W H I T E P A P E R

A Methodology for Superior Die Design - Combining the Best of Art and Science

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INTRODUCTION

The use of plastics has been steadily increasing for more than fifty years. For example, an average car contained 100 pounds of plastic in 1977, while in 2003 it contained about 275 pounds (Figure 1). Increased usage of plastics is particularly evident in the packaging industries. The European flexible packaging market expects to grow from $10.5 billion to $11.8 billion between 2003 and 2008. The average per capita plastics consumption is forecasted to increase by 46% in the United States and Western Europe, by 85% in Southeast Asia and by 104% in Eastern Europe between 2001 and 2010.

With this increased usage, manufacturers are beginning to more closely examine the processes that form the plastic products in order to bring their products to market faster and cheaper. Extrusion is one of the most widely used processes for polymer processing. Examples of extrusion include film, pipe, sheet, profiles, fiber and filament, wire and cable, and coatings coextrusion (see Figure 2). In each type of extrusion, the polymer is forced through a die to create the desired shape. Meeting the current and anticipated growth in demand of complex extruded shapes requires quick and accurate die design from the start. Ideally, the design of the die will minimize the process of trial and error and avoid costly shut down of production lines. Computer simulation (science) using computational fluid dynamics (CFD) can supplement existing experience (art) in the die design process by providing a cost-effective tool to investigate new design options. Moreover, coupling computational modeling with existing in-house experience facilitates the transfer of knowledge to the entire die design team and increases the range in possibilities for innovative approaches.

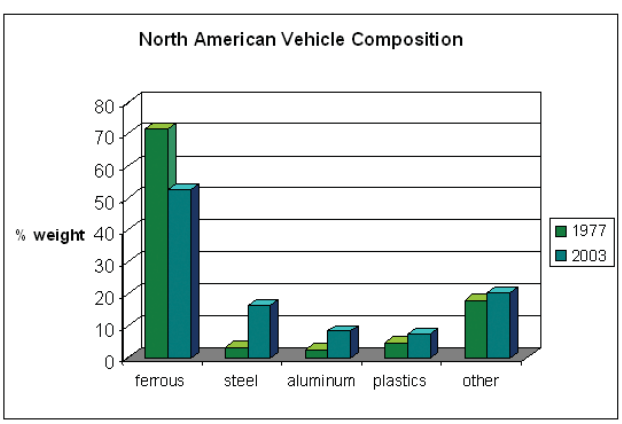

Figure 1: Plastics usage in US automotive industry Source: General Motors Corp., Detroit, MI

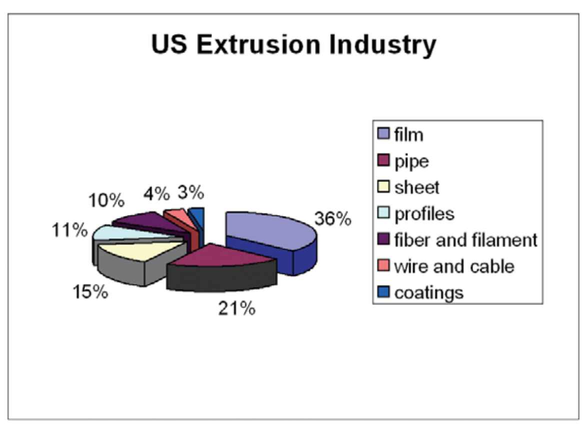

Figure 2: Distribution by type of extrusion, 1999 total: 40 billion pounds Source: Plastics Custom Research Services, Advance, NC

CURRENT CHALLENGES

For most companies, obtaining the final shape of an extruded product is a time-consuming trial and error process. It can take a few, or even a dozen or more, trials to get the correct die cut that will yield the desired part shape and dimensions. For an experienced die designer working on a simple shape, this process may take a short period of time, while more complicated shapes may take up to a few months using the trial and error method. There are many reasons for this delay, most involving a lack of understanding of the physics and the polymer flow inside and outside of the die. Complications associated with die design are:

- Die swell: As the melt leaves the die, it undergoes large deformation throughout the free jet. This phenomenon, known as die swell, may in fact result in actual contraction of the flow sections especially close to the die region. As a result, the die lip may be quite different than the shape of the extruded profile. The key to the exact die shape is the melt material {EPDM (ethylene propylene diene monomer rubber), polyvinyl chloride (PVC), high density polyethylene (HDPE)} and operating conditions (throughput, die temperature, melt temperature). Indeed, viscoelastic effects may occur for some materials at high flow rate. Such effects lead to stress relaxation as soon as the material flows out of the die inducing additional, possibly very large die swell, up to 300% in some extreme cases.

- Die imbalance: An unbalanced die will have the extrudate exiting the die at varying local speeds (more extrudate leaving one portion of the die than others). This may result in local deformation as explained above. This could also have a more dramatic and global effect, such as twisted or deformed extrudates.

- Co-extrusion: When different materials are co-extruded, they meet inside the die and flow adjacent to each other inside the die lip. The main difficulty in co-extrusion is to ensure a stable and continuous interface(s) between the different materials.

- Tight tolerances: The tolerances on the dimension of the extrudate product are usually very specific in the plastics and rubber industry. Whether this is for the external dimension of the profile or for the thickness of the co-extrusion layer, dimensions must be matched within tight margins.

- Die deformation as a result of high internal pressure: This is especially important while extruding very wide and thin films, because of the high pressure inside the die. The die gap may vary according to operating pressure.

EXTRUDATE PREDICTION VS. INVERSE DIE DESIGN

Typically, designers know the requested shape of the profile but do not know the corresponding die shape. The required die shape is determined by one of the following approaches:

- Extrudate prediction: By adjusting the die shape, the designer obtains the corresponding part shape and compares it to the required one; if it does not match, the process is repeated until the target shape is met. Essentially, this is a trial and error method that relies on the experience of the die designer. Extrudate prediction can also be accomplished using computer simulation.

- Inverse die design: the designer starts with the required part shape and uses computer simulation to automatically modify the die to craft the required part shape.

Figure 3 illustrates this extrusion analysis capability for the die and free surface flow. In the most common case, referenced as "extrudate prediction," one starts with a given die geometry (here a rectangle). A traditional die designer builds a die, conducts tests to determine the extrudate shape and then adjusts the die until the desired results are achieved. Even in common situations, this methodology can require numerous trial dies from an experienced designer.

By using the alternative approach of computer simulation, the designer calculates the deformations of the free surfaces originating from the die lip. The deformation of the free surfaces can come (i) from the velocity rearrangement due to the sudden absence of friction outside the die and (ii) possibly from the relaxation of stresses developed during the shearing experienced by materials with a considerable viscoelastic component. As a result of these anticipated deformations, it is necessary to design a die that accounts for these shape changes in order to obtain the required extrudate shape. The benefit of designing through virtual prototyping is substantial cost savings throughout the die development process.

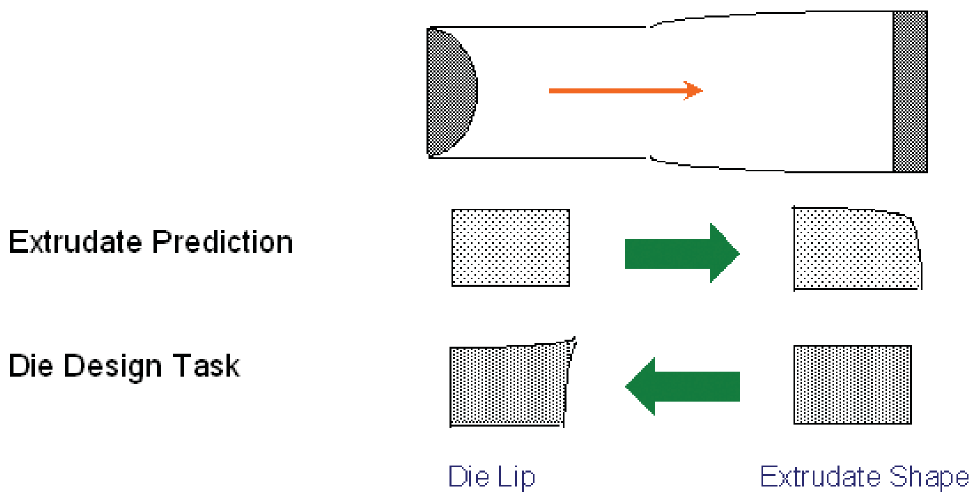

Figure 3: Direct and inverse extrudate prediction

Understanding what may cause the changes in extrudate shape is key to improving the die design process. For example, inside the die, a parabolic velocity profile is observed with zero or low velocity close to the wall due to the friction along the wall that slows down the flow. At the center of the flow section, the speed of the melt is much higher (see the top of Figure 3). In the free jet a couple of inches after the die lip, the velocity profile is perfectly flat: each particle has the same velocity since there is no wall to slow their momentum. Given these conditions, melt flowing in the vicinity of the wall inside the die will have to accelerate to the average velocity value in the free jet. Considering a constant local flow rate, the only way to accelerate the melt is to reduce the flow section; hence, we observe local contraction. On the other hand, melt flowing at the center of the domain has a velocity inside the die higher that the speed of the extrudate. This part of the melt must slow down. Again, considering a constant local flow rate, the only way to decelerate is to increase the flow area, leading to die swell. The velocity redistribution is more complex when three-dimensional effects are taking place, but the basic principles remain the same.

Virtual prototyping can also be effective for inverse die design. The boundary conditions between the die and the extrudate are modified so that the shape of the required extrudate profile can be prescribed and the shape of the die land profile becomes part of the solution. The die design technique implies a strategy to adapt the die lip to a section that is modified during the simulation to satisfy those requirements. This means that the result of the calculation is a design close to the die that takes those deformations into account to produce the desired profile. Inverse die design certainly looks more attractive from the designer point of view. This approach does reduce the number of iterations the designer has to go through. To maximize efficiencies, a CAD file for the die land can be output for direct read into a die cutting machine. Figure 4 (a) shows the cross section of the desired part (red) and the die shape predicted by inverse die design (blue). Clearly, local deformation due to shape change forces the die and the part not to have the same shape. Figure 4 (b) depicts the forward extrusion process based on the predicted die design.

Figure 4a: Desired part shape and die shape predicted by inverse die design; die (blue), part (red)

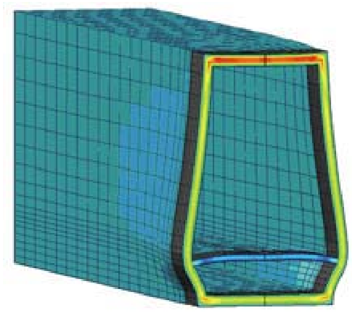

Figure 4b: Extrusion of part based on die shape predicted from inverse die design

In either case, estimating how the free surface of the melt will deform outside the die is crucial. When the material leaves the die, no matter how well balanced, residual deformations remain due to local velocity gradients (the melt in the vicinity of the die flows slower than the melt located at the center). For viscoelastic materials (e.g. some rubbers), relaxation of stress accumulated during the flow throughout the die land also causes some unusually large swelling. Depending upon the operating conditions and the material which is extruded, large deformations could be observed.

BALANCING THE DIE

For parts with complex geometry, involving thin and thick sections leading to large variations between local velocities, the deformations of the extrudate could become so large that the final product is no longer acceptable. A preliminary step to avoid this problem is to balance the flow of materials across the die lip, otherwise known as die balancing. This is the process of changing the die internals, in particular the adaptive section right before the straight die land, to yield a flow across the die exit as uniform as possible. Failing to do so could result in a twisting or bending extrudate as it leaves the die (see Figure 5) or to large deformations of the extrudate. Outside the die, all fluid in the extrudate will move at the same speed because of the absence of friction if the velocity is uniform at all points of the die exit. Through the proper balancing, starving sections (sections with too little flow) should be compensated by increasing the cross section of their adaptive section. Similarly, the sections upstream of areas where the melt flow is found to be high could be decreased (e.g. by the addition of a metal insert) to get a uniform flow at the exit section.

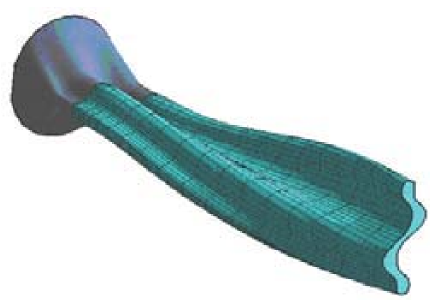

Figure 5: Twisted extrudate as a result of an unbalanced die

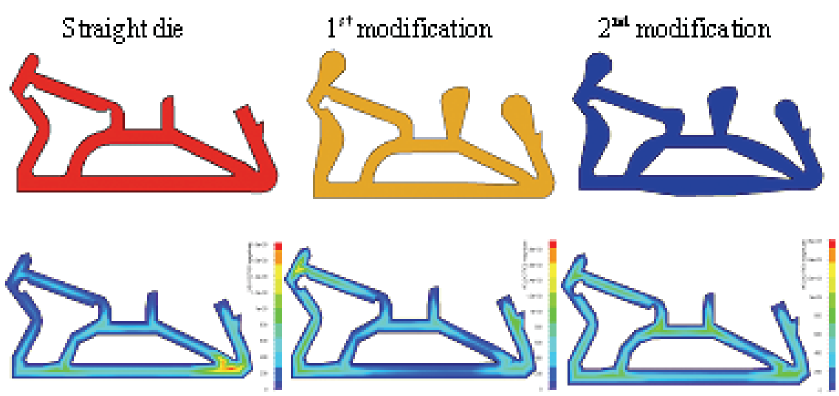

Figure 6: Process of balancing the die of a complex part

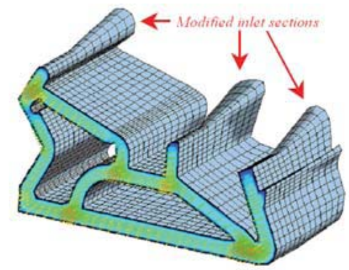

Figure 7: The final balanced die

Figure 6 shows a series of steps taken in the die balancing of a complex part. The upper portion of the figure shows the die exit cross section for each iteration while the lower figure shows the velocity profile - the brighter the color, the faster the extrudate is flowing. The ideal case is a uniform velocity (all the same color). As can be seen in Figure 6, minor modifications to the die exit can help balance the die. Figure 7 shows a three dimensional view of the final die shape and the corresponding velocity field.

OPTIMIZING DIE BALANCING

In many cases, adjusting the adaptive section of the die to get balanced flow is not a straightforward procedure. It involves several iterations especially for relatively complex dies. It is not profitable to test a large number of designs through either physical prototyping or virtual analysis. An optimization procedure ensuring flow uniformity at the die exit while allowing die dimensions to change would be a practical application. One advantage of optimization techniques is that by starting from a finite set of designs, a near optimum design may be obtained without having to test all possible designs, thus reducing the testing time, whether experimentation and/or CFD, considerably. A possible optimization methodology is presented in Figure 8. The method combines die design experience (in the initial die shape determination) coupled with computer simulation to eliminate many of the intermediate steps.

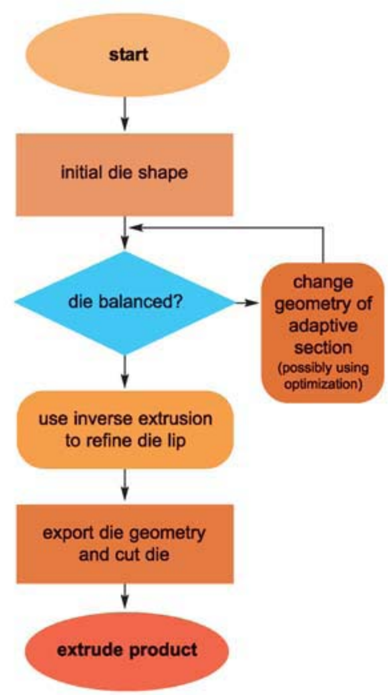

Figure 8: Die design optimization algorithm

CO-EXTRUSION

Many plastic or rubber products involve two or more materials such as the sponge and dense rubber sections in an automotive seal. Particularly in the case of a flat die, several layers of thin material are included in order to convey the right permeability, chemical inertia, to take advantage of different mechanical, chemical, optical properties, or to simply reduce the cost of the product by using cheaper, lower quality material (recycled plastics). Since

PROCESS MAKEOVER: CO-EXTRUSION

before

To design a die for a complex co-extruded part consisting of a sponge and a dense rubber, with arms and hollow sections, took more than eight weeks. Twelve dies were cut until the correct design was found. For each iteration, a new die had to be cut and the designer had to wait until the extrusion line was free to test out his new design.

after

When computer modeling was involved in the design process, the die of a similar part was obtained within only two weeks and only two dies were cut to obtain the final design.

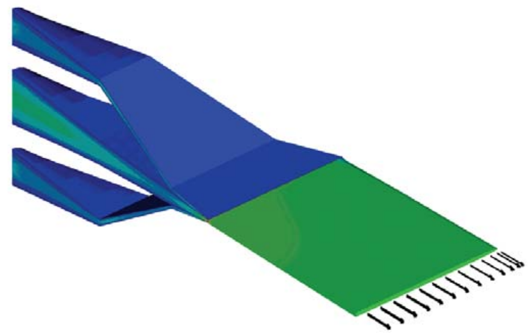

Figure 9: Co-extrusion of a multilayer sheet

there are more materials and more processes involved, analysis of co-extrusion becomes more complicated. If more than one material is extruded, one needs a specific extruder (one die inlet) for each material. The different polymers then flow together inside the die. The interface between these materials is initially unknown and usually takes on complex shapes. Different materials having different (rheological and thermal) properties lead to further variations of the flow pattern that cannot be neglected. In addition, the stress between the two materials is a question of great interest and often not well known. It is possible that the materials are not sticking together but may slip along each other leading to undesired defects. Computer simulation can be used to model co-extrusion as long as many of the above mentioned concerns are fairly well understood. Figure 9 shows a typical co-extrusion of a multilayer sheet.

FLOW INDUCED DIE DEFORMATION

In some cases, such as the flow of plastics through a flat die (T-die or coat hanger die), the flow of materials across a thin slit is so large that the pressure in the flowing plastics can deform the solid die. This phenomenon can be important as this may significantly impact the local flow rate, hence the local flow balance. Similarly, torpedoes may be used to maintain central section(s) of the die for a window profile die or a metal insert may be added in order to guide the materials. These metal parts inside the flowing materials may be subjected to forces large enough to deform and possibly break them. The stress analysis in the solid material is therefore a valuable output. Figure 10 presents one example of this effect.

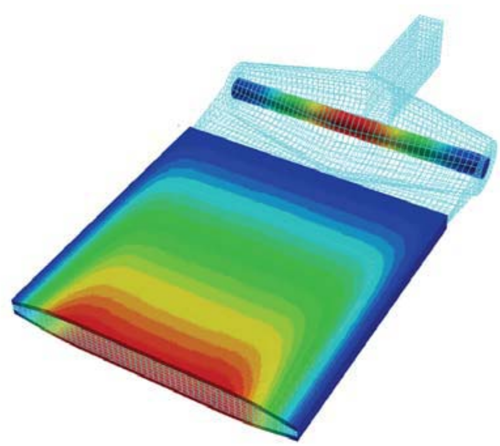

Figure 10: Vertical deformation of a coat hanger die – deformation exaggerated for visual purposes

CONCLUSIONS

There are many challenges facing the die designer, many of which have been presented here. The most common method to overcome these challenges is the die designer's years of accumulated experience. Die designers often use extrudate prediction (if this is the die shape, what does the extrudate look like?) iteratively to determine the optimum die shape. This paper presents a more cost-effective alternative to complement this approach: virtual simulation. Simulation techniques can also perform inverse die design (if this is the required extrudate shape, how should the die look?). By combining die design experience and computer simulation one can optimize die balancing. Finally, the problems of co-extrusion and flow induced die deformation have been briefly introduced.

Die design has been and will always utilize the 'artistic' component and experience of the die designer. However, introducing a new tool like virtual flow modeling will supplement the art with additional understanding of the extrusion process. This deeper level of knowledge will significantly reduce design cycle time.

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