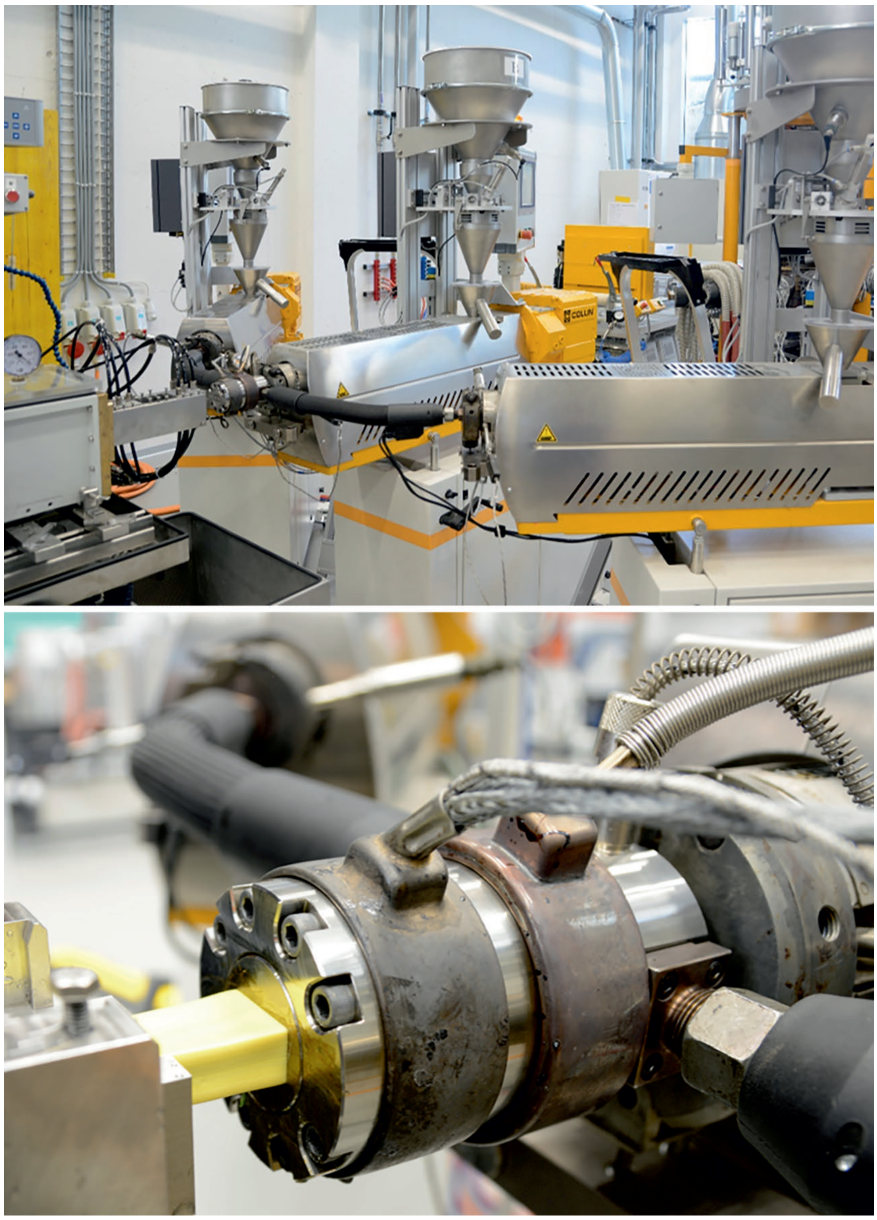
Rethinking Co-Extrusion

Additive Manufacturing and Simulation-Based Design as a Duo for Extrusion Dies

Combining additive manufacturing with a digital, simulation-based design process makes it possible to develop even highly complex extrusion dies in a time-saving and economical manner. Experts from the Eastern Switzerland University of Applied Sciences and ETH Zurich have successfully applied this technique using the example of a novel co-extrusion die.

Instead of using wire cutting or milling to manufacture extrusion dies from several plates, additive manufacturing makes it possible to fabricate complex-shaped extrusion dies as monolithic parts. This significantly reduces both the manufacturing costs of dies and the overall time required. Furthermore, the design freedom afforded by additive manufacturing can be used to integrate multiple flow distributors and so produce novel co-extrusion dies for multi-layer profiles (**Figs. 1 and 2**). However, the design and dimensioning of dies can be a time-consuming task.

To reduce the costs and effort required for the design, it is necessary to use computer-aided design (CAD). This includes automating the design of the die geometry and applying numerical flow simulations using CFD (Computational Fluid Dynamics). Such a digital design process makes it possible to rapidly and automatically generate die geometries and to simulate the distribution of the polymer melts within the die. In this way, the design of a die can be optimized and the effort and costs of physical run-in tests minimized. Thus, using a digital design process perfectly complements the advantages and freedoms of additive manufacturing. The example of a novel co-extrusion die is used to demonstrate how the two technologies can be effectively combined. The development was carried out as a collaboration between the Institute of Materials Engineering and Plastics Processing (IWK) of the Eastern Switzerland University of Applied Sciences (OST) and the Product Develop-



Field test: for the test, the co-extrusion die is connected to three extruders followed by a calibration unit © IWK

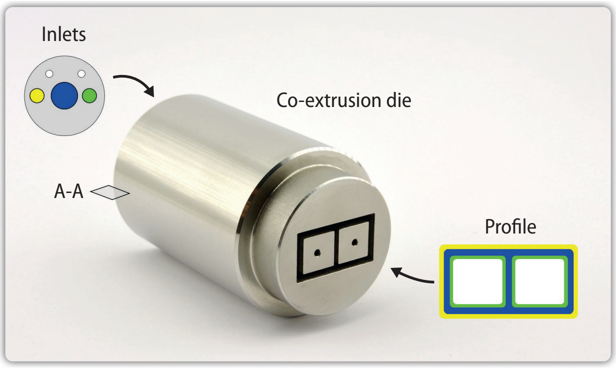


Fig. 1. Additive manufacturing enables the fabrication of novel co-extrusion dies Source: pd|z; graphic: © Hanser

ment Group Zurich (pd|z) of ETH Zurich, Switzerland.

Inputs and Boundary Conditions

The process of designing a complex additive manufactured co-extrusion die starts with the specification of a number of inputs (**Fig. 3**). These include the positioning of the die inlets and the shape of the extruded profile at the die outlet. In the example, the extrusion profile is defined by a rectangle made up of three material layers and containing two hollow chambers. At the die inlet, the polymer melts are fed through three round inlet channels. Further inputs define the extruded material and the process conditions during extrusion. For the rectangular profile, the base polymer is a polystyrene (Styrolution PS486N), with the individual material layers each colored differently with 3% color masterbatch. Selective laser melting (SLM) is used to additively manufacture the die from stainless steel. The build direction is oriented along the same axis as those of the flow channels and longitudinal axis of the die.

Automated Design Generation

The design of the die geometry is carried out based on the input data. This requires the creation of multiple, nested flow distributors (**Fig. 2**). In addition, channels are necessary to supply air to the hollow chambers of the profile. To reduce the design effort, the basic approach is to automate recurring and manual tasks and provide a design toolbox with predefined design elements. The toolbox devel- »

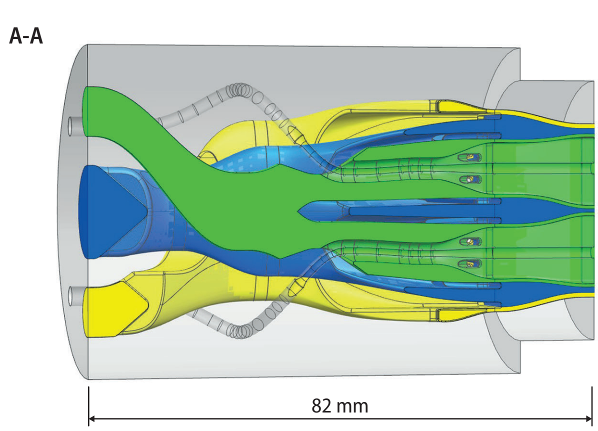


Fig. 2. Producing co-extrusion dies by additive manufacturing makes it possible to build in multiple, nested flow distributors © pd|z

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- Read the German version of the article in our magazine *Kunststoffe* or at *www.kunststoffe.de* oped at pd|z contains frequently needed building blocks such as various channel cross-sections, flow distributors, and guiding vanes. The designer specifies these elements, and algorithms then generate the associated geometry of the flow distributor (**Fig. 4**). This enables the time-efficient generation and adaptation of parametrically-defined die geometries.

In the next step, the resulting die design is analyzed to ensure that it complies with the manufacturing restrictions imposed by selective laser melting. For this purpose, the toolbox provides routines that automatically check minimum wall thicknesses and build angles. This permits the early detection of critical sections that could lead to defects during additive manufacturing. To achieve a production-ready design, the previously defined parametric building blocks are adjusted, and the die geometry is updated.

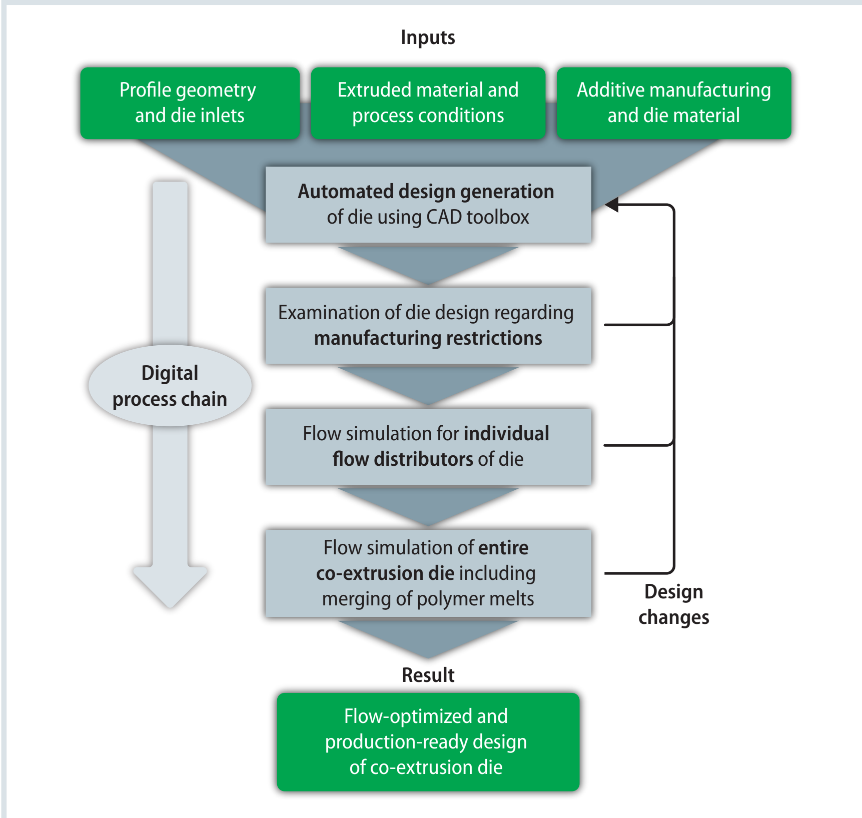

Fig. 3. The design of co-extrusion dies requires a digital process chain using automated design generation and numerical simulation Source: pd|z and IWK; graphic: © Hanser

Simulation-Based Die Design

The manufacturable geometry of the die is analyzed and optimized by means of flow simulations, using the program Ansys CFX (**Fig. 5**). The polymer melts are modeled as steady-state, incompressible and isothermal flows. The non-Newtonian viscosity behavior of polystyrene is characterized with the Carreau-Yasuda model. The mass flow rates of the polymer melts are specified at the die inlets. A pressure boundary condition is prescribed at the die outlet. Channel walls are modeled as frictionless, and defined with an adhesion condition.

Before analyzing the die as a whole, the individual flow distributors are first simulated separately. For each distributor, simulations are used to compute the pressure and velocity distributions within the polymer melt. The simulation results serve as a basis for making changes to the die (**Fig. 3**). The parametric building blocks that define the die design are adjusted either by the designer or via an automated optimization loop. This partly automated sequence of CFD simulations and design adjustments reduces the pressure drop and makes the velocity distribution at the outlet of each flow distributor more uniform.

The individual flow distributors being now optimized, the entire co-extrusion die is analyzed including all the polymer melts. A multiphase flow simulation calculates the merging of the polymer melts in the front section of the die (**Fig. 5**). The pressure fields from this flow simulation then form the boundary condition for a structural-

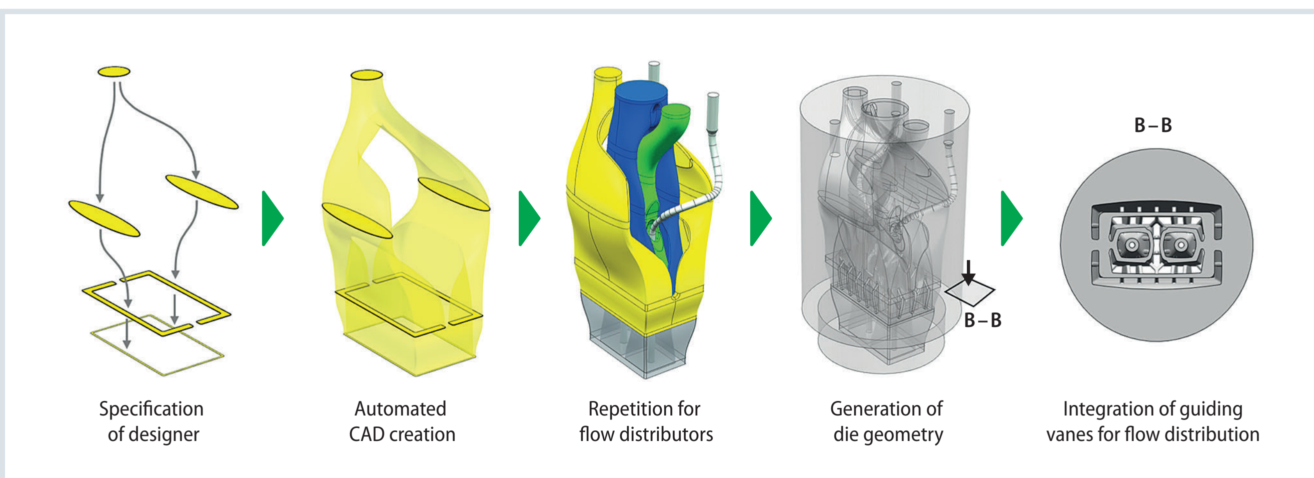

Fig. 4. The automated design of flow distributors helps in designing complex dies Source: pd|z; graphic: © Hanser

mechanical simulation, which is carried out using the finite element method (FEM) in order to calculate the maximum stresses and deformations in the die. Besides the steady-state normal operation, the die has to withstand transient operating conditions such as the start-up phase of the process or disturbances in the feeding of the materials. Again, the results of the simulations are employed for iterative and partially-automated modifications and improvements to the die design (**Fig. 3**). Using this procedure, it took only a few days to develop and optimize the die geometry for the rectangular profile.

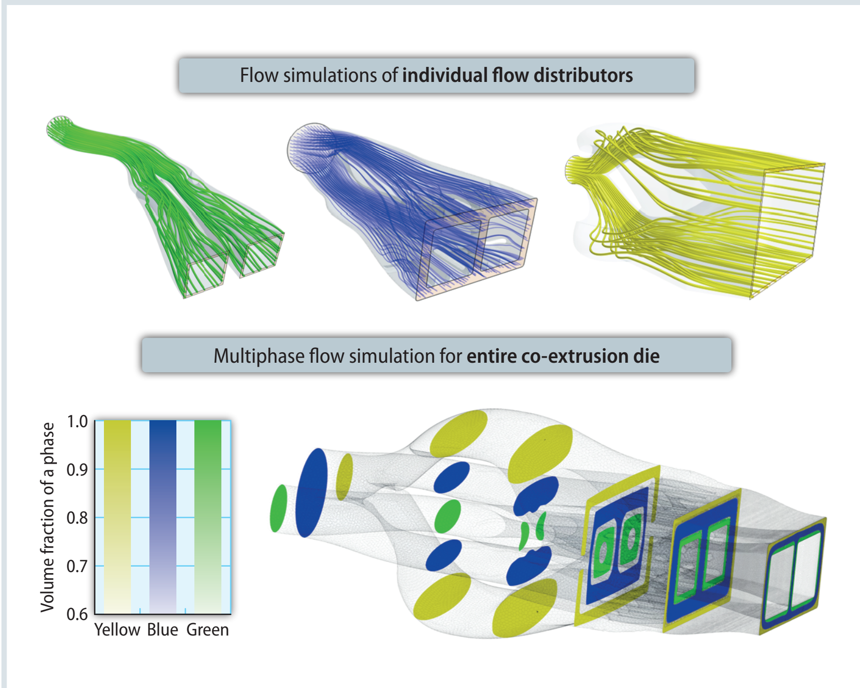

Fig. 5. Flow simulations make it possible to predict the distribution of polymer melts in individual flow distributors and in the die as a whole Source: IWK; graphic: © Hanser

Experimental Setup and Results

To validate the simulations, the die was manufactured using selective laser melting. In this process, a laser beam melts metallic powder which then fuses along the part contours for each layer of the part. After this build-up process, the part is cleared of non-solidified powder, thermally post-processed, and machined. An external service provider manufactured the die within a delivery time of one week. Other connecting parts required for assembly were manufactured using conventional processes.

The experiments were carried out at the facilities of IWK. Three extruders (type: E30PK and L/D30, manufacturer: Collin Lab & Pilot Solutions GmbH, Maitenbeth, Germany) were used in the experiment. For feeding the main layer, the die was directly connected to one of the extruders (**Title figure**). The other two extruders were each provided with a flexible heating hose (manufacturer: Hillesheim GmbH, Waghäusel, Germany). A calibrator, calibration table (manufacturer: Bernhard Ide GmbH & Co. KG, Ostfildern, Germany), and caterpillar haul-off (manufacturer: Graewe GmbH, Neuenburg am Rhein, Germany) followed the extrusion line. For the test run, the individual layers were fed in just as in the simulation, and the mass flows were regulated using gravimetric throughput control. Extrusion took place at a line speed of 1 m/min and a total throughput rate of 10 kg/h at a melt and die temperature of 200 °C.

During the test run, the velocity distribution at the die exit was analyzed visually by cutting off the profile at the die outlet. The individual polymer melts emerged uniformly as a co-extruded profile. The measured pressures of the mass flows (~ 42 bar) were comparable to the simulated values (~ 49 bar). To evaluate the extruded profile, a segment was cut off, and a specimen was prepared (**Fig. 6**). The distribution of the material layers predicted by the multiphase flow simulation agreed very well with that of the ground and polished specimen. This was the result of the very first test; adjustments to the die are expected to improve the layer distribution and obtain a minimum layer thickness in all areas of the profile.

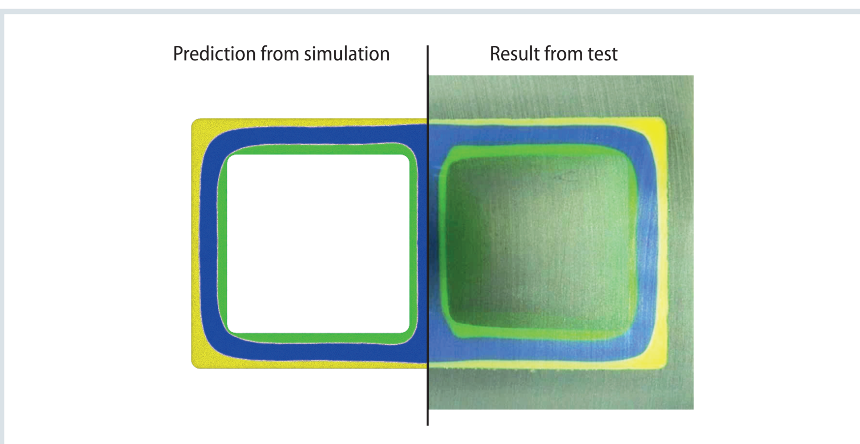

Fig. 6. The results of the multiphase flow simulation agree very well with the ground and polished sample of the extruded profile Source: IWK; graphic: © Hanser

Conclusion

Combining an automated and simulation-based design process with additive manufacturing results in quick and cost-efficient development and production of extrusion dies. The targeted use of both technologies leads to a drastic reduction in the overall time and costs of designing, analyzing, optimizing and manufacturing complex-shaped and functionally integrated dies. In the example, this has led to a very short, compact and flow-optimized co-extrusion die, which was successfully tested and validated at the very first attempt. ■