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QUALITY PREDICTION AND IMPROVEMENT OF EXTRUDED PROFILES BY MEANS OF SIMULATION

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Abstract

The paper presents recent studies in simulation of profile extrusion technology with the emphasis on product quality control and improvement. It includes balancing of the material flow by means of die design optimization, control of heat balance during extrusion process, controlling of location and strength of seam welds, minimizing distortion of the profile shape during cooling and heat treatment and prediction and improvement of the microstructure and material properties. The approach is based on numerical simulation and use of automated die design software and some industrial case studies are discussed.

Introduction

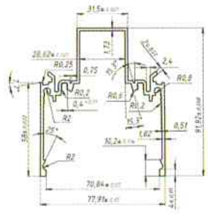
The simulation method implemented in the presented paper is based on an integrated approach that couples the Finite Element (FE) model of the material flow with the deformation and temperature in the die. This means that the elastic deformation of the die influences the material flow, while the die distortion itself is dependent on the contact pressure applied by the deformed material [1,2]. Such a coupled solution is obtained through several iterations combined with automated remeshing of the flow domain. With this method we get the most accurate results in the material flow and profile shape accuracy as well as temperature in the billet, die and profile. In case of taper heating of the billet, the initial temperature gradient is also taken into account. The solution shows possible distortion of the profile shape and variation of its thickness that may be significantly different than expected due to elastic deformation of the die orifice. Thus, a coupled simulation allows us to design dies to compensate for the elastic deformation of the die to keep the profile geometry within tolerances. It is also possible to take into consideration the profile shape distortion due to stretching and cooling.

The next important profile quality parameter is the location and the strength of seam welds. The simulation accurately predicts seam weld positions and the die designer can change their location by modifying the shape of the feeding channels. Seam weld strength is dependent on the length of the welding chamber, the pressure and temperature of the material in it, as well as the extrusion speed so the simulation allows analysis of all these parameters to get the best welding quality [3,4].

As soon as the profile exits the die we are able to simulate its cooling and get some prediction of the microstructure based on the model of dynamic and static recrystallization of aluminium alloys [5,6]. This model incorporates some empiric formulae and is supported by experimental investigation. Thus with the help of simulation, we are able to get significant economic benefits by controlling most of the quality parameters of an extruded profile such as its geometry, seam weld quality and finish properties.

Improving geometric accuracy of the profile in case of significant die deflection

The extruded material is subject to extremely high deformation and its flow through the die is very complicated. Ideally we would like to have uniform distribution of the axial velocity and constant temperature in the extruded material when it leaves a bearing to provide an undistorted profile shape. In reality the velocity and the temperature at the die orifice is not uniform. Thus the first task of a good die design is to balance the material flow through the bearing that should keep the profile shape within admissible tolerances. Furthermore, the accuracy of a profile is largely dependent on elastic deformation of the die that causes changing dimensions of a die orifice and small inclinations of some parts of the bearing. Such small choke or relief zones caused by elastic deformation may significantly change the conditions of the material flow. Thus the coupled approach to simulation is essential and has been proved in [2]. An industrial case study of extrusion of a solid profile presented below illustrates the significance of this approach. The numerical simulation was performed using QForm VX software in parallel to industrial trails for the solid aluminum profile shown in Fig. 1



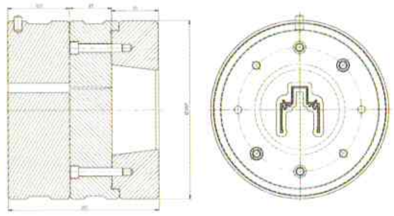


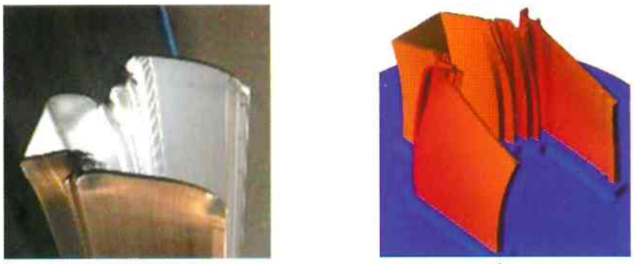
Figure 1. Extruded profile drawing
Figure 2. Initial design of a die set

The drawings of the extrusion die are shown in Fig. 2. As seen from the drawing the flat die has quite long console "tongue" of complicated configuration. The main process parameters of the industrial trail are presented in Table 1.

Initial billet temperature, °C	460
Billet diameter x Billet length, mm x mm	232x500
Extrusion ratio	74.47
Ram speed, mm/s	5.5
Press nominal load, MN	25
Billet material	AA6063

Table 1. Extrusion process parameters

The front tip of the profile obtained in the test extrusion is shown in (Fig. 3a) where we can observe non-uniform material flow causing severe distortion of the profile shape. The purpose of the simulation was to clarify the reason of such undesired material flow and find the way to fix the problem. Simulation has shown the same profile distortion pattern as in practice (see Fig. 3b) where the maximum speed is observed at the middle of the sides of the. We also see substantial deformation of the die. As shown in Fig. 4, the vertical displacement of console part of the die reaches 0.4 mm and it varies linearly reaching the maximum at its end. This causes inclinations on the bearing surface, mostly as local zones of relief, that reduce the effectiveness of the bearing to control of the material flow (yellow and green color areas in Fig. 5).



a. b.

Figure 3. Extruded profile: (a) actual profile shape; (b) simulated profile shape

Attempts to balance the material flow by changing parameters of the die set were ineffective. Particularly the variation of the bearings length within admissible ranges didn't help. This could be expected because large parts of the bearing have got relief due to inclination and cannot provide effective resistance to the material flow regardless of their length.

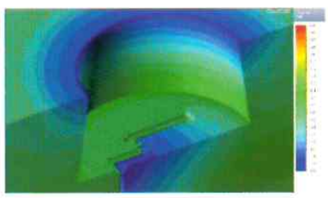


Figure 4. Axial displacement in the die (mm)
Figure 5. Bearing inclination in minutes

Thus the only way to get optimum material flow is to eliminate the undesired inclination of the bearing by avoiding large deflections of the die console. This might be done by means of adding the mandrel placed on three webs to take some part of the load by itself and reduce the console deformation. Different shapes of the proposed mandrel and webs have been tested by simulation trials to find the best design variant as shown in Fig. 6-9 together with respective distribution of the axial velocity in the profile. As we can see the third variant provides the most uniform distribution of the velocity (Fig. 9).

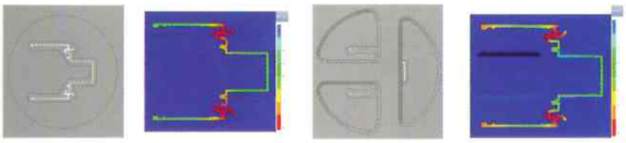


Figure 6. Die shape and velocity in case of initial design (flat die)
Figure 7. Die shape and velocity in the first variant with mandrel

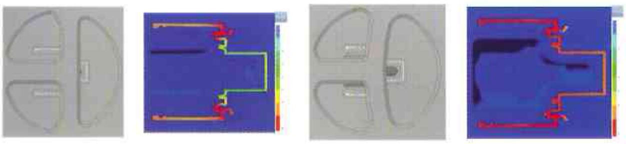


Figure 8. Die shape and velocity in the second variant with mandrel
Figure 9. Die shape and velocity in the third variant with mandrel

It is important to notice that the best effect can be obtained when the mandrel core has a small gap to the die console. As shown in Fig. 10, the mandrel core has about 0.5 mm displacement. According to this, in the final model of the die set, the gap between the die and mandrel was added in the area of possible mandrel core and die console contact to minimize the die console deformation (Fig. 11).

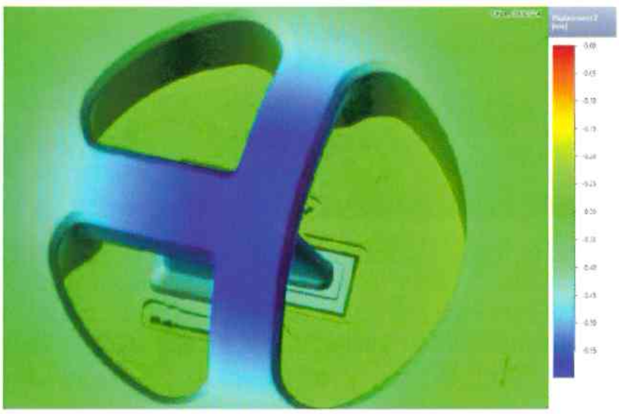


Figure 10. Axial displacement distribution in the third variant of the mandrel and web design.

Thus, such optimization allowed us to get die set geometry with much smaller die deformation in the bearing area and more even material flow. Now the bearing has less inclination and can be more effectively used for material flow control. Thus final tuning of the die design has been done be means of changing bearings length in some areas as shown in Fig. 12.

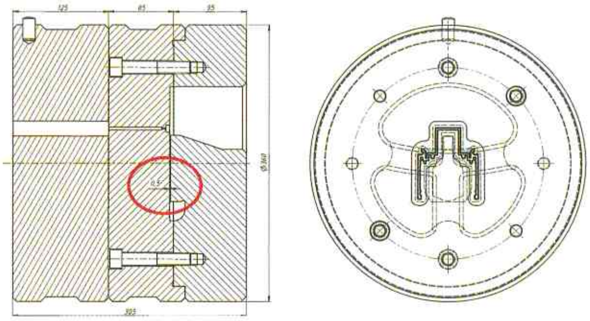


Figure 11. Drawing of the final tool set variant with the gap 0.5 mm (shown in red oval) between the mandrel core and the die

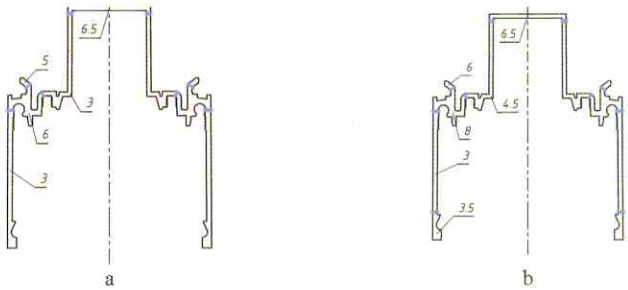


Figure 12. Bearing design modification: (a) initial variant; (b) final variant

The efficiency of the proposed die design and bearing modification is clearly seen by the uniform velocity distribution and accurate shape of the profile front tip (Fig. 13).

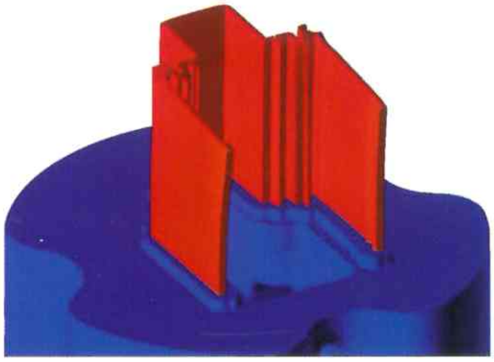


Figure 13. Axial velocity distribution with the third variant of mandrel design and modified bearing.

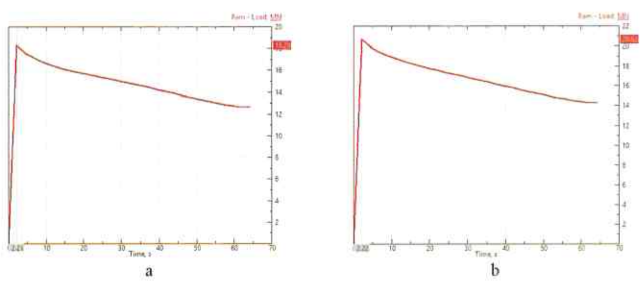


Figure 14. Load vs time graph: (a) initial flat die design; (b) final design with mandre

Meanwhile the newly designed die with mandrel may cause an increase of the load compared to a flat die. The simulation of the final die design has not shown significant increase of the load. It has changed from 18.3 MN to 20.6 MN that is still within the capacity of the press (Fig.14). Thus the developed die design as shown on Fig. 11 provides good quality profiles that have been produced without any die corrections.

Seam welds, distortion and material properties

Extruded hollow profiles 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 as well as its capability to estimate weld strengh. The most widespread test of the seam welds strength is a wedge test when a cone tool is pushed inside a hollow profile in the profile to a certain depth. We see an example of a weak seam cracking as a result of this test in Fig. 15.

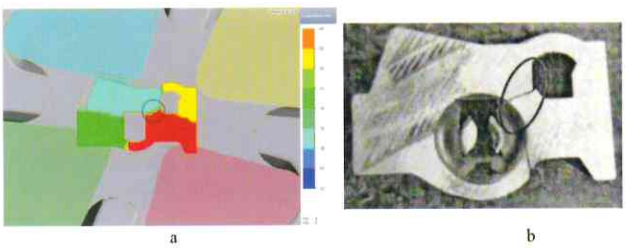


Figure 15. Location of the seam welds in the hollow profile shown by merging colors in simulation (a) and the crack along the seam weld in the wedge test shown by the oval (b).

There are several empiric criteria of seam weld quality estimation which include dependence on different parameters in a welding chamber (hydrostatic pressure, temperature, strain and velocity) and extruded alloy [3, 4]. One of the most efficient ways to improve the quality is by extending the length of the welding chamber and increasing the pressure in it as illustrated in Fig. 16 and 17 for the above profile. As we can see extending the length of the weld chamber by 50% increases the pressure nearly two times from 50 MPa to about 100 MPa that significantly improves seam weld strength.

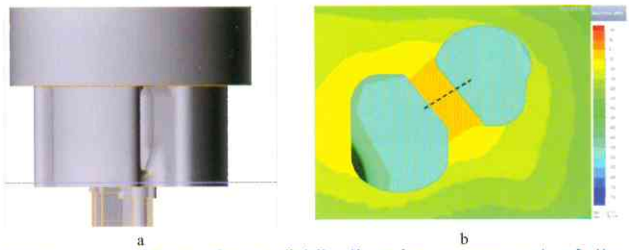


Figure 16. Mean stress distribution in a crosscut of the welding chamber in initial die design.

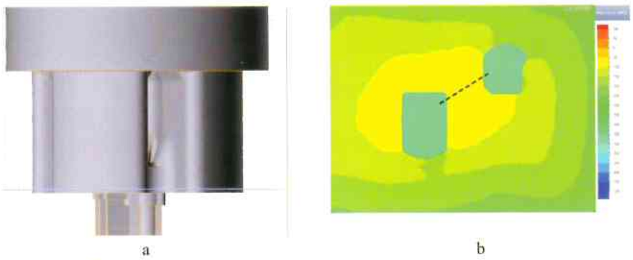


Figure 17. Mean stress distribution in a crosscut of the welding chamber in modified die.

When the profile leaves the die orifice its configuration may differ from the designed one. It happens because the elastic deformation of the dies and, for example, instead of straight profile legs we can have bent legs as shown in Fig. 18 a.

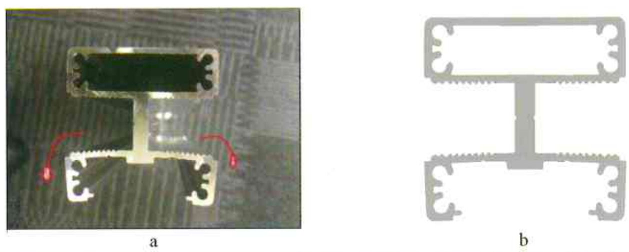


Figure 18. Slight bending of the profile "legs" due to die deformation in reality (a) and predicted in simulation (b).

By means of simulation we can predict (Fig. 18b) and consequently compensate this undesired effect by die design modification. Similarly, we can estimate the distortion of the profile after cooling or heat treatment operations as shown in Fig. 19 where the difference of dimensions between two initially parallel legs in the hot profile reaches 0.4 mm at room temperature. Respective modification of the die orifice configuration may compensate for this distortion and provide the profile dimensions in the cooled extrusion to be within the specified tolerances.

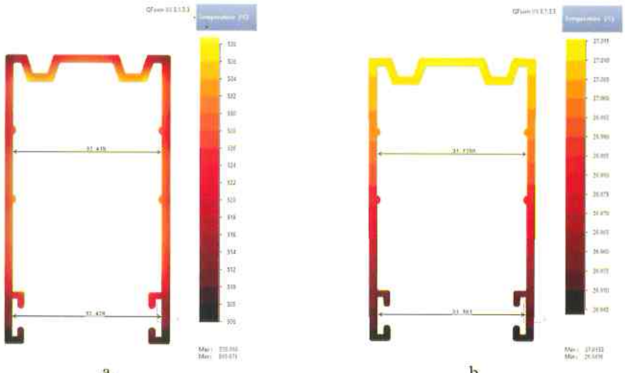


Figure 19. The profile dimensions in hot state and after cooling.

The micro structural model has been included in simulation both at the stage of extrusion and subsequent cooling. It is based on the development of the method published in works [5, 6]. As a result, we can observe average grain length, grain thickness and subgrain size in a profile immediately after extrusion as a result of deformation and after cooling due to static recrystallisation (Fig. 20).

Conclusions

By means of simulation it is possible to analyse and control several aspects of the quality of extruded profiles such as straightness of the material flow, shape distortion due to elastic deformation of dies and cooling. The simulation is able to predict seam weld locations and provide information for their strength estimation. With the help of microstructure models for dynamic and static recrystallisation of aluminium alloys it is also possible to analyse grain size distribution in finish product depending on the material extrusion parameters and cooling conditions. Further development of the presented approach supposes its extend to wider range of materials and including the estimating of the surface quality.

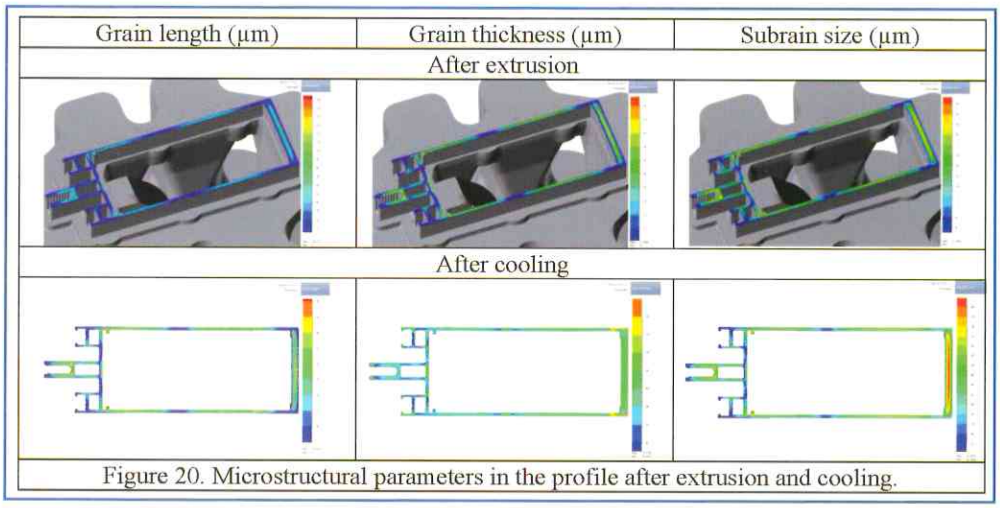


Figure 20. Microstructural parameters in the profile after extrusion and cooling.

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