Model Based Optimization of Forging Process Chains under the Consideration of Penalty Functions

Matthias Dannenberg¹,a, Alexander Georgiadis²,b and Bernd-Arno Behrens¹,c

¹ Institute of Forming Technology and Machines, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany
² Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

a dannenberg@ifum.uni-hannover.de, b georgiadis@ifw.uni-hannover.de, c behrens@ifum.uni-hannover.de

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Abstract. For the production of forged components, it is necessary to coordinate and optimize the production stages along the different process chains. This includes the mainstream processes as well as the associated process chains and the respective processes of die manufacturing. Until now, these processes and process chains are commonly planned and optimized independently due to different and often contradictory target criteria. This paper deals with an extended approach to a holistic planning and optimization of forging process chains by means of the optimization technique Genetic Algorithm (GA) in order to reduce production costs and time.

Introduction

Generally, the production of forged components is carried out by multistage forging processes, which are supplemented by additional alternative predecessor and follow-up manufacturing processes, like grinding or turning. This leads, upon reversion, to alternative process chains. The planning and optimization of these process chains regarding technological and economical specifications (e.g. production costs and cycle times) as well as external specifications (e.g. quality issues) represents one key factor for the competitiveness of mass production in any industrial sector. These processes and process chains are frequently optimized independently, due to their different or even contradictory targets, e.g. production costs and time [1].

For an optimal coordination of the whole process chain, consisting of forging die manufacturing and process chains of the forged component, it is necessary to consider the dependencies among the consecutive production stages and between these two process chains.

Therefore, a method for a holistic optimization of process chains was developed in collaboration between the Institute of Forming Technology and Machines (IFUM) and the Institute of Production Engineering and Machine Tools (IFW) at the Leibniz Universität Hannover [2]. By means of this method the high planning effort compared to conventional simulation methods (e.g. Finite Element Simulations) could be reduced by using generic process models and GA. Furthermore, this method supports the process planner in determining the optimal parameter set (e.g. forging temperature and feed rate of the turning process) in order to meet the target criteria (production costs and time) in the design phase of alternative process chains with due regard to component quality. With the identified optimal set of parameters, numerous time consuming FE-simulation runs can be saved.

This paper illustrates the state-of-the-art, the above-mentioned method as well as an expansion of this method. The focus of the further development is to consider additional manufacturing processes to increase the flexibility of process planning and allow an integrative and fast benchmark of different process chains.

In the following section, the procedure of the method for a holistic optimization of process chains using GA will be briefly described. Subsequently the modelling of alternative process chains will be presented. The optimization of the process chains by using penalty functions is part of the next section. Finally an outlook on future research work will be given in the last section.
Method for a holistic optimization of process chains for the manufacturing of forged components

In the following the developed method for an optimal planning of process chains for the manufacturing of forged components will be presented. The method consists of three main steps illustrated in Fig. 1. Based on a previous selection of the additional manufacturing processes as well as an analysis of the resulting relevant dependencies, process parameters and the respective value ranges, process chains are modelled by generic process models. These functional models, based on empirical and analytical data, are used within the following adapted GA. Applying the GA the optimized combination of process parameters is determined under consideration of the target criteria production costs and time as well as quality-related requirements of the workpiece.

Figure 1: Method for a holistic planning and optimization of process chains

Modelling of alternative process chains. The modelling step of alternative process chains is based on processes that are required for manufacturing a down-scaled sleeve for mounting needle bearings used in automobiles which represents a typical forged component. The process chain for the production of the sleeve consists of the manufacturing processes: separation, heating, forming, heat treatment and cutting (Fig. 2). For each manufacturing process, alternative processes were identified. For instance the blank could be separated by sawing and shearing as an alternative to the previously considered cut-off turning process. For the holistic planning and optimization the process chain of die manufacturing is considered and expended by alternative manufacturing processes like eroding and hard grinding (Fig. 2). Dependencies between single processes and the process chains for the production of forged components and the manufacturing of forging dies were analysed mathematically and then emulated and integrated in the corresponding process models. Analogous to the rigid process chain in [2], three different types of dependencies are to be considered within the modelling of the alternative process chains regarding their significance for the defined target criteria (Fig. 2):

- in-process dependencies between the target criteria and the process parameters within one process (e.g. tempering process),
- process-process dependencies between two or more processes within one process chain (e.g. between heating and forging process) and
- global dependencies between two process chains (here: forging die manufacturing and forged component production).
The mathematical modelling of the processes and dependencies with regard to the target criteria represents the basis for the subsequent process chain optimization. For this reason process models, based on literature and own investigations, were developed [2]. Hence, the further processing of calculated data (e.g. MATLAB®) is simplified and an easy verification method is possible. Due to a clear model structure faults in the process models can be quickly detected and patched at short notice. Fig. 3 shows an excerpt of the process model to calculate the production time of a band sawing process. The mathematical description is complicated, due to the dependencies between upstream and downstream processes of the process chain. For example, the heating temperature of the workpiece can be varied during the heating process. Consequently, the required forming force in the subsequent forging process and the wear of the forging die are affected. This leads to varying energy costs and main times of both processes. Hence, the choice of the heating temperature has an impact on unit costs and production time.

In order to gain a better understanding of the influence and dependencies of the variable process parameters as well as to verify the results (e.g. production time) of the process models, sensitivity analyses have been done. Exemplary results of the analyses for the separating process are presented in the following section.

Figure 3: Excerpt of the process model to calculate the production time of the band sawing process

Figure 2: Alternative process chains with different types of dependencies

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Regarding the separation three production technologies (band sawing, circular sawing and shearing) were chosen and analyzed by using the developed process models. Here, the main time has a decisive influence on the production time and depends on the used technology, the basic material (42CrMo4 or C60) and the cutting parameters (e.g. cutting rate, feed per tooth). Therefore, sensitivity analyses of the three named separating processes were conducted in order to investigate the impact of different combinations of parameters (Fig. 4). Due to technological and material reasons, lower and upper bounds of cutting parameters were defined prior to the analyses (e.g. upper bound of band saw cutting rate for C60: 45 mm/min, lower bound: 15 mm/min).

![Figure 4: Results of the sensitivity analyses for band sawing, circular sawing and shearing](image)

In the context of the sensitivity analyses, three groups of cut settings were defined (low, average, high) and further divided depending on the cut basic material for purposes of comparability. Table 1 exemplarily shows selected variable process parameters for the three separation processes for C60.

<table>
<thead>
<tr>
<th>Separating process</th>
<th>Groups</th>
<th>Low</th>
<th>Average</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band sawing</td>
<td>Feed rate [mm/min]</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Circular sawing</td>
<td>Feed rate [mm/min]</td>
<td>25</td>
<td>27.5</td>
<td>30</td>
</tr>
<tr>
<td>Shearing</td>
<td>Cutting velocity [m/min]</td>
<td>5</td>
<td>12.5</td>
<td>20</td>
</tr>
</tbody>
</table>

The analyses revealed that shearing clearly provides the best outcomes concerning the main time. Nevertheless, due to the high carbon content of 42CrMo4 and C60 (C > 0.35 %) cracks can occur during the shearing process [3]. This example demonstrates the complexity of this high-dimensional optimization problem. In addition to the main time also quality aspects have to be considered. This consideration can be done via constraints in the following optimization procedure. For this purpose, a powerful optimization technique combined with mathematical process models is necessary to find the best possible process chain set-up. Thus, one important point is the selection of a suitable optimization algorithm which is fast and robust concerning the adaption to changing demands or constraints in order to achieve the best possible results. Due to the resulting high complexity, semi-guided heuristic methods are effective for process chain optimization [4]. In this context, GAs will be applied as a relevant heuristic method for complex optimization problems.

**Optimization of the process chains by using penalty functions.** The GA represents a subgroup of the Evolutionary Algorithms [5]. The pivot idea of the GA is to imitate the biological evolution process with genetic mechanisms like selection, crossover and mutation [6]. GAs are especially applied, when high-dimensional optimization problems with numerous variable parameters need to
be optimized. This is particularly the case, if there are non-linear or non-differentiable target functions to solve and non-linear restrictions to consider [7].

Before starting the optimization procedure, a fitness function $FF$ has to be designed. The magnitude of this function reflects the quality of the generated solutions. The optimization of practical problems is often associated with constraints that limit the permissible search space [6]. Constraints can be equations or inequalities [8]. In literature, there are several approaches to considering restrictions in connection with fitness functions [9]. The most popular approach in this regard is the use of penalty functions $P^*$ [10]. The development of the penalty function is always problem-specific [9]. By the use of penalty functions invalid solutions are punished within the fitness function [11]. This can be done by considering a solid penalty-independent value from the extent of the violation or by variable penalty values depending on the extent of the violation [12]. It is generally recommended to punish less hard at the beginning than at the end of the optimization procedure [9].

The previously built process models form the basis for the following design of the fitness function for the GA. Therefore, all process models describing the occurring production costs and time consumption are designed under defined penalty functions, for instance to limit machine-related restrictions like the maximum forming force or quality issues of the workpiece like the roughness that have to be considered. The used fitness function $FF$ is described in (Eq. 1). It consists of the single fitness functions of target criteria production costs $FF_C$ and production time $FF_t$ including a weighting factor $g$. This factor allows to weight the target criteria for instance to regard the results from the previous sensitivity analyses or later for the process planner to weight the target criteria after the needed preferences. The penalty function $P_C$ for each process $k$ is integrated in the fitness function of the costs (Eq. 2). If the fitness function and the constraint is invalid (e.g. maximum forming force will be exceeded) a penalty value $P_C$ is added to the value of $FF_C$. In order to punish the solution $x$ less hard at the beginning and harder at the end of the optimization process a quadratic penalty function has been chosen [11]. In this function the percentage penalty value depends on the actual generation $Gen_{act}$ and on the maximal number of generations $Gen_{max}$ of the optimization run and is multiplied by the production costs $P_{c,k}$ of the process (Eq. 3).

$$FF(x) = \sum_{i=1}^{n} g_i \times FF_C(x) + \sum_{i=1}^{n} g_{1-i} \times FF^*_t(x)$$

with

$$FF_C^*(x) = \begin{cases} FF_C(x) & \text{if } x \text{ is the guilty solution} \\ FF_C(x) + P_{c,k}^*(x) & \text{otherwise} \end{cases}$$

with

$$P_{c,k}^*(x) = \left( \frac{Gen_{act}}{Gen_{max}} \right)^2 \times P_{c,k}(x)$$

For the penalty function of the workpiece roughness two different penalty values had to be chosen. This step was necessary to consider the following cases:

- determined roughness is lower than the required roughness (case one) or
- determined roughness is higher than the required roughness (case two).

In case one the violation of the constraint will be punished less hard than the violation of the constraint in case two. These functions form the basis for the use of the GA for different process chains and for the following investigations of the project. Results of the GA, published in [1], for a static process chain already demonstrated that this method in general is able to reduce the planning effort and production time and costs in comparison to a conventional planned process chain.
Summary and Outlook

The research presented in this article shows an approach to a holistic optimization of forging process chains based on sensitivity analyses, to identify the influence of the focused different manufacturing processes and on a GA using penalty functions. These functions contribute to considering technological constraints of the processes and to avoid non-realizable solutions. The developed method will be a fast tool for process planners facilitating the choice of optimal process parameters for different and complex process chains in the early stages of the design phase. The further research focus on the implementation of the aforementioned additional process models of the manufacturing processes in the developed software prototype. Furthermore, the used GA has to be adapted to allow a fast and integrative planning of different manufacturing process chains for forging and the respective tooling.

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References

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