5 %. The ALE approach of HyperXtrude does not allow to evaluate the pressure evolution during die filling-in. For this reason the results shown in Fig. 7 are valid only for dies stored with billet material.

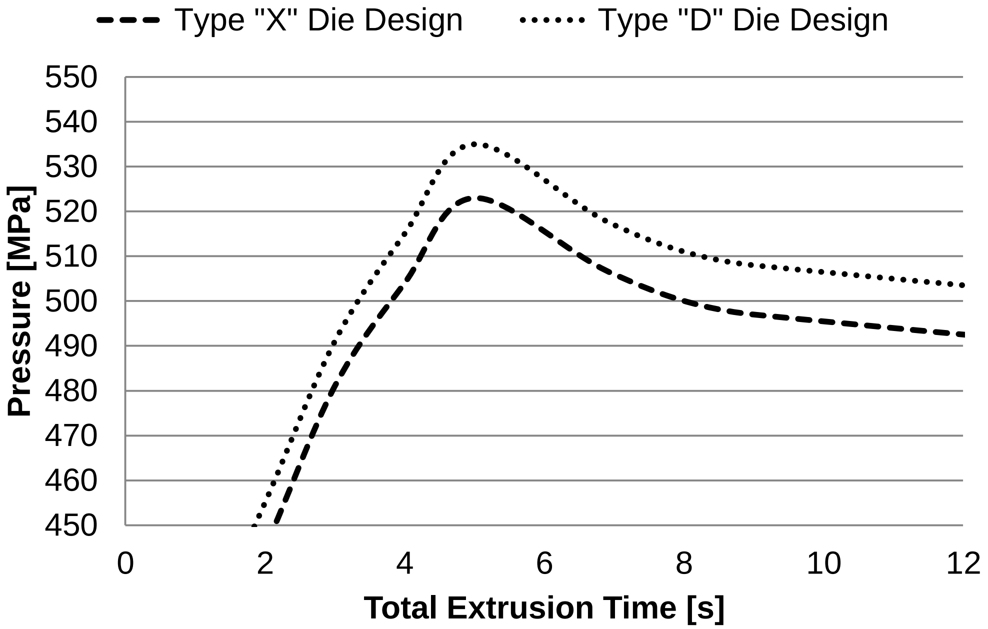

Figure 7: Comparison between type "D" and type"X" designs in terms of pressure on mandrel [MPa].

Fig. 9 and Fig. 10 show the numerical results in terms of Von Mises stress along the leg. Sections were taken next to the central mandrel were the highest stress was predicted; Fig. 8 shows the location of the section investigated.

In the "D" solution a peak Von Mises stress of 900 MPa was found on the back side of the leg next to the central mandrel (due to the thinning of the leg) while the stress on the incoming edge was very low (about 200 MPa). On the "X" die a 10 % higher peak stress value was found (around 1000 MPa).

Results underlined by the comparison between type "D" and type "X" designs shows that a conical lowering of the leg can reduce by merely 2 % the load on the legs while it determines an increasing of the peak stress by almost 10 %. This implies that the adoption of a conical lowering of the leg should be carefully sized.

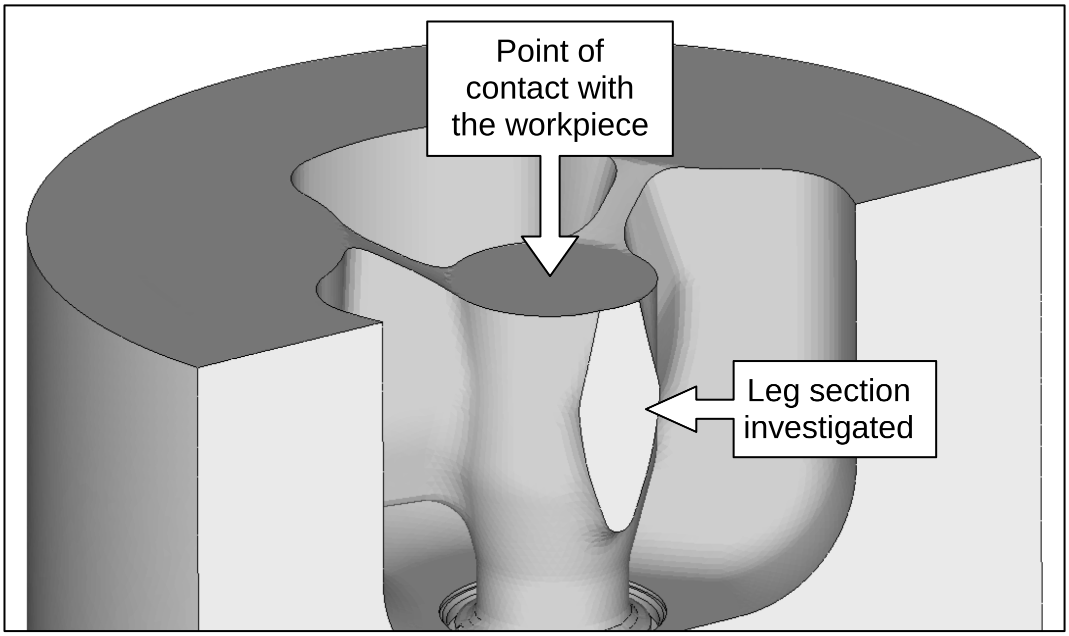

Figure 8: Section view of the tool model used for the stress analysis (type "X" design).

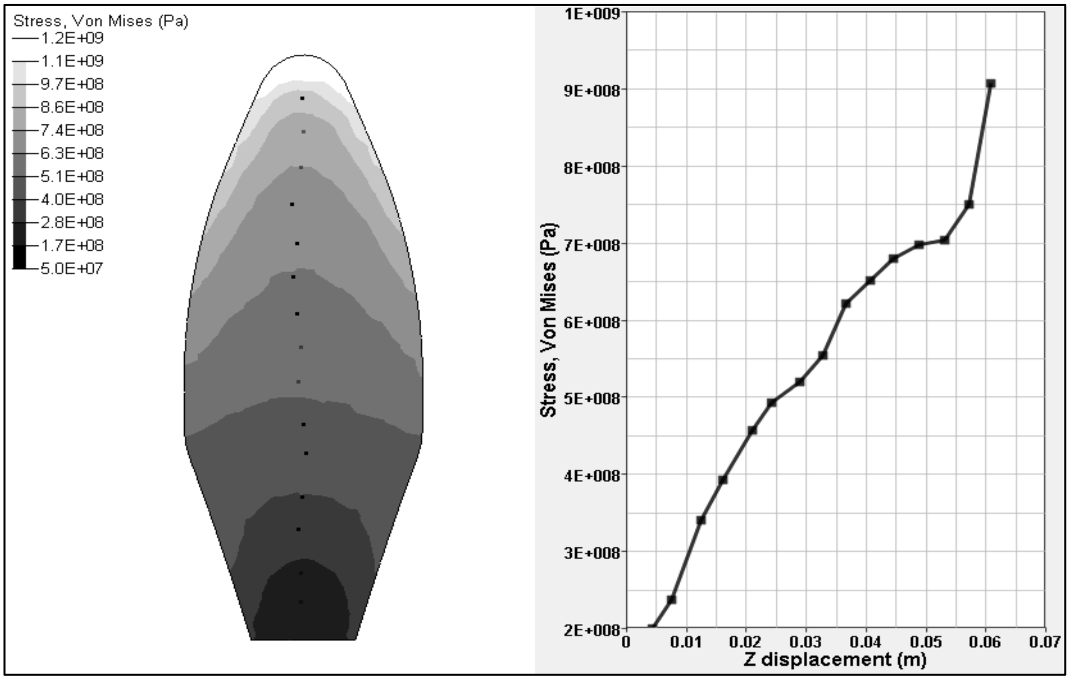

Figure 9: Predicted (Von Mises) stress along the leg section for type "D" design.

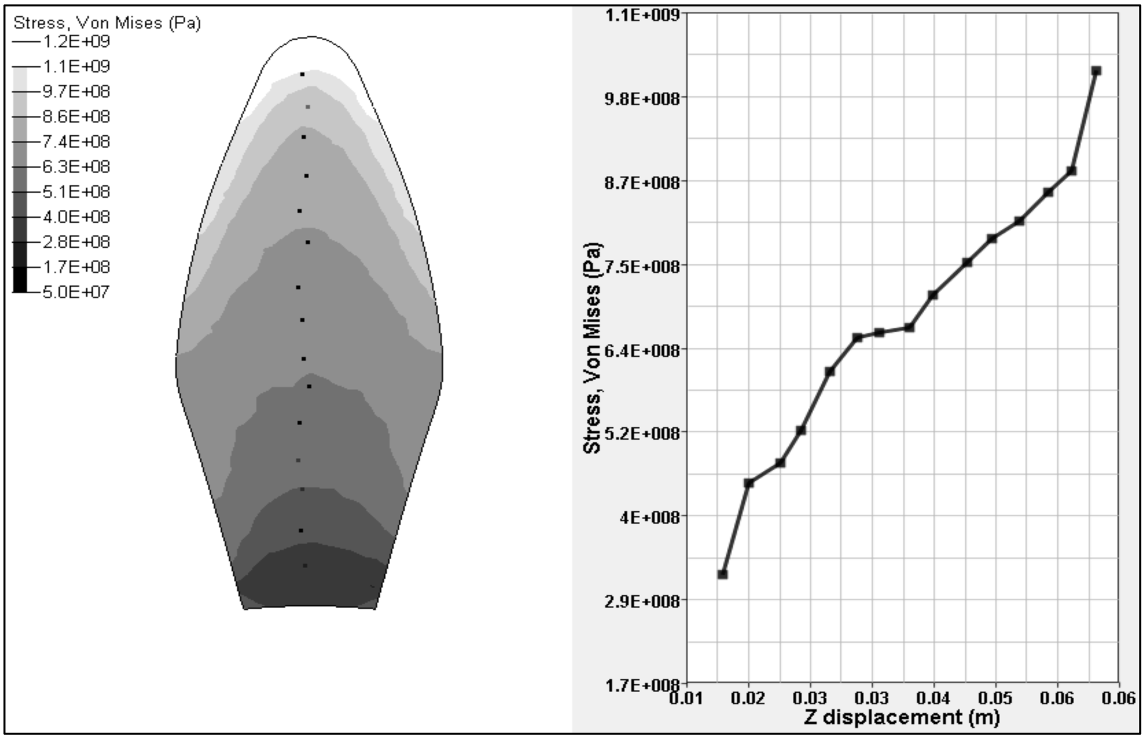

Figure 10: Predicted (Von Mises) stress along the leg section for type "X" design.

Conclusions

Several numerical simulations at fixed boundary conditions were performed in order to evaluate quantitatively the influence of portholes dies design practices on ram force, stress on mandrel legs and extrudate temperature. In particular it was found out that:

- chamfers on leg entrance imply lower ram force during extrusion. Our recommendation is to add chamfers to mandrel legs and not radii at corners;
- a mandrel with a conical lowering at the inlet does not reduce significantly the force required to extrude a billet into a pre-filled porthole die;
- the addition of an undercut at the exteriors of the ports can reduce the RAM force;
- the addition of a relief on the legs and central mandrel can reduce the RAM force more than the adoption of an undercut on ports;
- the adoption of a radius at the bearings inlet reduces significantly the extrudate temperature;
- only the sum of several design practices can reduce significantly the resistance to flow of a well designed extrusion die.

Further investigations will be done in order to understand the sensitivity of the obtained results varying the geometric scale of the process.

Acknowledgments

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