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ORIGINAL ARTICLE

Individualized production in die-based manufacturing processes using numerical optimization

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Abstract Individualized production, which is a major goal of many high-wage countries, describes a production process in which all elements of a production system are designed in such a way that they enable a high level of product variety at mass production costs. This paper demonstrates recent advances in the individualized production with die-based manufacturing processes, namely high-pressure die casting and plastics profile extrusion. Within these application areas, the chosen approach aiming at individualized production is based on the use of numerical die and process design. The design procedure relies on numerical process simulations based on a nonlinear optimization library and a spline-based geometry kernel. All components interact automatically without requiring user interaction; thus, a completely independent optimization cycle can be achieved. The numerical optimization helps to reduce—or even eliminate—the so far very characteristic manual reworking steps of an original die or process design. These reworking steps are a major cost factor when it comes to individual production. Their abolishment through the presented numerical approaches therefore represents a large step towards the concept of individualized production.

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1 Introduction

The industrial production in high-wage countries is exposed to enormous competition from low-wage countries. In order to maintain competitiveness and compensate disadvantages in terms of production costs, high-wage countries focus on differentiation strategies and surpass others in the quality of their products and services. However, the ongoing technological developments and the steady economic growth lead to an improvement of product quality in low-wage countries. That is why high-wage countries will not be able to maintain their competitive advantages by simply improving their standing in differentiation strategies. Instead, they need to work on the solution of the polylemma of production [2] and thereby combine the advantages of the different market strategies [30].

The polylemma of production hereby refers to two fundamental dichotomies: The market-oriented dichotomy and the resource-oriented dichotomy. On the one hand, the resource-oriented dichotomy focuses on the resource tie-up in a company and describes the goal conflict between planning orientation, in which the synchronization of production resources is optimized, and value orientation, which aims at achieving the highest system dynamics. The market-oriented dichotomy on the other hand describes the conflict between manufacturing products at mass production costs (scale) and matching the production to individual customer demands (scope) [2, 31].

In particular, the conflict between scale and scope is gaining importance against the background of increasing individualization imposed by customer demands and increasingly shorter product life cycles. One approach to realize individual production at mass production costs is to adapt die-based mass production processes towards smaller lot sizes. In the context of die-based manufacturing processes, like high-pressure die casting (HPDC) or plastics profile extrusion, the major prerequisite is to decrease the costs in the design and manufacturing phase as these fixed costs are the cost driver in die-based manufacturing processes.

To decrease the costs, the new approach is to shorten the time for die design and die manufacturing by the implementation of numerical optimization in order to decrease the number of redesigns and so-called running-in trials. The conventional die design process focuses heavily on the experience of the die designer. For example, in extrusion die design, an iterative die modification process consisting of extensive running-in trials and subsequent reworking of the flow channels follows the manufacturing of the die. These iterative modifications can cause up to 40–60 % of the total die costs in the case of extrusion dies [22]. Similar issues appear in the high-pressure die casting industry with the dies being even more costly and the process being more complex.

Besides its advantages, numerical optimization creates new challenges for the die and process design. In this paper, we propose general methods in order to iteratively evaluate and optimize the die and the process in plastics profile extrusion and high-pressure die casting. Both manufacturing methods are faced with situation-specific challenges in the formulation of objective functions, constitute equations, applicability, and integration in existing design and manufacturing processes. While the method chapter outlines a common basis, the application chapter addresses the manufacturing processes individually. In the conclusion and outlook, this paper finally addresses necessary steps towards fully automatic die design.

2 Methods

The state-of-the-art method of die and process design is based on the experience of design engineers. They start with the development of a first draft that is created and improved with the assistance of CAE tools. Afterwards, the die is manufactured and tested during so-called running-in trials, see Fig. 1 (dotted line) [20]. During the running-in trials, the die geometry is modified and process parameters are improved based on experience in several steps. After these iterations, the die is ready for productive use.

As a new approach, the number of running-in trials during the design phase is minimized by introducing the optimization procedure described above into the die development process as depicted in Fig. 1 [5, 8]. With this change, the design engineer obtains an optimized die as well as a set of process parameters in an automatic manner, after providing the draft. Afterwards, the die will be manufactured according to the optimized geometry and the, now reduced in their amount, running-in trials begin.

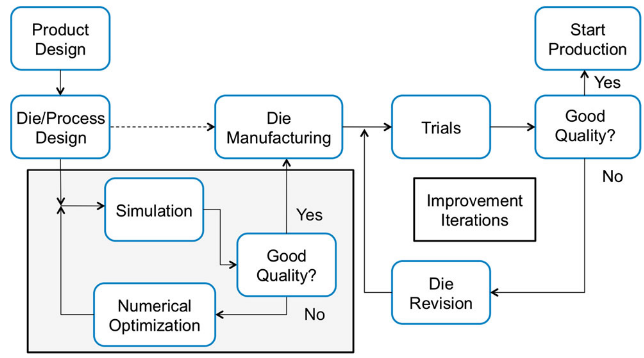


Fig. 1 Die development process with integrated numerical optimization

While computing power increases and simulation models improve, the goal is to eliminate the running-in trials completely and trust the numerical optimization only, what was demonstrated already for an L-Profile by Siegbert et al. [32].

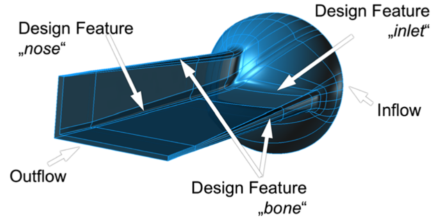
In order to perform numerical die and process design, we formulate the given task as the following optimization problem:

$$\text{minimize} \quad J(\boldsymbol{u}, \boldsymbol{\alpha}), \tag{1}$$

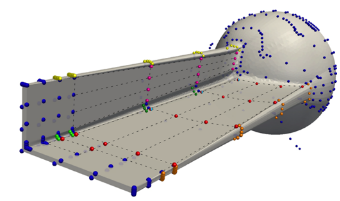
$$\text{subject to} \quad \boldsymbol{c}(\boldsymbol{u}, \boldsymbol{\alpha}) = \boldsymbol{0} \text{ on } \Omega = \Omega(\boldsymbol{\alpha}), \tag{2}$$

where $\boldsymbol{\alpha}$ are the design variables, i.e., certain geometry properties of the die and process parameters, and $\boldsymbol{u}$ are state variables, e.g., the flow properties of the melts. $J(\boldsymbol{u}, \boldsymbol{\alpha})$ is the so-called objective function, which is a measure for quality [8, 25]. As its minimum value is the indication for optimal quality, the objective function has to be chosen carefully. The choice will have a major impact on the optimization outcome. The partial differential equations (PDEs) describing the underlying physical phenomena are represented by the constraint $\boldsymbol{c}(\boldsymbol{u}, \boldsymbol{\alpha})$ in a region Ω. The constraint $\boldsymbol{c}(\boldsymbol{u}, \boldsymbol{\alpha})$ in this case is the Navier-Stokes equations. The region Ω encompasses the die geometry and parts of the considered machinery. As both, extrusion and high-pressure die casting, require different formulations considering each of the terms described above the specific form, of especially the objective functions is elaborated in the application chapter in detail.

The optimization is performed as shown in Fig. 1. Beginning with a first draft of the geometry and the process, a finite element simulation of the relevant parts of the manufacturing process is performed using an in-house solver



(a) Flow channel of an extrusion die producing an L-profile.



(b) Parameterization of the geometry. Each color represents a degree of freedom.

Fig. 2 The geometry of the die and its parameterization

[1] or various commercial solvers. These are interchanged in a modular tool chain. With the results of the solver, the objective function is then evaluated inside an optimization kernel on top of the nonlinear optimization library NLopt [15]. While solving the optimization problem using NLopt's algorithms, the optimization kernel adjusts the design variables based on its results [5] and creates—if necessary—a modified geometry using T-Splines [23]. Subsequently, a new simulation using the adjusted design variables is performed. This procedure results in an optimization routine that will be iterated until an optimal set of design variables is found. The optimization algorithms in NLopt were benchmarked before in [33], which led to the usage of BOBYQA [28], COBYLA [27], DIRECT [16], and CRS2 [17] as optimization algorithms.

At the current state, the number of running-in trials can be reduced significantly. This will allow an earlier Start of Production (SOP) and therefore a shorter Time-to-Market (TTM), which is becoming more important due to shortening product life-cycles and competitiveness with low-wage countries.

In the next section, this general approach is applied to two different die-based manufacturing processes: plastics extrusion and high-pressure die casting.

3 Application

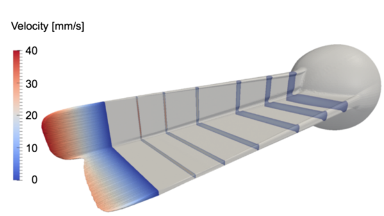
3.1 Plastics profile extrusion

The first area of application of the presented approach is the shape optimization of polymer extrusion dies. In plastics profile extrusion, a continuous profile is produced by pressing plastics melt through a die. The die hereby represents the predominant influence factor on the product's shape, e.g., the die in Fig. 2a produces an L-profile.

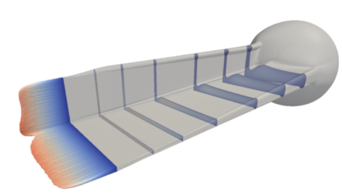
In extrusion die design, the complex and non-intuitive material behavior of polymers is a major obstacle. This makes it hard to determine a die geometry that produces the desired profile cross section. Therefore, the automatic determination of a die geometry that produces a desired profile cross section downstream becomes the optimization task.

State-of-the-art research in this area has, for example, been collected in [7]. Two distinguishing criteria are the choice of design objective and the geometry representation. Concerning the design objective, the homogeneity of the outflow velocity distribution is considered the prime quality criterion by most researchers [8, 35, 39, 41]. This criterion can be backed by secondary criteria such as pressure loss or dwell periods. Another possible criterion is the shape accuracy after the profile has left the supporting walls of the extrusion die, e.g., investigated in [4]. The geometry representation is, in die optimization, mostly handled parametrically, with either simple geometric parameters (height and length) in [3] or spline-based as in [19].

The profile shape is mainly dictated by the velocity distribution at the outflow of the die [20]. In our approach, a homogeneous outflow distribution, also called balanced flow [24], is achieved by adapting different design features of the extrusion die [32] by the modification of control points of T-splines defining the basic geometry [21], see Fig. 2b. Based on the numerical optimization of these features, a homogeneous outflow velocity distribution [5] can



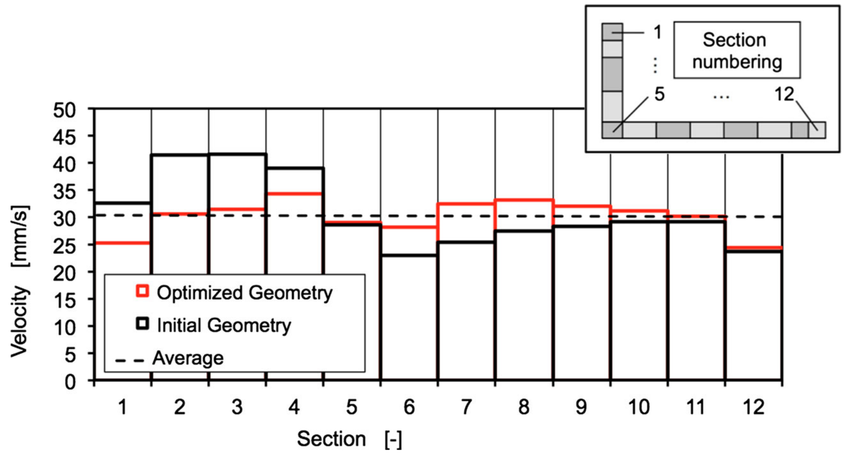
(a) Initial die with respective outlet velocity distribution.



(b) Optimized die with respective outlet velocity distribution.

Fig. 3 Initial and improved velocity distribution and die geometry using all features

Fig. 4 Comparing the average velocity of the outflow sections to the individual sections before and after optimization



be obtained, which aids production quality and brings the profile downstream closer to a desired nominal one.

Approaching the shape optimization problem, a Nested Analysis and Design framework for the problem at hand [21] is equipped with XNS, the already mentioned in-house finite element flow solver, NLopt [15] as optimization kernel and a geometry kernel to handle the T-Spline description of the die. The sensitivities, required by NLopt, can be calculated generally by several methods: direct, adjoint [34], by automatic differentiation [11] or by finite differences. The latter are utilized in our approach.

As described earlier, our design objective is a homogeneous outflow velocity at the exit of the die. One possible quantification of this aim is the objective function

$$J = \sum_{section} (\bar{u}_{section} - \bar{u})^2. \quad (3)$$

It is based on a subdivision of the outflow of the extrusion die into several sections and computes the variance of the local average velocity $\bar{u}_{section}$ compared to the overall average outflow velocity $\bar{u}$ and is well established [5, 10, 24]. In the case, where the average velocity of each section $\bar{u}_{section}$ is equal to the overall average velocity $\bar{u}$, the objective function will reach its minimum value of zero and a perfectly homogeneous outflow velocity distribution will be established.

The framework has been applied to an L-profile extrusion die. The numerical optimization resulted in the following improvement [32]:

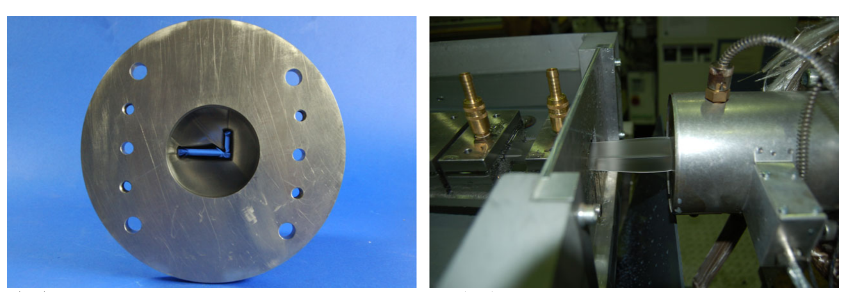
As can be seen, the optimized die (Fig. 3b) reflects the convergence of the average outflow velocity of the single sections towards the overall average outflow velocity, which is shown in detail in Fig. 4. The optimized die, manufactured by the Institute of Plastics Processing (IKV), produced an L-profile after zero iterations, as can be seen in Fig. 5b [13].

3.2 High-pressure die casting

High-pressure die casting, just like plastics profile extrusion, is a manufacturing process that is only profitable for very large lot sizes. This is mainly due to the high costs of die design and manufacturing. As a means of reducing the influence of the cost-drivers, Queudeville et al. have investigated the modularization and standardization of high-pressure die casting dies [29]. It was found that a large number of die components can be modularized; however, others need to remain individual. The latter category contains, besides the cavity, the gating and the temperature-control system.

Usually, the design, especially of the individual die components, requires several simulations and trial runs in order to achieve a good filling of the cavity and a homogeneous temperature profile in the casting. The work that has

Fig. 5 Display of the manufactured die and the extrusion process



(a) View from extruder on the die. (b) The process of production.

been carried out in the context of plastics profile extrusion implies that the numerical optimization is a viable approach to make this process more efficient. In order to optimize the high-pressure die casting process, it is necessary to understand the process together with its main challenges.

In high-pressure die casting, molten metal is injected into a steel die at high flow velocity and pressure. The process itself can be divided into three phases as can be seen in Fig. 6. These are (1) the slow injection phase; (2) the cavity-filling phase; and (3) the solidification phase.

1. The slow injection phase starts once the metal is transferred from the holding furnace into the shot sleeve. During this phase, the molten metal is pushed towards the gating system under moderate plunger acceleration in order to achieve a complete filling of the shot sleeve. The plunger movement is chosen in such a way that air entrapment is minimized.
2. Thereafter, the cavity-filing phase begins. During this phase, the plunger is accelerated to a much higher velocity in order to fill the cavity within a few milliseconds. This phase is mainly influenced by the design of the gating system. The aim of the cavity-filling phase is to achieve a homogeneous melt distribution in the cavity.
3. Subsequently, in the last phase, the metal solidifies while a high pressure is applied. This part of the manufacturing process is greatly influenced by the temperature-control system of the die. During the solidification phase, the aim is to achieve a homogeneous temperature distribution in order to avoid tensions in the resulting product.

While the use of numerical simulations as a CAE tool is very common in the high-pressure die casting industry [9], there are only few approaches focusing on an automated design process. Approaches using DOE have been carried out in [36, 37], but they are lacking an automated optimization routine. Other approaches focus only on the improvement of specific parts of the process or the die design. Hillbinger and Zamora report on the optimization of the plunger acceleration and velocity of the plunger during the slow injection phase [12, 40]. Other topics are the improvement of cavity filling [6, 14] or the optimization of temperature-control systems [18].

The numerical optimization presented in this paper, different from the ones that have been mentioned above, focuses on a holistic approach for an automated die and process design. In order to be able to validate the results of the optimization and to improve the underlying models from the very beginning a benchmark die has been designed (Fig. 7). This modularized die makes it possible to exchange the inserts separately, which allows the use of several different die designs. Another important feature is the two-cavity layout that makes it possible to check different temperature-control system channel designs against each other. The part has been designed as a square plate with a varying wall thickness, which results in a more inhomogeneous temperature distribution and a stronger tendency towards tensions and distortion. This has been done on purpose in order to be able to examine these important issues. To ensure that all the process information needed can be gained, the die is equipped with more than 30 temperature and pressure sensors. Thermocouples are placed on the inlet and outlet of the tempering channels in order to collect data about the heat transferred by the tempering system. Other sensors are placed directly beneath the surface of the inserts to obtain a good overview of the temperature distribution inside the die. With the help of the pressure sensors, it is possible to determine the resulting pressure during the solidification phase as well as the contact pressure between die and casting.

As in the extrusion application, XNS [1] is used for the simulation of the metal and air flow. It is again coupled to NLopt [15] as optimization kernel. The two-phase flow is modeled by the instationary Navier-Stokes equations

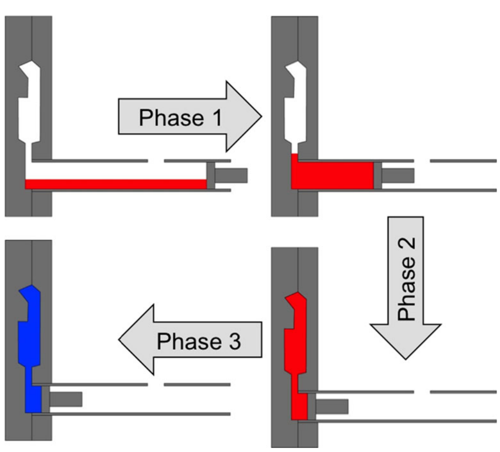


Fig. 6 Phases of the high-pressure die casting process

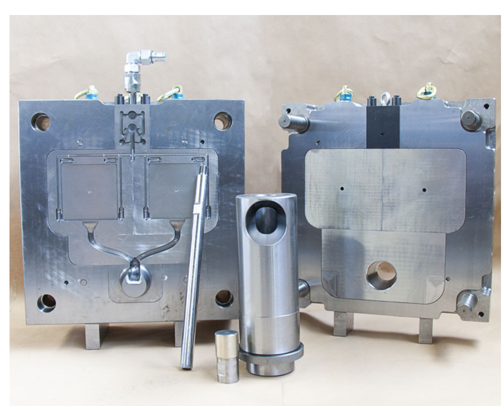
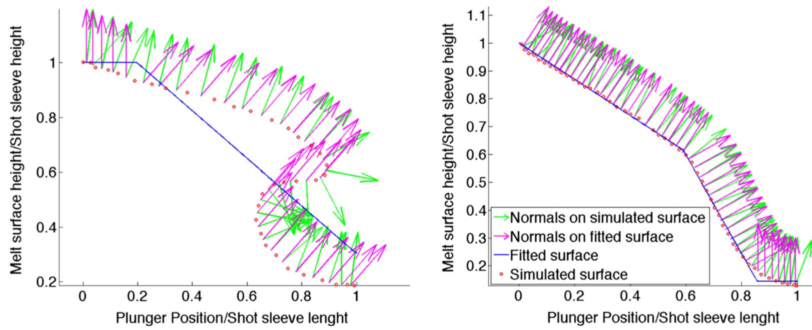


Fig. 7 Modularized die for the validation and further improvement of the numerical optimization

Fig. 8 Differences in objective evaluation for a high and a low quality surface geometry



(a) Surface with low quality. (b) Surface with high quality.

with the Level-Set approach [38]. Molten metal and air are considered to be Newtonian fluids.

In contrast to plastics profile extrusion, high-pressure die casting is an unsteady process. Thus, state variables depend on time: $u = u(t)$. As a result, there arise some challenges in formulating objective functions. These issues lead to a much more complex objective evaluation than in the extrusion application. Because of this, the approach carried out in the context of extrusion die optimization is modified. This means that the three process phases are optimized sequentially. For each phase, a separate objective function is used and the optimized result from the previous phase is used as starting point. Consequently, the optimization effort is reduced enormously compared to a direct optimization of all three phases in one step.

In the first phase, the plunger velocity and acceleration are the design variables. They influence the shape of the phase-interface. In order to reach a minimal air entrapment and prevent breaking waves, two types of interfaces are compared in the objective function. On the one hand, there is the simulated interface, and on the other hand, there is an interface, which is based on a model and fitted to the simulated data. The simulated interface can be extracted from the level-set field by finding the intersection of the zero level-set with the element edges. This results in a set of points x_i where the melt height is known. The model for the fitting is

$$f(x) = \begin{cases} H & \text{if } 0 \le x \le x_1, \\ ax + b & \text{if } x_1 \le x \le x_2, \\ cx + d & \text{if } x_2 \le x \le x_3, \\ e & \text{if } x_3 \le x \le L, \end{cases} \quad \text{with } b \le a \le 0, \tag{4}$$

where a, b, c, d, e, x_1, x_2, and x_3 are the parameters, which are determined by a least-squares fit. H and L are the shot sleeve height and length. In order to get the simulated surface as close as possible to the model, the following objective function is used:

$$J(\boldsymbol{u}, \boldsymbol{\alpha}) = \sum_j \sum_i ||\boldsymbol{n}_{fit_j}(\boldsymbol{x}_i) - \boldsymbol{n}_{sim_j}(\boldsymbol{x}_i)||_2. \tag{5}$$

$\boldsymbol{n}_{fit_j}(\boldsymbol{x}_i)$ and $\boldsymbol{n}_{sim_j}(\boldsymbol{x}_i)$ are the normals on the fitted resp. the simulated phase-interface at timestep j and position $\boldsymbol{x}_i$.

The result for a valid surface structure and an undesirable structure with a breaking wave are shown in Fig. 8 for one time step.

For the following phases, similar approaches with different objective functions are used.

4 Conclusion

The increasing individualization of customer demands requires an adaptation of mass production processes to smaller lot sizes. For this purpose, a method to reduce fixed costs in the design and manufacturing of the die and process has been developed and successfully applied.

The previously described methodology provides a fast and efficient way to automatically design and improve both the process parameters and the shape of the die in die-based manufacturing processes.

In the case of plastics profile extrusion, the developed optimization framework was used to automatically optimize the shape of the flow channel in the extrusion die. The numerical improvement of the flow channel geometry was validated for an L-shape profile and leads to a significant contribution to the design goal of a uniform velocity distribution at the die outlet.

In the case of the high-pressure die casting, the numerical optimization has three potential application areas. First, the slow injection phase of the process has to be optimized in order to guarantee a better filling of the die in the subsequent process. Furthermore, numerical optimization can be used to optimize the design of the gating system, which is essential for a homogeneous filling of the cavity during the cavity-filling phase. Finally, the temperature-control system can be adapted in order to achieve a homogeneous temperature distribution in the die. This is necessary in order to avoid the development of tensions in the resulting product during the solidification phase.

5 Outlook

In future work, the presented approach needs to be validated by experiments for high-pressure die casting, utilizing the dies shown above, as was already done in plastics profile extrusion.

For the purpose of defining objective functions and therefore key quality parameters, the high-pressure die casting die is equipped with a measurement system. This system is focused on the events taking place on the inside of the die. Therefore, it is expected that this can aid to obtain a much better understanding of this heavily used manufacturing process. Furthermore, this will improve the models on which simulation software is build. Mature models are essential to deliver the information needed for the evaluation of the objective functions during the optimization process.

For the extrusion process, besides the ongoing application of our approach with industrial partners, the optimization framework will be extended by the simulation of the die swell [4, 26]. Furthermore, the numerical swell experiments will be validated with practical investigations utilizing inline profile measurement systems. With this solution a complete inverse design process will be established, which returns an optimized die, based solely on the target geometry of a desired product.

In a further step, generative manufacturing techniques such as Selective Laser Melting (SLM) or laser metal forming will be used to manufacture certain components of the dies. This is a necessity since it will otherwise not be possible to implement all results from the numerical shape optimization due to the limitations of traditional manufacturing techniques in the tool-making business.

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